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PROACTIVE INTERFERENCE IN A SEMANTIC SHORT-TERM MEMORY DEFICIT: ROLE OF SEMANTIC AND PHONOLOGICAL RELATEDNESS

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Abstract

Previous research has indicated that patients with semantic short-term memory (STM) deficits demonstrate unusual intrusions of previously presented material during serial recall tasks (Martin and Lesch, 1996). These intrusions suggest excessive proactive interference (PI) from previous lists. Here, we explore one such patient's susceptibility to PI. Experiment 1 demonstrated patient M.L.'s extreme susceptibility to PI using a probe recognition task that manipulates the recency of negative probes (the recent negatives task). When stimuli consisted of letters, M.L. showed greatly exaggerated effects of PI, well outside of the range of healthy control participants. Experiment 2 used a variation of the recent negatives task to examine the relative contribution of semantic and phonological relatedness in PI. This task manipulated semantic and phonological relatedness of probes and recently presented list items. Relative to healthy control participants, patient M.L. showed exaggerated interference effects for both phonological and semantically related probes, both for probes related to the current list and for probes related to the previous list. These data have important implications for theories of semantic STM deficits. Specifically, these data suggest that it is not the rapid decay of semantic representations that is responsible for difficulties in short-term recall, but rather the abnormal persistence of previously presented material. We propose that this susceptibility to PI is the result of a deficit in control processes acting on STM.

Key words: proactive interference, semantic short-term memory, working memory, executive control, left inferior frontal gyrus

Introduction

Contemporary models of short-term and working memory have increasingly emphasized interference, with some models proposing that resistance to interference is a fundamental feature of working memory (Engle et al., 1999; Hasher and Zacks, 1988). Inhibitory control processes may be important in explaining individual differences in working memory performance as well as age-related decline of working memory.

Hasher and colleagues (see May et al., 1999) have examined age-related cognitive decline from the perspective of inhibitory models of attention and memory. They have argued that the critical component of attention and memory processing is an ability to inhibit irrelevant information to allow processing of more relevant material. May et al. (1999) proposed several functions for inhibition in working memory. These functions include restricting the contents of working memory to only relevant information, removing no longer relevant items from working memory and restraining the production of prepotent or dominant responses.

Miller et al. (1993) have proposed an "active reset mechanism" that "clears out" or "resets" memory traces between trials to "avoid cross-trial interference", which is similar to the May et al. (1999) proposal of a role for inhibition in removing no longer relevant items. Miller et al. (1993) recorded from neurons in the anterior inferior temporal cortex of monkeys performing a delayed match to sample task. Inferior temporal neurons have often been studied in delayed match to sample paradigms and are believed to represent "storage" of representations. In these tasks, a sample stimulus was presented (e.g. a picture), followed by zero to four distracter stimuli during the delay. Finally, a probe stimulus was presented and the animal responded by releasing a lever if the last stimulus matched the initial sample stimulus. The general finding was suppression of neural activity in the inferior temporal lobe when a probe stimulus matched the original sample stimulus. Miller et al. (1993) examined another condition in which the sample stimulus and probe stimulus matched and were then followed by another trial in which the same stimulus served as the sample. Crucially, in this condition, no suppression was observed in response to the sample that matched the sample and probe in the previous trial. Thus, the suppression effect did not bridge the 1-2 second interval *between* trials, although it did bridge up to 5 seconds *within* a trial. This effect prompted the authors to infer "an active reset process" that "clears out or resets the memory traces of stimuli from one trial to the next" to "avoid cross-trial interference" (Miller et al. 1993, p. 1475). Furthermore, the authors speculated that this signal might arise from prefrontal cortex. This "reset process" corresponds closely to the second function of inhibition proposed by Hasher and colleagues (May et al., 1999) – deleting items that were once relevant but are no longer relevant.

Engle and Kane (2004) have demonstrated that susceptibility to interference in several different tasks is correlated with working memory span, as low span subjects demonstrate greater interference effects than high span subjects. Performance differences between subjects with low and high working memory spans have been observed in a number of seemingly diverse tasks, including the Stroop task, antisaccade task, negative priming tasks, and tasks that induce proactive interference (PI) (see Engle and Kane, 2004 for a review). Engle and colleagues have argued that executive control of attention is responsible for the relationship between working memory and interference resolution.

Interestingly, some neurologically-damaged patients with short-term memory (STM) deficits also show unusual interference effects. Our laboratory has become interested in the possibility that these interference effects may be particularly important for explaining the pattern of STM deficits exhibited by patients that we have claimed have a deficit in the short-term retention of semantic information. Next, we briefly describe our model of STM, which has proposed dissociable semantic and phonological STM capacities.

The existence of separable semantic and phonological capacities in STM is supported by unique patterns of patient performance on various tasks that tap STM. For example, patients with semantic STM deficits show no advantage for words relative to nonwords (no lexicality effect), while patients with phonological STM deficits fail to demonstrate normal phonological similarity effects. Patients with semantic STM deficits perform better on a rhyme probe task (a task tapping phonological retention) relative to category probe task (a task tapping semantic retention), while phonological patients are better on the category probe than rhyme probe task (Freedman and Martin, 2001; Martin and He, 2004; Martin et al., 1994). It is assumed that patients with semantic STM deficits are unable to accurately maintain lexical-semantic representations in STM. On the other hand, cases with phonological STM deficits are unable to adequately maintain phonological information and depend upon lexical-semantic information during recall. Importantly, this work by Martin and colleagues (Freedman and Martin, 2001; Martin and He, 2004; Martin et al., 1994) has demonstrated that these deficits in retention are not attributable to mere difficulty in phonological processing or semantic knowledge, as these patients typically have very good single-word processing. For example, these patients are very good on tasks such as naming single pictures and repeating single words.

Phonological STM deficits and semantic STM deficits also have very different consequences for tasks tapping language comprehension and production (Martin et al., 1994; Martin and Romani, 1994; Freedman et al., 2004; Martin and He, 2004). Moreover, the two types of deficits appear to result from damage to different areas of the brain. Phonological STM deficits have been associated with lesions to left parietal areas, while semantic STM deficits are associated with damage to the areas of the left frontal lobe. Functional neuroimaging data also support dissociations of maintenance of phonological and semantic representations (Martin et al., 2003; Shivde and Thompson-Schill, 2004). For reasons outlined below, we are particularly interested the role of the left inferior frontal areas in semantic STM.

With respect to intrusions, Martin and Lesch (1996) reported that patients with semantic STM deficits produced a high proportion of intrusions of previous list items during serial recall tasks. While most of the patients' errors were omissions, intrusions were observed on those trials on which they produced an incorrect word. For example, given the list "dog, chair, moon", a patient might respond "dog, chair". When subsequently given another list, "cat, desk, bike", the patient might respond, "cat, chair". Table I displays the intrusion data for the two patients with semantic STM deficits (M.L. and A.B.) reported in Martin and Lesch's (1996) paper, and also shows the data for patient E.A., a patient with a phonological STM deficit who was later tested on the same materials. These intrusion data are previously unpublished. Importantly, while these intrusions were common for the patients with semantic STM deficits, they were almost non-existent for the patient with a phonological STM deficit. Martin and Lesch (1996) noted that these intrusions for the patients with semantic STM deficits were "consistent with the idea that the failure to recall certain items is not due to the complete loss (through decay) of trace information", but rather to "competition among traces". Moreover, PI must presumably be invoked to account for such intrusions. From this perspective, interference among items, rather than decay, may be responsible for failures of recall for the patients with semantic STM deficits.

The infrequency of intrusions during serial recall (relative to omissions) makes it difficult to analyze them quantitatively. Thus, another method for studying PI is needed. In this paper we use a probe recognition task first developed by Monsell (1978) that taps PI. As in all probe recognition tasks, a list of items is presented followed by a probe and

TABLE I

Intrusions/overall error responses during serial recall, excluding failures to recall – Patients A.B., M.L., E.A. Number of lists in which intrusions were present relative to lists in which errors of any type occurred (excluding omissions)

	Two-word lists	Three-word lists
Semantic STM deficits		
M.L.	4/9	12/14
A.B.	11/28	1/8
Phonological STM deficit		
E.A.	1/24	0/13

subjects indicate whether the probe appeared in the list. However, Monsell's (1978) paradigm included a crucial condition intended to reveal PI. Specifically, negative probes were included that did not appear in the current list, but did appear in the list presented immediately before – these are termed "recent negative" probes. On other negative trials, probes were presented that did not appear in the immediate list or the previous two lists – these are termed "nonrecent negative" probes. Likewise, the same "recent" *versus* "nonrecent" manipulation was applied to the positive probes. The principle effect of these manipulations is observed in the contrast of "recent negative" *versus* "nonrecent negative" probes; reaction times are longer (and accuracy often poorer) for the recent negatives compared to nonrecent negatives. In the interest of parsimony, we will refer to this task as the "recent negatives task".

The recent negatives task has been employed in a number of papers in the neuroimaging literature. These studies have consistently reported greater activation in the left inferior frontal gyrus (LIFG), specifically in Brodmann's Area (BA) 45, during recent negative trials when compared to nonrecent negative trials. This increased activation in the LIFG has been attributed to control processes involved in the resolution of interference, rather than reflecting interference itself. For example, Jonides et al. (1998) assumed that an inhibitory mechanism must be necessary to overcome the PI resulting from involuntary persistence of items that appeared in previous lists. The need to employ this inhibitory mechanism causes longer reaction times for recent negative trials and results in the increased hemodynamic activity in the left prefrontal cortex (BA 45). Similarly, in another study using event-related functional magnetic resonance imaging (fMRI), D'Esposito et al. (1999) attributed increased activation of BA 45 to an "interference resolution process" which could possibly represent the inhibition of a prepotent tendency to respond "yes" (given that the probe was observed, but not in the present list). Importantly, this activation of BA 45 was present only after the probe was presented, presumably when the probe was compared to the list items maintained in memory. D'Esposito et al. (1999) contend that this activity represents an executive function related to the left prefrontal cortex. Of particular interest to the present study, the patients with semantic STM deficits reported by Martin and colleagues (Martin and He, 2004; Martin and Lesch, 1996; Martin and Romani, 1994; Martin et al., 1994) have lesions that include left prefrontal areas and BA 45.

We have become interested in the possibility that a deficit in inhibition might explain the STM impairment seen in patients with a semantic STM deficit (Martin and Lesch, 1996). Hamilton and Martin (2005) examined the performance of patient M.L., who shows a semantic STM deficit, on a number of verbal and nonverbal tasks thought to require inhibition. These tasks included the recent negatives task, Stroop task, antisaccade task, and a nonverbal Stroop-like task that induced manual response interference. Patient M.L. showed greatly exaggerated interference effects, substantially outside the range of older control participants, on both the Stroop task and the recent negatives task, both of which use verbal stimuli. In contrast, he performed normally on both of the nonverbal tasks, including the antisaccade task.

Present Study

The present study further examined the exaggerated effects of PI reported for M.L. in Hamilton and Martin (2005) using variations of the recent negatives task. Experiment 1 investigated patient M.L.'s susceptibility to PI using letter stimuli in the recent negatives task. Our previous experiments used only words as stimuli. Letters, which have typically been used in studies of neurally intact individuals, are of interest due to their relative lack of semantic information. Assuming that short-term maintenance of letters depends primarily on the retention of a phonological code, Experiment 1 began to address whether M.L. has difficulty overcoming interference from phonology in STM. Experiment 2 presents data from an experiment specifically designed to examine the relative contributions of semantic and phonological representations in patient M.L.'s susceptibility to PI. Experiment 2 used a variation of the probe recognition task (similar to the recent negatives task) formulated by Bartha et al. (1998). This variation allowed us to determine whether patient M.L.'s exaggerated effects of PI are primarily attributable to persistence of semantic representations, phonological representations, or both. Based on previous evidence of M.L.'s greater difficulty in maintaining semantic relative to phonological information (Martin and He, 2004; described in the next section), we predicted that he would show greater evidence of interference from persisting semantic representations.

Patient History

Patient M.L.

Patient M.L. is a 62-year-old right-handed male with a left-hemisphere lesion resulting from a cerebrovascular accident (CVA) in 1990. He completed two years of college coursework and was employed as a draftsman prior to the CVA. Our previous descriptions of M.L.'s lesion were based on a neurological report from 1992. This report included an evaluation of a computerized tomography (CT) scan and indicated that M.L.'s lesion includes the left frontal and parietal operculum, with atrophy noted in the left temporal operculum and mild diffuse atrophy. However, as part of our research program, we have begun to acquire structural MRIs for all of the patients participating in our research. Structural MRI scans of patient M.L. have revealed that his lesion is larger than indicated by the neurological report and includes not only the LIFG, but also areas more superior to LIFG. In addition, M.L.'s lesion includes substantial areas of the left parietal lobe. The left temporal lobe appears to be spared.

On the word list materials reported in Martin and He (2004), M.L. was 77% correct for two word lists and 10% correct for three word lists (where correct responses are complete lists, recalled in order). As reported by Martin and Lesch (1996) and Freedman and Martin (2001), a number of features of M.L.'s STM deficit support the conclusion that he has a deficit in semantic retention. For instance, he shows no advantage for word recall over nonword recall (Martin and Lesch, 1996). Moreover, he performs much better on a probe task requiring detection of rhyming words relative to a probe task requiring detection of semantically related words. Freedman and Martin (2001) computed a composite z-score for performance on a number of measures tapping semantic and phonological retention. M.L.'s semantic retention composite score was – 2.59 whereas his composite phonological retention score was – .23. In contrast, patient E.A., with a phonological retention deficit, obtained a semantic composite score of 3.86 and a phonological composite score of – 3.95. M.L. demonstrates good comprehension of conversational speech on clinical exam but his narrative production is plagued by word-finding difficulties and reduced phrase length. He demonstrates no apraxia of speech and his repetition of single words is excellent (96% correct).

Importantly, M.L.'s difficulties with semantic retention on STM tasks and with spontaneous speech cannot be attributed to difficulty in comprehending word meanings or producing individual words. Martin and Lesch (1996) reported that M.L. scored above the mean for control subjects on the Peabody Picture Vocabulary Task (Dunn and Dunn, 1981), a standardized test of word comprehension, using norms for 40-year-old subjects, the highest age for which norms are available. On the Philadelphia Naming task (Roach et al., 1996), which requires naming pictured objects, M.L. scored 98% correct, which was above the mean for control subjects (96% correct). As reported by Martin and He (2004), he performed at a normal level of accuracy on unspeeded and speeded tasks examining living-nonliving judgments and category judgments. His reaction times on the living-nonliving judgments were just outside the normal range, but on the category judgments were substantially longer than controls. However, as argued by Martin et al. (1994), the category judgments place some demand on semantic STM, as the subject must retain the category label while deciding if the exemplar is a member of the category.

Experiment 1
Recent Negatives Task Using Letter Stimuli

Hamilton and Martin (2005) demonstrated that M.L. showed a greatly exaggerated interference effect (731 msec relative to control mean of 91 msec) on a recent negatives task that used lists composed of 16 words. The present experiment was carried out to determine if this effect was replicable using letter stimuli rather than words. Previous studies of the recent negatives effect have typically used letter stimuli (Monsell, 1978). Given the relative lack of semantic content for letters compared to words, it is possible that smaller interference effects would be obtained if M.L.'s exaggerated PI is primarily attributable to the persistence of semantic information.

Method

Older Control Participants

Thirty participants matched with patient M.L. for age and education served as a control group in the experiment (mean age for controls = 62.7 years, SD = 9.4; mean education for controls = 3.8 years, SD = 1.23). These older controls were recruited from a pool of regular participants at the Brain and Language Laboratory at Rice University.

Stimulus Materials

Following the paradigm specified by Monsell (1978), a probe recognition task was constructed using 16 consonants (C D F G H J K L N P R S T X Y Z). Three list items were presented serially and followed by a probe. Subjects were asked to make a key press to indicate whether the probe appeared in the list. Trial lists and probes were subject to the following constraints:

- no list repeated an item from the immediately previous list;
- positive and negative probes were presented with equal frequency;
- recent and nonrecent trials were presented with equal frequency;
- probes from the immediately previous trial were never presented on the current trial.

Each trial began with a flashing fixation point that appeared for 1100 msec, followed 100 msec later by the first list item. Three list items were presented serially for 750 msec each and were

TABLE II
Reaction time (RT, in milliseconds) and accuracy Experiment 1 – Patient M.L. and older controls

Participant	Recent negative	Nonrecent negative	Recent positive	Nonrecent positive	Recent- Nonrecent negatives
			Reaction time (millisec)		
Controls					
Mean	862 (235)	836 (209)	826 (211)	839 (211)	27*
Patient M.L.	2810 (1318)	1821 (1124)	1557 (1107)	2125 (2063)	988*
			Accuracy – % Correct		
Controls					
Mean	96.2	98.8	98.2	97.4	2.6*
Patient M.L.	62.5	50	91.7	79.2	12.5

Note. Standard deviations appear in parentheses.
*Significant interference effect, $p < .05$.

separated by a 100 msec inter-stimulus interval. One hundred msec following the presentation of the last item, a fixation point appeared followed immediately by the probe stimulus (resulting in a 'retention interval' of 850 msec). The probe stimulus appeared on the screen for 750 msec and then disappeared. The next trial began 1000 msec after the subject pressed a response key.

Each trial was drawn from one of four conditions – recent negative, nonrecent negative, recent positive and nonrecent positive. For recent negatives, a list is presented, followed by a probe that did not appear in the list (a negative probe), but did appear in the previous list. Again, the presence of a letter that was presented in the previous trial now appearing as the present trial's probe is the source of an interference effect. The effect is indicated by longer reaction times and lower accuracy in this condition relative to the nonrecent condition.

Results

Reaction time and accuracy data for all participants appear in Table II. Older controls were 27 msec slower to respond to recent negative trials relative to nonrecent negatives [$t(29) = 2.10$, $p = .044$]. Older controls were also less accurate on recent negative trials (96.2%) relative to nonrecent negative trials (98.8%) [$t(29) = 3.36$, $p = .002$].

M.L. demonstrated a greatly exaggerated interference effect relative to older controls. He was 988 msec longer to respond to recent negatives compared to nonrecent negatives, which was statistically significant in a test using items as the random variable [$t(25) = 2.06$, $p = .049$]. This interference effect was well outside the range of control interference and was 13.9 standard deviations above the mean interference effect for controls. M.L. also showed some evidence of facilitation on the positive trials as he was 568 msec faster to respond to recent positives than nonrecent positives, although this difference failed to reach significance [$t(39) = 1.12$, $p = .269$].

To address the possibility that M.L.'s exaggerated interference effect on the negative trials was merely a function of his longer overall reaction times in the task (see Verhaeghen and De Meersman, 1998), interference effects were also calculated using a more conservative log transformation. The log transformation minimizes the influence of outliers and the difference between logarithms (as in the recent negatives minus nonrecent negatives difference used to calculate interference effects in this paradigm) is equivalent to a ratio (Meiran, 1996). When reaction times for controls and M.L. were submitted to log transformations, M.L.'s interference effect was 6.205 standard deviation above the mean interference observed in the older control group.

M.L.'s accuracy was much poorer than controls overall, particularly on the negative trials (see Table II). His accuracy was significantly higher on the positive (85% correct) than on the negative trials (56% correct) [$t(94) = 3.28$, $p = .001$]. M.L. performed slightly better on the recent than nonrecent negatives; however, this difference was far from significant [$t(46) = .86$, $p = .39$]. He also showed somewhat higher accuracy on the recent than nonrecent positives, although this difference also failed to reach significance [$t(46) = 1.22$, $p = .228$].

Discussion

In Experiment 1, the effect of PI observed in the recent negatives task with normal healthy participants (indicated by increased RT) was found to be dramatically exaggerated for patient M.L., a patient who produced many intrusions of previously presented items during serial recall tasks. Thus, M.L. shows greatly exaggerated PI from letter stimuli as well as word stimuli (as reported in Hamilton and Martin, 2005), despite the relative lack of semantic information in letters. His overall performance is poorer with letter stimuli relative to his performance with the word stimuli. Given that letter memory presumably depends mainly on the retention of phonological representations, the results suggest that M.L. has difficulty with the persistence of phonological codes in STM, in addition to any difficulty with the persistence of semantic codes. This issue will be addressed directly in Experiment 2.

M.L.'s higher accuracy on the positive trials compared to negative trials indicated a bias to say "yes". One possible explanation for M.L.'s poor performance on both recent and nonrecent negative trials is that PI from previously presented trials served to create a positive response bias by way of increased activation for all previously presented items. In other words, even a nonrecent negative trial elicited sufficient PI to generate a "yes" response from patient M.L. A similar pattern was reported in Hamilton and Martin (2005) for stimuli repeatedly sampled from a set of 16 words, where M.L. scored 98% correct on the positive trials and 75% correct on the negative trials. However, in that study, he was significantly more accurate on the nonrecent negatives (88% correct) than on the recent negatives (63% correct). Behavioral data from an unpublished event-related potential study using the recent negatives task is consistent with the notion that repeated sampling from the same stimuli set leads to the poor performance on nonrecent negatives relative to positive trials (Martin et al., 2004). In that study, word stimuli were used and stimuli were repeated only as needed to create the recent negatives condition (thereby greatly expanding the number of unique stimuli in the task). The results showed that M.L. performed at about the same level on the positive trials (73% correct) and nonrecent negative trials (77% correct). He still performed very poorly on the recent negative trials (38% correct).

The results of Experiment 1 also illustrate the seemingly paradoxical nature of patient M.L.'s semantic STM deficit. Although patient M.L. has great difficulty recalling even three words in serial recall tasks, he is plagued by PI from items in previous lists. Importantly, these data are not easily accommodated by a theory hypothesizing overly rapid decay of STM representations as the cardinal feature of STM deficits. If rapid decay of STM representations were to explain M.L.'s STM deficit, one might reasonably expect smaller effects of PI.

Experiment 2

Experiment 2 was formulated to determine whether list items sharing only semantic or phonological features with probes are sufficient to produce PI. Bartha et al. (1998) demonstrated that semantic relatedness does elicit PI in STM tasks in healthy participants. Experiment 2 attempted to not only examine semantic interference effects for patient M.L., but to also further investigate the role of phonological representations in eliciting interference.

Data from older controls and undergraduate students is also of interest in Experiment 2. Bartha et al. (1998) examined interference effects only from probes semantically related to items in the same list, whereas Experiment 2 examined semantic and phonological interference effects for probes related to items in either the current list or the preceding list. These manipulations may provide insight into the role of both phonological and semantic representations in generating interference across multiple lists in healthy participants.

Experiment 2 should also provide additional insight into the nature of M.L.'s deficit, addressing the level at which M.L. is failing to inhibit previously presented stimuli. If one assumes that his semantic STM deficit results from the rapid decay of semantic representations, M.L. would be predicted to show little or no PI from semantically related probes. However, he might show normal or exaggerated interference to phonologically related probes if his failure to adequately maintain semantic representations results in a reliance on phonological information. Alternatively, if some type of inhibitory mechanism is failing to operate on both semantic and phonological representations in STM, M.L. may show interference effects exceeding normal interference observed in healthy controls for both semantically and phonologically related probes.

Method

Participants

In addition to patient M.L., we tested fourteen older control participants recruited from a participant pool maintained by the Brain and Language Laboratory at Rice University (mean age = 66 years, SD = 5.8; mean education = 4 years, SD = 1.41). Twenty-five Rice University undergraduates also participated in Experiment 2. These participants were enrolled in a Psychology course and received course credit for participation.

Stimulus Materials

Using methodology similar to that presented in the experiment above, Experiment 2 attempted to determine whether probes that shared only semantic or phonological features with items in the same or previous list were sufficient to induce interference. To address this question, probes were constructed to maximize their phonological or semantic similarity with a single list item. Examples of all four types of trials appear in Table III.

In both examples of phonologically related trials, the list item "HAIR" (presented in either the immediate list or the previous list) shares phonology with the probe word "PEAR". Phonologically related stimuli appear in Appendix A. It was hypothesized that PI would result from these shared

TABLE III

Stimuli for Experiment 2 – All stimuli were presented serially in uppercase letters

Phonologically related – Same list trials

List items	Probe	Response
GUN LOG HAIR ←	PEAR	"NO"

Phonologically related – Previous list trials

List items	Probe	Response
GUN LOG HAIR	TEA	"NO"
HUB BOOK SKY	PEAR	"NO"

Semantically-related – Same list

List items	Probe	Response
GUN BAR FROG ←	TOAD	"NO"

Semantically-related – Previous list

List items	Probe	Response
GUN BAR FROG	TEA	"NO"
HUB BOOK SKY	TOAD	"NO"

phonological features. Similarly, in the examples of semantically related trials, the probe "TOAD" shares semantic features with the previously presented list item "FROG". Semantically related stimuli appear in Appendix B. It is hypothesized that PI will result when a list item presented in the same trial or the immediately previous trial is semantically related to a subsequent probe (in this case 'TOAD'). Note that "semantically related" includes items that are not strictly synonyms, as were used in Bartha et al. (1998). In the present experiments, semantically related items were items judged to share semantic features. Judgments of semantic relatedness were made by the authors.

Reaction times and accuracy for the "phonologically related" and "semantically related" trials, for previous list and same list conditions, were contrasted with "unrelated negative" trials. "Unrelated negative" trials are probes that share no features with previously presented list items.

Experiment 2 was administered over two separate days, separated by at least three days, but typically by one week. Participants received 12 blocks of 28 items on each day for a total of 24 blocks and 672 total trials. Each block included both phonologically-related and semantically-related trials.

The experiment contained 42 trials from the "semantically-related – same list" condition, 42 trials from the "semantically-related – previous list" condition, 42 trials from the "phonologically-related – same list" condition, 42 trials from the "phonologically-related – previous list" condition and 168 trials of the "unrelated negative trials". Therefore, one half of the negative trials were either semantically or phonologically related to previously presented items, while one half were completely unrelated to previously presented items. Again, the "unrelated negative trials" serve as a comparison condition with which to compare the negative responses that involve a semantically or phonologically related probe. In addition, 336 positive probe trials were presented, such that there were also equal numbers of negative and positive trials.

The stimulus presentation rates were as follows. Each trial began with a 1000 msec presentation of a flashing fixation point followed by a 100 msec interval. Next, each of the three words was presented serially for 1000 msec, separated by a 100 msec inter-stimulus interval. The third word was followed by a 100 msec interval and then a fixation point was presented ('XXXX') for 1000 msec. This provided a brief retention interval of 1100 msec. The probe word immediately followed the fixation point and was displayed for 750 msec. Participants were encouraged to provide their response as "quickly and accurately as possible" following the onset of the probe word. The trial was terminated after 10 seconds to minimize the possible influence of extreme outliers on subsequent trials. In other words, this response window was necessary to prevent subjects from essentially undermining the chosen inter-trial interval by delaying their responses. For the phonologically related stimulus pairs, visual similarity likely plays at least some role in determining familiarity between probes and list items. We attempted to minimize the role of visual similarity by choosing pairs of words that were judged to be visually less similar (i.e., 'PEAR-HAIR' as opposed to 'FAIR-HAIR'). Also, all list items and probes were presented in upper case. This should have served to maximize the similarity of both phonologically related and unrelated probes to the list items and eliminated distinctive word shape cues that might have been more similar for the phonologically similar than unrelated items if lower case presentation had been used.

Results

Results for Experiment 2 are discussed for undergraduate and control participants followed by the results for patient M.L. (control participants were matched roughly for age and education with patient M.L.). Reaction time and accuracy data appear in Table IV (phonologically related trials) and Table V (semantically related trials). Incorrect trials were removed for the reaction time analysis. All responses greater or less than 2.5 standard deviations from each subject's mean for each trial type were removed from the reaction time analysis. Interference effects for each condition were calculated by subtracting mean reaction times for unrelated negative trials from the mean of each related condition.

Undergraduate Participants

Reaction time. On the phonologically related same list trials, undergraduate participants

TABLE IV
Mean reaction time (RT, in milliseconds) and accuracy for phonologically related trials in Experiment 2 – Controls and patients

Participant	Phonological-same list	Phonological-previous list	Unrelated-negative
	Reaction time (millisec)		
Undergraduate controls	750* (202)	686 (155)	700 (163)
Controls	861* (201)	810 (209)	785 (180)
M.L.	1596* (975)	1485* (656)	1209 (617)
	Accuracy – Proportion Correct		
Undergraduate controls	97	98	97
Controls	97*	99	99
M.L.	83*	90	94

Note. Standard deviations appear in parentheses.
*Significant interference effect, p < .05.

TABLE V
Reaction time (RT, in milliseconds) and accuracy for semantically related trials in Experiment 2 – Controls and patients

Participant	Semantic-same list	Semantic-previous list	Unrelated-negative
	Reaction time (millisec)		
Undergraduate controls	744* (208)	702 (183)	700 (163)
Controls	825* (199)	790 (177)	785 (180)
M.L.	1565* (978)	1703* (904)	1209 (617)
	Accuracy – Proportion Correct		
Undergraduate controls	97	97	97
Controls	99	99	99
M.L.	95	93	94

Note. Standard deviations appear in parentheses.
*Significant interference effect, p < .05.

demonstrated a 50 msec interference effect [t(24) = 4.11, p < .0001]. On the phonologically related previous list items, they showed no interference. In fact, undergraduate participants were 14 msec faster to reject probes that were phonologically related to an item in a previous list, although this difference was of only marginal statistical significance [t(24) = 2.028, p = .0538].

Undergraduate participants showed a statistically significant 44 msec interference effect for semantically related same list trials [t(24) = 3.15, p = .004]. On the semantically related previous list items, there were no differences (semantically related previous = 702 msec, unrelated negative trials = 700 msec). In summary, undergraduate subjects showed statistically significant interference effects for both phonologically and semantically related items, but only for those related to items in the same list.

Accuracy. As is apparent in Tables IV and V, there were no significant differences in accuracy among the negative conditions. Undergraduates were 96% correct on positive trials.

Older Control Participants

Reaction time. On phonologically related same list items, older control subjects showed a statistically significant interference effect of 76 msec [t(13) = 5.57, p < .0001]. Older controls showed a 25 msec interference effect for phonologically related previous list trials; however, this difference did not reach statistical significance [t(13) = 1.35, p = .20]. On semantically related same list item, older controls demonstrated a statistically significant 40 msec interference effect [t(13) = 4.00, p = .002]. On the semantically related previous list items, older controls showed no interference effects [t(13) = .30, p = .77].

Thus, as was the case for the undergraduate participants, older subjects showed statistically significant interference effects for both phonologically and semantically related probes, but only for probes related to items in the same list.

Accuracy. On probes that were phonologically related to items in the same list, older controls were 97% correct. This difference, when compared to accuracy on unrelated trials (99%), was statistically significant [t(13) = 2.32, p = .04]. On all other negative conditions, older control participants were 99% accurate. They were 98% accurate on all positive trials.

Patient M.L.

Reaction time. M.L. showed statistically significant interference on all four related conditions. On the phonologically related-same list trials, M.L. showed a 387 msec interference effect [t(184) = 2.93, p = .003]. On the phonologically related- previous list trials, M.L. showed 276 msec interference effect [t(187) = 2.41, p = .017]. On the semantically related-same list trials, M.L. showed a 356 msec interference effect [t(189) = 2.81, p = .005]. For the semantically related- previous list trials, M.L. showed a 494 msec interference effect [t(188) = 3.98, p < .0001].

Using log-transformed data, M.L.'s interference effect for phonologically related-same list trials was 2.243 standard deviations above the mean of older control participants. His interference effect for phonologically related-previous list items was 2.710 standard deviations above the older controls' mean. On the semantically related-same list items, M.L. was 4.548 standard deviations above the control mean and on the semantically related-previous list items; he was 5.582 standard deviations above the mean.

Accuracy. On the unrelated negative trials M.L. was 94% correct. M.L. was 83% correct on the phonologically related-same list items, which was significantly less accurate than his accuracy on the unrelated negative trials [t(208) = 2.29, p = .02]. There were no other statistically significant differences among other trial types. M.L. was 92% correct on the positive trials.

Discussion

Both older control subjects and undergraduate subjects showed significant interference effects for both phonologically related and semantically related probes, but only when the probe was related to an item in the same list. This replicates the semantic interference reported by Bartha et al. (1998) in a similar probe recognition paradigm. In addition, Experiment 2 also demonstrated that similar interference effects exist for phonologically related probes. Importantly, the presence of semantic interference effects provides additional evidence that semantic codes are active in STM, a point ignored by many models of short-term and working memory. However, in older control and undergraduate participants, these interference effects did not extend to probes that were related to items in previous lists. The marginally significant difference between the phonologically related – previous list condition and the unrelated condition demonstrated by undergraduate participants' demands replication. Given data from older control participants and the fact that there is no currently available explanation for such an effect, it seems likely that a larger experiment with more power would not replicate this effect.

When considering reaction times, patient M.L. showed statistically significant interference effects on all four related trial types. Importantly, he demonstrated interference effects for both phonologically and semantically related probes and this interference was apparent for probes related to items in both same lists and in previous lists. Consistent with his greatly exaggerated interference effects on previous versions of the recent negatives task, M.L. also appears to be much more susceptible to semantic and phonological interference in Experiment 2. Consequently, the pattern for M.L. did not fit that predicted by an assumption that he had difficulty inhibiting only semantic representations. Interpretation of this result is provided in the general discussion.

General Discussion

The presence of exaggerated PI effects in a patient with a STM span of two to three items is problematic for theories proposing that STM deficits result from the rapid decay of representations. These exaggerated interference effects were demonstrated using variations of the recent negatives task with patient M.L. We have hypothesized that these interference effects are related to deficits in inhibitory executive functions or control processes operating on STM.

Using lists of three words, patient M.L., a patient with a semantic STM deficit, showed significant interference even when probes were only phonologically or semantically related to list items. The results were surprising given that his STM pattern has implicated specific difficulty with retaining semantic information. If his deficit were due solely to a rapid loss of semantic information, then no semantic interference would have been predicted. If his deficit were due solely to difficulty inhibiting semantic information, then interference from semantically but not phonologically related list items would have been predicted. Neither of these patterns was observed. The results instead suggest that he has difficulty inhibiting both phonological and semantic representations. We have noted elsewhere that the patients we have labeled as semantic STM deficits are also somewhat impaired in their retention of phonological information (Martin et al., 2003). Their phonological retention is better than that of patients identified as phonological STM deficit patients, but they clearly perform below normal on tasks that might be thought to tap mainly phonological representations, such as nonword list recall (e.g., Martin et al., 1994). Consequently, it may be the case that they have deficits inhibiting all types of verbal information. On the other hand, patients with phonological STM deficits may, in fact, have a specific deficit resulting in the rapid loss of phonological information – which results in a more severe deficit on tasks tapping phonological retention.

Of course, the present data do not allow us to unequivocally rule out the possibility that rapid decay plays some role in M.L.'s deficit. As a pointed out by a reviewer, Conrad (1960) was concerned with essentially the same phenomenon that led us to the current series of experiments-namely, intrusions of previously presented list items during short-term serial recall. Conrad (1960) found that when errors occurred during recall of a list, they typically took the form of serial order intrusions from the previous list (i.e., the intruding item was from the same serial position, but from the previous list). Conrad (1960) reported that intrusions decreased when the inter-trial interval was increased from 15 seconds to 25 seconds to 40 seconds. Conrad (1960) concluded that a "decay theory of immediate memory" was the likely explanation of his data. One of the many variations of the recent negatives task that we have administered to M.L. included increasing the inter-trial interval from 1000 msec to 4000 msec. One would expect that if representations were decaying rapidly, M.L. would experience less interference when the interval between lists is increased. We found that this manipulation produced no difference in M.L.'s interference effect on the recent negatives task. His interference effect as measured by the recent negatives *versus* nonrecent negatives was 1059 msec and his accuracy on the recent negatives trials did not improve. Thus, increasing inter-trial delay from one to four s did not improve M.L.'s performance on this task. Of course, it is possible that an even longer delay between trials would reduce the interference effect. Future manipulations of inter-trial delay may determine just how long this information persists.

Another piece of evidence arguing against a rapid decay account is M.L.'s performance on the positive trials. If decay occurred very rapidly for M.L. such that he had difficulty discriminating between a positive trial and a partially matching negative trial, then one might have expected that his accuracy would be poor on early list items on the positive trials[1]. This was not the case, however. In Experiment 2, his accuracy on the positive trials by serial position was: 1) 95%, 2) 89%, and 3) 92% (for Experiment 1, the serial position data for positive trials are complicated by the inclusion of the recent positive condition in which there are two serial positions to consider, one for the item matching in the same list and one for the item matching in the previous list, for which the serial positions may differ).

Patient M.L.'s data have important implications for conceptualizations of semantic STM deficits. These data suggest that M.L.'s memory deficit is not merely the result of rapid decay of representations in STM. Instead, these experiments demonstrate that M.L. is plagued by the persistence of representations in STM. Such persistence is ostensibly a result of a deficit in a control mechanism presumed to be inhibiting no-longer relevant representations in STM. While this effect may at first seem quite paradoxical, such an account would accommodate some of the memory deficits observed in patient M.L. Most notably, the present experiments strongly suggest that M.L.'s tendency to produce intrusions during serial recall is an extreme case of PI. More speculatively, persistent activation of representations in STM could serve to effectively disable STM buffers needed for short-term recall. Without an inhibitory mechanism, short-term buffers might succumb to catastrophic activation (and subsequent interference) and be unable to accurately resolve representations held during short-term maintenance. In other words, short-term maintenance of information may necessarily require an inhibitory component or control process that selects relevant information from among many competing representations active in STM.

It should also be noted that the account we have offered to explain M.L.'s deficit is in accord with models of working memory and executive attention proposed by Hasher and Zacks (1988). As discussed previously, this model has emphasized the role of inhibitory executive control processes in determining an individual's performance on working memory tasks. In particular, M.L.'s performance on the recent negatives task could be attributed to a deficit in the "deletion" function of inhibition (May et al., 1999), which is responsible for removing no longer relevant representations from the focus of attention. Without such an inhibitory control mechanism to delete previously presented items from STM, M.L. is overwhelmed by PI. The neurophysiological work of Miller et al. (1993) further suggests that such a mechanism (inferred from behavioral data by Hasher and colleagues; see May et al., 1999 for a discussion of the role of PI in determining STM span) appears to be instantiated in the primate brain.

Recently, several patients with left frontal lesions have been reported who have been argued to have deficits in control processes involved in language processing. These patients have difficulty with speech production tasks, though their performance on standardized picture naming tasks may be at least relatively well preserved. For example, McCarthy and Kartsounis (2000) and Wilshire and McCarthy (2002) reported patients that performed poorly during repeated naming of a small set of items, particularly when the set of items were semantically related and when the presentation rate was fast. This problem was attributed to difficulty in selecting among competing lemma representations (i.e., lexical representations that contain syntactic but not phonological information). Similarly, Schwartz and Hodgson (2002) reported a patient (M.P.) who was much more impaired in producing the names of pictured objects when describing several presented in a scene than when naming the same pictures presented singly. They hypothesized a deficit in syntactic control processes that serve to boost the activation of an appropriate lemma representation when it is to be selected for production. Another study of relevance to the current data was reported by Robinson et al. (1998), who attributed a case of dynamic aphasia to the inability to resolve interference "under conditions when there are many competing verbal response options and a greater amount of mutual inhibition…".

It is tempting to attribute all of these cases to difficulty with inhibition of competing lexical representations. This competition may stem from

[1]Hamilton (2004) also examined the performance of patient E.A., a patient with a phonological STM deficit, on Experiment 2. However, interpretation of these data was complicated by the E.A.'s bias to respond "no" in the task. Specifically, her accuracy was greater than 98% for each of the negative conditions, but only 62% on the positive trials. When analyzing serial position effects of the positive trials, E.A. was 53% correct on probes that matched an item in the first serial position, 51% correct when probes matched an item in the second serial position and 81% when a probe matched an item in the third serial position. Such a serial position pattern on the positive trials clearly differs from M.L.'s and seems more consistent with overly rapid decay. Given E.A.'s better performance for trials that matched the third serial position, interference effects were recalculated for only probes that were phonologically or semantically related to items in the third serial position. When interference effects were recalculated in this manner, E.A.'s interference effects (as measured by reaction times) were not statistically significant and within the range of control participants.

selecting among several semantically related items. Similarly, in phrase or sentence production, a single item appropriate for a syntactically-specified serial position might need to be selected from a set of activated items. However, in other experiments with M.L. using materials from the studies cited above, M.L. did not show many of the features demonstrated by these other cases (see Crowther et al., in press). Thus, it seems likely that there are a variety of control mechanisms involved in language processing that are localized in left frontal regions, with different mechanisms affected in different patients.

While we believe that M.L.'s data suggest a role for inhibition and interference in conceptualizing semantic STM deficits, these data do not rule out the possibility that other patients with semantic STM deficits do experience rapid decay of semantic representations. Obviously, to determine whether the constellation of inhibitory and STM deficits presented in this paper is unique to M.L., these experiments should be replicated with other patients identified as having semantic STM deficits.

Thus, future research should further pursue the possibility that semantic STM deficits result from persisting activation of representations in STM. Moreover, this persistence of activation may cause an inability to properly resolve interference among appropriate verbal representations.

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Appendix A

Experiment 2 – Phonologically-related pairs. All words were presented in uppercase

Dean	Scene	Cloak	Stroke
Pearl	Curl	Grail	Sale
Call	Haul	Bed	Thread
Guile	Tile	Gale	Pail
Sauce	Cross	Bait	State
Sweat	Bet	Cane	Brain
Fist	Cyst	Swell	Jail
Four	Pore	Ton	Sun
Floor	Gore	Gate	Freight
Plume	Room	Flood	Bud
Gauge	Cage	Isle	Smile
Dye	Thigh	Knead	Greed
Dome	Foam	Beau	Foe
Fruit	Loot	Caulk	Talk
Herb	Curb	Fright	Bite
Thumb	Gum	Gene	Mean
Guide	Bride	Foul	Owl
Thyme	Lime	Chew	Due
Soak	Poke	Ghoul	Mule
Merge	Urge	Burn	Learn
Bench	Lynch	Doe	Throw
Stain	Crane	Debt	Set
Shrewd	Nude	Rule	Stool
Ghost	Toast	Steak	Fake
Guest	Vest	Make	Ache
Moon	June	News	Snooze
Dare	Bear	Gain	Mane
Verse	Purse	Sheet	Meat
Suede	Maid	Sew	Go
Ease	Cheese	Fry	Die
Noun	Crown	Chain	Pane
Type	Stripe	Mile	Style
Jinx	Links	Poll	Coal
Sight	Kite	Hair	Pear
Drought	Scout	Tough	Snuff
Stray	Grey	Light	Site
Weight	Gait	Troupe	Snoop
Score	Pour	Jaunt	Font
Vein	Lane	Stein	Mine
Chief	Beef	Flow	Dough
Stew	Clue	Crew	Blue
Hurl	Girl	Sign	Fine

Appendix B

Experiment 2 – Semantically-related pairs. All words were presented in uppercase

Barge	Raft	Plane	Jet
Dress	Skirt	Whine	Cry
Yarn	Twine	Smirk	Grin
Plate	Dish	Wick	Fuse
Dock	Pier	Swine	Pork
Crime	Theft	Road	Street
Boot	Shoe	Yacht	Boat
Mound	Pile	Bag	Sack
Soot	Ash	Bunk	Cot
Tomb	Crypt	Brush	Comb
Hat	Cap	Pew	Bench
Mouse	Rat	Beach	Shore
Urn	Vase	Song	Hymn
Clock	Watch	Box	Crate
Pledge	Oath	Creek	Stream
Paste	Glue	Gown	Robe
Block	Cube	Scheme	Plot
Blouse	Shirt	Rent	Lease
Thread	String	Skin	Flesh
Rag	Cloth	Stripe	Line
Blame	Fault	Bee	Wasp
Boar	Hog	Dart	Spear
Ill	Sick	Rock	Stone
Nun	Monk	Threat	Risk
Cup	Mug	Chair	Seat
Ewe	Lamb	Damp	Moist
Shout	Yell	Shrub	Bush
Screw	Bolt	Lawn	Yard
Hive	Nest	Dog	Hound
Oak	Elm	Dirt	Soil
Tire	Wheel	Ice	Sleet
Prank	Hoax	Kid	Child
Frog	Toad	Jolt	Shock
Troll	Elf	Bliss	Joy
Fight	Brawl	Bean	Pea
Pipe	Hose	Oil	Grease
Shape	Form	Crook	Thief
Job	Work	Test	Quiz
Trail	Path	Quail	Dove
Cheat	Fraud	Meal	Food
Limb	Branch	Swan	Goose
Fang	Tooth	Throat	Neck