Research Article

The Role of Inhibitory Control in Forgetting Semantic Knowledge

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ABSTRACT—*Previous research has shown that episodic retrieval recruits inhibitory processes that impair memory for related events. We report two experiments examining whether inhibitory processes may also be involved in causing semantic memory lapses. In a semantic retrieval-practice paradigm, subjects were given trials presenting a cue (a homograph in Experiment 1, a category in Experiment 2) linked to many different items in semantic memory. For each cue, subjects used general knowledge to generate no (baseline), one, four, or eight different items of semantic knowledge. Afterward, we determined through an apparently unrelated free-association test whether a critical nonpracticed concept associated to the cue had been inhibited. Both experiments found that generating items from semantic memory suppressed competing concepts, and that this impairment was cue independent. These findings show that inhibitory control processes overcome interference during semantic retrieval and that recruitment of these processes may contribute to semantic forgetting.*

Everyone occasionally consults the dictionary to determine the meaning of a forgotten word. Sometimes this happens because the word was learned poorly. Other times, however, the lapse is accompanied by the feeling that one once knew the meaning. Reviewing the word's definition often brings an "aha!" that confirms this feeling. These experiences are not limited to word meanings; people may forget the names of other people they once knew, old telephone numbers they dialed hundreds of times, or facts about a concept or topic with which they were once familiar. These examples illustrate that although semantic memories may be more firmly entrenched than episodic memories, they too are subject to forgetting. This article is concerned with the mechanisms that produce semantic lapses. Our claim is that they are produced, in part, by an inhibitory control process recruited during semantic retrieval to overcome interference from related semantic memories. Inhibition suppresses competing concepts, making them more difficult to recall. We argue that this process is analogous to or the same as the inhibitory mechanism that produces forgetting in episodic retrieval, and that this mechanism may be supported by the prefrontal cortex.

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INHIBITORY PROCESSES IN EPISODIC RETRIEVAL

A number of findings suggest that episodic retrieval recruits inhibitory processes to suppress competing traces (for reviews, see M.C. Anderson, 2003; Levy & Anderson, 2002). This idea is often studied with a procedure known as the retrieval-practice paradigm. In this paradigm, subjects study exemplars from taxonomic categories (e.g., *fruit-orange*, *fruit-banana*, *tree-oak*) and then practice retrieving half of the exemplars from half of the categories by recalling those studied items given a category and letter stem as cues (e.g., *fruit-or___*). Each practice item is tested several times. After a delay, subjects are tested on all items. Unsurprisingly, practice improves delayed recall of the practiced items. More interestingly, it impairs recall of the remaining unpracticed exemplars of the practiced categories, a phenomenon known as *retrieval-induced forgetting* (M.C. Anderson, Bjork, & Bjork, 1994). Retrieval-induced forgetting has been replicated across a range of stimuli, including propositions, personality traits, visuospatial materials, and eyewitness events, suggesting a general involvement of inhibition in episodic forgetting.

Although retrieval-induced forgetting has typically been attributed to inhibition, retrieving a memory might cause other effects that impair memory for related traces (see M.C. Anderson & Bjork, 1994, for a review). For instance, retrieval might strengthen the association between the retrieval-practice cue (e.g., *fruit*) and the practiced trace (e.g., *orange*). This might cause the strengthened memory to intrude persistently during later attempts to use that cue to recall other memories (e.g., *banana*) associated to it (e.g., Rundus, 1973). Such *blocking* processes are built into many models of retrieval (J.R. Anderson, 1983; Raaijmakers & Shiffrin, 1981) and do not require inhibitory mechanisms to explain retrieval-induced forgetting. Retrieval practice on target items may also weaken the association linking the practice cue to competing memories, making it difficult to access those items when the practice cue is presented later. Again, inhibition is unnecessary, by this view.

Several findings have strongly supported the inhibition account, however. Most noninhibitory theories predict that retrieval-induced forgetting should be found only when the cue used to perform retrieval practice is presented during attempts to recall related traces (M.C. Anderson & Spellman, 1995). According to the blocking theory, for example, presentation of the retrieval-practice cue on the final test causes the practiced memory to perseverate and block related traces; according to the unlearning view, related traces are hard to recall because their link to the retrieval-practice cue has been damaged. By these views, as long as the item suffering retrieval-induced forgetting (e.g., *banana*) is tested with a separate cue (e.g., *monkey-b*____; hereinafter referred to as an *independent probe*) not associated to either the retrieval-practice cue (*fruit*) or the practiced item (*orange*), no impairment should occur. If the memory is inhibited, however, impairment should generalize to independent probes. Many studies have supported the inhibition view, finding cue-independent forgetting with a variety of stimuli (e.g., see Levy & Anderson, 2002, for a review). Impairment is also tied to the need to resolve interference from competing items during retrieval practice (M.C. Anderson, Bjork, & Bjork, 2000; see Levy & Anderson, 2002, for a review), as predicted by the inhibitory control view.

The work described thus far focused on the role of inhibition in episodic retrieval of studied items. Does a similar mechanism play a role in semantic forgetting? This question encompasses two issues. First, can semantic retrieval, in place of episodic retrieval practice, induce inhibition? Second, can semantic memories be inhibited?

INHIBITORY PROCESSES IN SEMANTIC RETRIEVAL

Several lines of evidence suggest that semantic retrieval recruits inhibitory control. In an early study, Blaxton and Neely (1983) examined how quickly subjects could retrieve a category exemplar from general knowledge (e.g., retrieve *bass* when prompted with *FISH b*) after having retrieved either one or four prime exemplars from that same category (fish) or from a different category (fruits). Subjects were faster to retrieve the target (*bass*) after retrieving one item from the same category (e.g., *trout* when given *FISH t*) than they were after retrieving one item from another category (e.g., *orange* when given *FRUIT o*). However, priming was eliminated when subjects retrieved four primes before the target, suggesting that the initial priming is gradually suppressed with increasing numbers of semantic retrievals. Interestingly, when primes were instead presented intact for speeded naming, the target retrieval was primed regardless of the number of preceding prime items. In other words, as with episodic retrieval-induced forgetting, inhibition was tied to the need to actively recall prime items.

Although the foregoing results are consistent with inhibition, noninhibitory theories can also explain the impairment. For instance, according to the blocking approach, subjects may have been slower to generate the target after generating four primes because generation strengthened the primes in semantic memory, blocking access to the target item. Naming those same primes may not have slowed target retrieval simply because naming may not have strengthened the primes to the same degree—a possibility consistent with the encoding advantage associated with generating items compared with reading them (Mulligan, 2001; Slamecka & Graf, 1978). Similar ambiguities arise for other findings that might be construed as reflecting semantic inhibition (e.g., Brown, 1981; Karchmer & Winograd, 1971). Showing that impairment is cue independent would provide evidence specifically favoring inhibition.

Bäuml (2002) recently provided evidence for inhibition in semantic retrieval that cannot be easily explained by blocking. Subjects studied category exemplars and then generated new exemplars of the studied categories in a semantic retrieval-practice phase. Following the practice phase, recall of the previously studied exemplars was impaired, showing that semantic retrieval can cause episodic forgetting of related items. Replacing semantic retrieval practice with extra study exposures to the same new exemplars yielded no impairment. Thus, as did Blaxton and Neely (1983), Bäuml found evidence for memory impairment that was induced only by active semantic recall. Unlike Blaxton and Neely, however, Bäuml (2002) showed that retrieval practice and extra study exposures facilitated the practiced items to the same degree. This suggests that blocking does not underlie this effect because impairment should have been found in both conditions. However, because Bäuml measured the effects of semantic retrieval on episodic memory, the issue of whether semantic representations can be suppressed remains unaddressed.

The study of lexical ambiguity resolution also provides evidence for inhibition in semantic retrieval. For example, Simpson and Kang (1994) found that priming one meaning of a homograph (e.g., bank stream) slowed responses to the alternate meaning on subsequent probe trials (e.g., bank money). Gernsbacher, Robertson, and Werner (2001) found a similar effect using sentences rather than single-word primes and targets. A common interpretation of these findings is that the homograph's visual word form activates its competing meanings, and the selection of the more contextually appropriate meaning during the prime trial inhibits the other meaning. However, studies supporting this idea typically measure inhibition using speeded-response tasks. Reaction times on probe trials can be slowed not only by inhibition, but also by the tendency for the probe trial to briefly remind subjects of the prime trial (because of the repetition of the homograph across trials), leading to distraction or response conflict. The contributions of these factors may increase when both meanings remain active (M.C. Anderson & Spellman, 1995; Gorfein, 2001; Shivde & Anderson, 2001). Thus, slowed reaction time to process an alternative meaning can be interpreted as evidence that this meaning is highly active, not suppressed. Similar concerns apply to evidence for semantic inhibition obtained with the rare-word paradigm (Dagenbach, Carr, & Barnhardt, 1990). In the current study, we sought to reduce the contributions of response conflict so that we could firmly establish the role of inhibition in semantic forgetting.

SEMANTIC RETRIEVAL-INDUCED FORGETTING: GOALS AND DESIGN

In the present experiments, we sought to determine whether retrieving an item from semantic memory inhibits other concepts that compete with it during retrieval. To more clearly implicate inhibitory processes, we measured inhibition with recall probability rather than with reaction time, and we tested subjects with an independent probe (M.C. Anderson & Spellman, 1995) to circumvent associative interference. If inhibition causes semantic retrieval-induced forgetting, impairment should be evident even when effects of decision conflict are minimized and the affected concepts are not tested with the cue used to induce inhibition.

In our new procedure, we eliminated the study phase of the retrieval-practice paradigm and asked subjects to perform semantic retrieval practice on concepts from their general knowledge. We performed two experiments, differing in the materials employed. In Experiment 1, we examined whether retrieving one meaning of an ambiguous word would suppress concepts associated to its alternate meaning. Cues were homographs (e.g., *PRUNE*) that had a dominant noun meaning (e.g., "fruit") and an unrelated, subordinate verb meaning (e.g., "to trim"). Subjects were asked to use general knowledge to generate an associate to each homograph's verb meaning that matched a word fragment provided with the homograph (e.g., the cue for *trim* was *PRUNE T_ _ M*). Interference from the word's dominant noun sense had to be overcome for subjects to comply. For example, thinking of the verb meaning of *prune* requires putting aside the fruit meaning, which springs to mind, in favor of the concept of trimming (the subordinate sense; see Fig. 1a). If semantic retrieval inhibits interfering meanings, this task should make subjects less likely to generate concepts associated with the noun meaning on a later free-association test. For each homograph, subjects generated either no (baseline), one, four, or eight different associates to the verb meaning (number of associates was manipulated within subjects), so that we could explore the buildup of semantic inhibition with increasing numbers of semantic retrievals. In Experiment 2, we performed the same manipulation, except that we asked subjects to generate exemplars of well-known categories (e.g., *SEASONING NU*) and determined whether these retrievals suppressed a particular high-frequency exemplar not generated during semantic retrieval practice (see Fig. 1c).

To measure whether semantic retrieval practice caused inhibition, we followed this task with an apparently unrelated semantic retrieval test. For this test, we adapted the independent-probe method (M.C. Anderson & Spellman, 1995) to determine whether semantic retrieval-induced forgetting was cue independent. After semantic retrieval practice, we probed the accessibility of concepts that were likely to have caused interference during the retrieval-practice phase. In Experiment 1, we tested the noun sense of each homograph (e.g., the "fruit" sense for *prune*) with a cue related to that concept but not associated to the homograph (e.g., *YOGURT F*). When given these

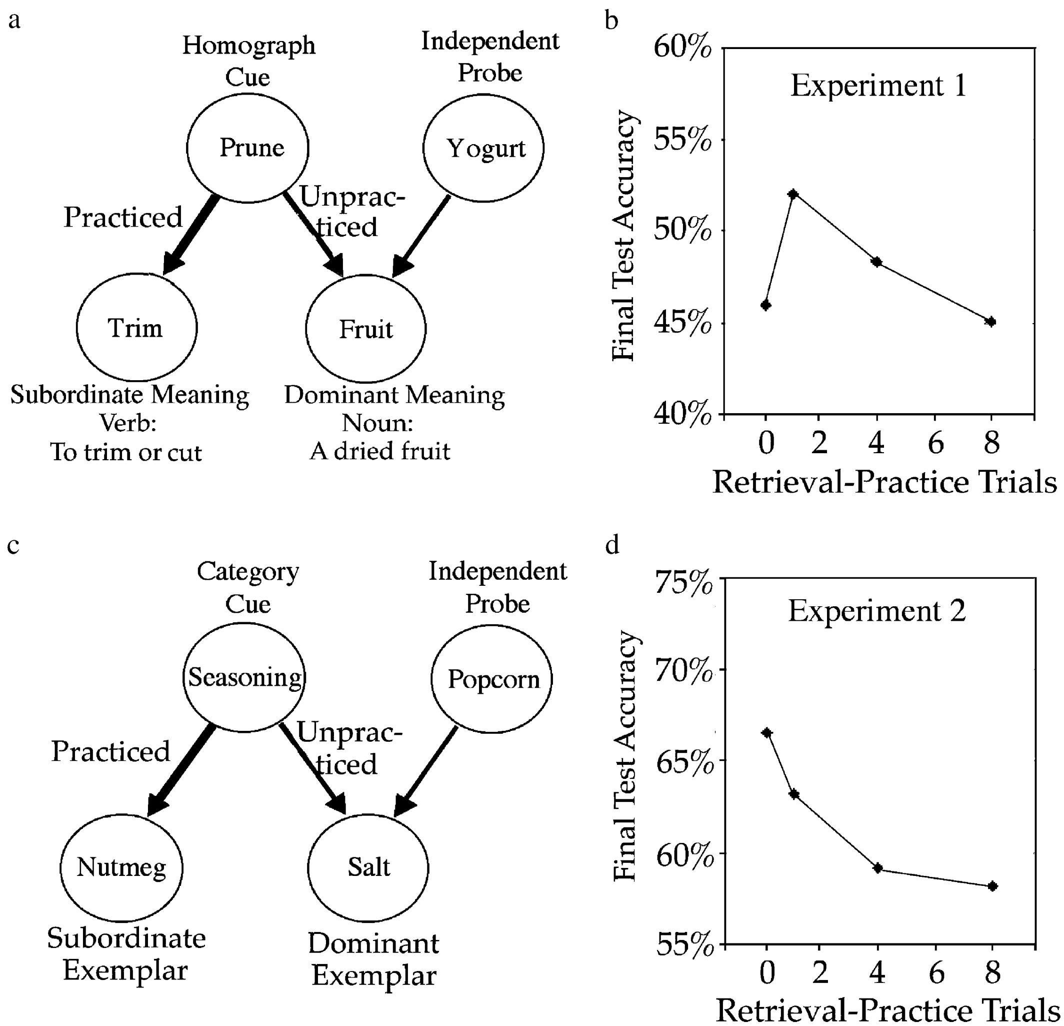

Fig. 1. Schematic representations of the semantic retrieval-induced forgetting paradigm used in Experiments 1 and 2, along with the data from these experiments. Experiment 1 (a) involved semantic retrieval of the verb meanings of homographs, and Experiment 2 (c) involved semantic retrieval of category exemplars. Thick arrows indicate weaker items that were practiced, and thin arrows indicate dominant competitors that were not practiced. The accessibility of the homographs' noun meanings and of the categories' more dominant exemplars was later tested with an independent probe, as illustrated. The graphs in (b) and (d) depict performance on the independent-probe test in Experiments 1 and 2, respectively, as a function of the number of semantic retrieval-practice trials on subordinate items.

cues, subjects were asked to say the first thing that came to mind that was related to the cue and began with the letter provided. If the noun meaning of the homograph had been suppressed, subjects should have grown less likely to provide the related word on the free-association test, even though the potential for blocking was circumvented. In Experiment 2, a similar test was constructed for our categorical materials; the final test probed a high-frequency exemplar (e.g., *salt*) of one of the categories for which semantic generation had been performed (e.g., *seasonings*), but with an independent cue unrelated to the category or any of its other exemplars (e.g., *POPCORN S*). If generating several exemplars suppresses competing items, subjects should have grown less likely to provide the target on the free-association test.

METHOD FOR EXPERIMENTS 1 AND 2

Subjects

In Experiment 1, 96 University of Oregon undergraduates (28 male) participated to fulfill a course requirement. In Experiment 2, 64 subjects participated (20 male). Subjects were between 18 and 35 years old.

Design

The number of fragments given for each cue during the retrieval-practice phase (none, one, four, or eight) was manipulated within subjects. The dependent measure was the percentage of independent-probe items completed with the target response on the final test.

Materials

Semantic Retrieval-Practice Stimuli

In Experiment 1, the stimuli included 24 homographs, each with two qualitatively different meanings: one noun and one verb. The noun meaning was always dominant (e.g., for *sock*, the noun sense "footwear" is dominant over the verb sense "to hit"), as determined by previous studies (Nelson, McEvoy, Walling, & Wheeler, 1980; Twilley, Dixon, Taylor, & Clark, 1994). For each homograph, eight words associated with the nondominant verb meaning were also generated. For instance, for *sock*, the verb associates were *punch*, *bruise*, *smack*, *fist*, *clobber*, *injure*, *strike*, and *fight*. These associates were used to produce word fragments for semantic retrieval practice.

Each homograph was pseudorandomly assigned to one of four sets that were equivalent in length and frequency of homographs and associates. The four sets were assigned to the four presentation conditions (no, one, four, or eight presentations) equally often, across subjects. In addition, the order of fragment presentation for a given homograph was counterbalanced so that every fragment was presented to at least 1 subject in every position for the one-, four-, and eight-presentations conditions. Fragments from different homographs were intermixed, and the average serial position in the retrieval-practice phase of the items in the one-, four-, and eight-presentations conditions was equated. The first and last few items were fillers to reduce primacy and recency effects.

The stimuli for Experiment 2 included 24 categories. For each category, eight exemplars were generated for use in semantic retrieval-practice. As in Experiment 1, each category was pseudorandomly assigned to one of four sets equivalent in exemplar length and frequency, as well as length, frequency, and dominance of critical items. Dominance was estimated using several norms (e.g., Battig & Montigue, 1969; McEvoy & Nelson, 1982). The same counterbalancing measures and constraints on presentation order used in Experiment 1 were used in Experiment 2.

Final Test Probes

In Experiment 1, we examined whether each homograph's noun sense was suppressed. To construct test items, we first used association norms (Nelson, McEvoy, & Schreiber, 1998) to identify a critical associate related to each homograph's noun meaning. For example, the associate for the noun meaning of *prune* was *fruit*. We then used association norms to develop a test probe (i.e., independent probe) of each of these associates (e.g., *yogurt*; see Fig. 1c). Each test item consisted of an independent probe and the initial letter of the homograph's associate (e.g., *YOGURT F*). An effort was made to ensure that each independent probe was related neither to the homograph for which it was used nor to the verb or noun meanings of any other homographs. We equated the average serial position on the final test across the four presentations conditions (no, one, four, or eight retrieval-practice trials).

In Experiment 2, we examined whether generating several exemplars of a category suppressed a preselected high-frequency exemplar of that category. Independent probes for this critical exemplar were generated in the same way as in Experiment 1, and all procedural controls applied to Experiment 1 were applied to Experiment 2.

Procedure

The procedures for semantic retrieval practice were similar in Experiments 1 and 2. In Experiment 1, each homograph was presented by itself, and subjects were given up to 6 s to press a button to indicate whether they knew its verb meaning. The button press caused a fragment to be presented to the homograph's right. Subjects were given up to 8 s to generate and say aloud a word that both fit the fragment and was related to the verb meaning. Following a response, the correct answer was displayed for 2 s, and then the next trial began after an intertrial interval of 1 s. In Experiment 2, each category was presented simultaneously with a two-letter stem for an exemplar (e.g., *SEASONING NU*), and subjects were given 8 s to generate a word that belonged to the category and began with the letters provided. All other aspects of the semantic retrieval-practice phase were identical to the procedure in Experiment 1.

After retrieval practice, we tested subjects' ability to access critical target items. In both Experiments 1 and 2, subjects viewed each test item and generated a word that began with the letter provided and was related to the independent probe. The test items remained on the screen for 4 s or until a response was made. In Experiment 1, we assessed knowledge of the homographs' verb meanings with a post-experimental vocabulary test.

RESULTS

In Experiment 1, we excluded scores for homographs for which subjects could not identify the verb meaning on the postexperimental vocabulary test. In Experiment 2, 9 subjects were replaced because they had less than 5 hr of sleep. All findings reported here remained significant when all of the data were considered.

Semantic Retrieval-Practice Performance

In Experiment 1, subjects knew the verb meanings of the homographs (i.e., pressed the "know" button) on 89.2% of the trials and were able to solve 66.2% of the associated fragments. In Experiment 2, subjects generated 64% of the retrieval-practice exemplars.

Final Semantic Retrieval Task

Inhibitory Effect in Experiment 1

As shown in Figure 1b, generating associates to the subordinate meaning of a homograph modulated the accessibility of its competing sense on the free-association task. This modulation followed a nonmonotonic function, characterized by an initial rise in accessibility after one retrieval practice, $F(1, 92) = 4.89$, $MSE = 362.67$, $p < .03$, followed by suppression (relative to the one-practice condition) after eight retrievals, $F(1, 92) = 5.10$, $MSE = 449.02$, $p < .03$. Performance did not go reliably below baseline after eight retrievals, however, $F < 1$. This nonmonotonic pattern reflects a high degree of intrusiveness from the noun meaning during the initial retrieval-practice trial (e.g., try reading "prune" without first thinking of its "fruit" sense).

Inhibitory Effect in Experiment 2

As shown in Figure 1d, generating exemplars of a category impaired subjects' ability to recall the target on the free-association test. Subjects recalled fewer targets after both four and eight semantic retrievals than after no related exemplars were generated (i.e., baseline condition), $F(1, 32) = 6.63$, $MSE = 266.08$, $p < .01$, and $F(1, 32) < 7.04$, $MSE = 348.09$, $p < .01$, respectively. Unlike in Experiment 1, however, the function relating the number of retrievals to recall followed a monotonic pattern, declining significantly below the preexperimental baseline.

GENERAL DISCUSSION

Previous work on retrieval-induced forgetting has focused on the role of inhibition in episodic forgetting. However, interference also occurs in semantic retrieval, suggesting that inhibitory control should have a role in semantic forgetting. Although several lines of evidence suggest that semantic retrieval impairs access to semantically related concepts, these studies did not isolate inhibition as the source of impairment. In the present study, we applied the independent-probe method (M.C. Anderson & Spellman, 1995) in a new semantic retrieval-practice paradigm to examine the role of inhibition in semantic memory lapses. Our findings provide clear evidence for inhibition: Generating general knowledge from semantic memory impaired access to competing concepts on a later free-association test. Impairment occurred regardless of whether competition was between alternative meanings of ambiguous words or between multiple exemplars of a category. This decline in accessibility occurred even though the suppressed item was tested with an independent cue unrelated to ones used in the initial semantic retrieval-practice phase, and even though the inhibited words themselves never appeared in the prior phase. That semantic retrieval practice impairs related items and that these effects are cue independent suggests that inhibition underlies semantic retrieval-induced forgetting.

Although semantic inhibition was found in both experiments, the findings with homograph stimuli appear weaker than those obtained with categorical materials because items in Experiment 1 were not impaired below baseline performance. The lack of below-baseline impairment in the eight-presentations condition in Experiment 1 was due to an initial rise in performance not found for category exemplars. One might speculate that this initial rise reflects an important difference between lexical access and other forms of semantic retrieval. Although we cannot exclude this possibility, we think it unlikely for two reasons. First, similar nonmonotonic patterns have been observed in many inhibition paradigms, using different kinds of stimuli. As noted earlier, Blaxton and Neely (1983) found that generating one exemplar primed a critical target item, but that generating four gradually suppressed that priming. Similar patterns have been observed in episodic retrieval-induced forgetting studies (e.g., Shivde & Anderson, 2001), work with the think/no-think procedure using arbitrary (highly trained) paired associates (e.g., M.C. Anderson, Reinholz, Mayr, & Kuhl, 2004; Levy, Reinholz, & Anderson, 2004), and in a study of semantic satiation (Kuhl & Anderson, 2004). The recurrence of this pattern indicates that it is a common outcome in paradigms that require competition to be resolved. Second, there is a good theoretical reason for the pattern. Whenever a competitor is strongly related to a cue, the initial wave of activation spreading to it is difficult to counter with inhibition. Essentially, the dominant competitor is retrieved too quickly and intrudes, leaving it primed. After the initial practice trial, the weaker practice item grows more accessible, making it easier to select that item and to suppress the competitor. If correct, this analysis suggests that the dominant senses of our homographs may simply have been more intrusive than our critical category exemplars. Given these considerations, it seems more likely that the two experiments measured a common inhibitory process than that they measured two distinct processes, and that the differences in the form of the functions obtained derived from variation in interference from competitors.

In the past several years, growing evidence has shown that the ability to overcome interference during semantic retrieval is mediated by left inferior prefrontal cortex (LIPFC; see Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Damage to LIPFC causes semantic retrieval difficulties that are disproportionately large when stronger competitors need to be suppressed (Thompson-Schill, D'Esposito, & Kan, 1999), in addition to causing a tendency to perseverate previously given semantic fluency responses (Baldo & Shimamura, 1998). Neuroimaging studies show that LIPFC is activated during semantic retrieval (Petersen, Fox, Posner, Mintun, & Raichle, 1988), particularly when the cue-target associations are weak (Wagner, Paré-Blagoev, Clark, & Poldrack, 2001), when there are multiple competitors in memory (Desmond, Gabrieli, & Glover, 1998; Thompson-Schill et al., 1999), or when there is a strong competitor (Abdullaev & Posner, 1998)—that is, under the same conditions shown to require inhibitory control in studies of retrieval-induced forgetting (M.C. Anderson & Spellman, 1995; Carr & Dagenbach, 1990; Levy & Anderson, 2002). Given the similarity of the interference demands present in semantic retrieval practice to those repeatedly shown to recruit LIPFC, our task seems likely to have involved this area. If this speculation is correct, our findings suggest that LIPFC may exert control over semantic retrieval through inhibition.

In conclusion, the present findings show that semantic retrieval, like episodic recall, recruits inhibitory mechanisms that suppress competing traces. This suppression induces a deficit in the accessibility of competing concepts. Although we cannot determine from this study how long semantic inhibition lasts, analogous findings in research on episodic memory (e.g., M.C. Anderson et al., 1994) suggest that such effects could produce persistent semantic forgetting. If so, perhaps those times when one needs to look up the meaning of a forgotten word or when one becomes confused about ideas once familiar may not always indicate deficiencies in how well the material was learned; rather, these experiences may reflect inevitable fluctuations in the accessibility of knowledge arising from the need to suppress conceptual distraction. Thus, the very mechanisms that allow effective concentration may also render all of us vulnerable to forgetfulness.

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