THE TIME COURSE OF LEXICAL ACTIVATION
DURING SPOKEN WORD RECOGNITION:
EVIDENCE FROM UNIMPAIRED AND APHASIC INDIVIDUALS

BY
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B.A., UNIVERSITY OF ROCHESTER, 1996

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN THE DEPARTMENT OF COGNITIVE & LINGUISTIC SCIENCES
AT BROWN UNIVERSITY

PROVIDENCE, RHODE ISLAND
MAY 2005
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This dissertation by Eiling J. Yee is accepted in its present form by the department of Cognitive and Linguistic Sciences as satisfying the dissertation requirement for the degree of Doctor of Philosophy.

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PEER-REVIEWED ABSTRACTS


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Acknowledgements

Heartfelt thanks go to my two wonderful advisors, Julie Sedivy and Sheila Blumstein. Without their insights, encouragement, enthusiasm, openness and assistance, this project would not have been possible. I am particularly grateful to Julie for stressing the value of theoretical motivation, and to Sheila for emphasizing the importance of communicating ideas clearly and precisely. I was fortunate to have valuable feedback from committee member Jim Morgan, and at an earlier stage in this project, from William Heindel. I am also grateful to Mike Tanenhaus for first introducing me to the world of psycholinguistics and for welcoming a clueless undergraduate into his exciting lab.

Fellow students and post-docs played an enormous role in making Brown a positive place to work and study. I am indebted to Katherine White for countless wide-ranging discussions from theoretical to practical, for providing counsel and encouragement at every critical juncture and for being extraordinarily generous with editing advice. Thanks also go to Jesse Hochstadt for his keen insights, for innumerable intellectually stimulating and highly entertaining (often simultaneously) debates, and for recording so many words, and to Paul Allopenna, not only because his research helped inspire much of the work here, but also for guidance in getting started with lexical access research and for always being willing to provide advice, discuss ideas, and play tennis. I am also very lucky to have had two terrific collaborators, Jason Taylor and Daphna Heller, who were able to make even projects with inconclusive results intellectually rewarding and fun. It was a privilege to have been a part of the Sedivy and Speech labs, whose members provided fellowship and valuable feedback and assistance. Two labmates in particular, Jong-Yoon Myung and Aparna Nadig, were wonderful comrades-in-eye tracking.

Several others also contributed to this project in a variety of ways: Kathy Kurowski and Cara Misiurski recruited patients and made patient testing both run smoothly and also a lot of fun. Andrew Duchon wrote programs to process eye movement data. Anjula Joshi, Natasha Trentacosta and Michele Hebert ran numerous subjects. John Mertus and Bob Fifer’s expertise and friendly faces made computer problems much more bearable. I am also very grateful for the knowledge and assistance of Pat Squadrito, Christie Crozier and Reinette Sousa, as well as prior department staff members.

My experience at Brown was all the more rewarding because of the friends who made my time here so enjoyable. In addition to those mentioned above, Melissa & Tim Kearns, Seth Blau, Emily Myers, Pat Foo, Marianne and Matt Harrison, Quoc Vuong, Eva Palmer, Julie Pierce and Yi Cheng all had a role in helping me finish, whether by discussing research or by providing much-needed distraction from research. I am also grateful to the rest of the faculty, post-docs, grad students and staff in the Cognitive and Linguistic Sciences for making the department such a warm place to study and work.

I am also enormously fortunate to have had an extraordinary amount of encouragement from family and friends. My parents, Nancy and Sam Yee and my brother Brian helped me in ways far too numerous to list, but most importantly through their constant loving support. All of the Ryans, but especially cousins Kevin and Morgan, made living in Providence a joy. And my dear girlfriends Melissa, Sarah and Fleur, were incredibly supportive and understanding. Finally, words simply cannot express my gratitude to Andrew Duchon for his infinite patience, for listening to and understanding all the difficulties along the way, both practical and conceptual, and for giving me invaluable advice, encouragement, and support at every single step.

I am grateful for support from the Jacob K. Javits Fellowship Program and from a Joukowsky Presidential Fellowship.
ABSTRACT

This dissertation investigates the activation of phonological and semantic information during spoken word recognition. Experiments 1-3 explore the time course of spoken word recognition in unimpaired individuals by monitoring eye movements as participants select a named object from a computer display. In Experiment 1, eye movements are rapidly drawn to pictorial representations of both the named object (e.g., “hammer”) and semantically related items (e.g., nail), demonstrating the swift activation of semantic information during word recognition. In Experiments 2 and 3, items semantically related to onset (i.e., cohort) or rhyme competitors of an uttered word become active enough to draw visual attention (e.g., “hammock” activates nail via hammer; “pear” activates tiger via bear). In Experiments 2 and 3, semantic information about competitors is activated only briefly; this likely explains why we are not consciously aware of activating the meanings of unintended candidates.

Experiments 4-7 use the same methodology to explore the time course of spoken word recognition in Broca’s and Wernicke’s aphasics. Wernicke’s aphasics exhibit heightened, and Broca’s aphasics exhibit reduced sensitivity to phonological onset competitors (Experiment 4), while for rhyme competitors (Experiment 5) this pattern reverses. Like unimpaired individuals in Experiment 1, both groups of aphasics fixate on items semantically related to an uttered word (Experiment 6). However, Broca’s aphasics, unlike Wernicke’s aphasics and unimpaired individuals, do not appear to activate semantic information about onset competitors of an uttered word (Experiment 7). These findings demonstrate that eye movement monitoring has the potential to provide insight into the mechanisms underlying the lexical processing deficits of brain-damaged patients. In particular, if lateral inhibition is assumed, these data are consistent with the proposal that the lexical processing deficits of Broca’s aphasics are due to reduced lexical activation, and that those of Wernicke’s aphasics are due to increased lexical activation (Milberg, Blumstein & Dworetzky, 1987). Furthermore, since inhibition may also account for how unimpaired individuals so quickly and accurately settle on the correct word despite the partial activation of so many lexical candidates, inhibition is hypothesized to be a critical component of spoken word recognition.
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INTRODUCTION

People talk fast. Typically, we produce up to 3-4 words per second. Yet despite the rapid rate of the speech we hear, we usually manage to understand what is said. This success indicates that our comprehension system must be similarly fast, and considering the difficulty of the task, quite efficient. One of the (many) problems that our comprehension system has to overcome in order to keep pace with the input is temporary ambiguity; since speech is produced sequentially and we use a limited number of speech sounds to produce thousands of unique words, the speech we hear at a given moment is usually consistent with any one of a large number of words (e.g., “ham”, could continue as “hammer”, “hammock”, “hamster”, “hamper”, “hamstring”, etc.). The absence of clear word boundaries in natural speech is another significant problem that must be overcome in order to keep pace with the input; at any point in time, it may not be clear whether we are hearing the beginning of one word or a continuation of a different word (e.g., is it “pay performs” or “paper forms”?).

Understanding the process that allows us to quickly and (usually) accurately select the correct word from among the thousands of candidates in the mental lexicon is the goal of research on spoken word recognition. Although the question of how individual words are selected (or segmented) from fluent speech and the question of how words become active and interact with each other are far from independent, in this dissertation the focus is on the latter question. Segmentation is addressed only in so far as it pertains to activation and competition.

The first part of this dissertation explores the time course of spoken word recognition – specifically, how lexical candidates are activated and compete – in unimpaired individuals. First, it is shown that when an object is named, eye movements are drawn to pictorial representations of both the named object and semantically related items, demonstrating the activation of its semantic network as well as its phonological form. This demonstration is significant because it provides information about the time course over which semantic information about a word is accessed in a task unlikely to be affected by strategic influences. Next, it is shown that we temporarily activate semantic information about phonological competitors of the uttered word. The semantic information is activated quite briefly; this likely explains why it is that we are not consciously aware of activating the meanings of unintended candidates.

In the second part of this dissertation, eye movements are used to explore the time course of spoken word recognition in individuals with Broca’s and Wernicke’s aphasia. To our knowledge, the series of studies described here is the first use of this methodology to study
spoken language processing in aphasia\textsuperscript{1}. The data presented demonstrate first that both Broca’s and Wernicke’s aphasics are sensitive to phonological competition during spoken word recognition, though in different ways, and then that both groups of aphasics experience competition from items semantically related to an uttered word. Next, it is shown that Wernicke’s, but not Broca’s aphasics temporarily activate semantic information about onset competitors of the uttered word. It is argued that these data are most consistent with the hypothesis that lexical processing deficits in these patients arise from abnormal lexical activation. Specifically, Broca’s aphasics appear to have decreased levels of lexical activation whereas Wernicke’s aphasics appear to have increased levels of lexical activation. A simple model demonstrates how a version of the reduced/increased activation hypothesis that incorporates lateral inhibition can account for the aphasic data. Finally, since the aphasic results imply that inhibition plays a significant role in activating and deactivating candidates, it is suggested that inhibition may also help account for how we so quickly and accurately settle on the correct word despite the partial activation of so many lexical candidates.

\textsuperscript{1} At least two studies have examined eye movements in Broca’s aphasics: one during reading (Klingehofer & Conrad, 1984) and another during speech production (Donders & van Vlugt, 1986).
PART 1: ACCESS TO SEMANTIC INFORMATION DURING SPOKEN WORD RECOGNITION: EVIDENCE FROM UNIMPAIRED INDIVIDUALS

Most words are temporarily ambiguous, with many words remaining ambiguous until after their offsets. For example, in the phrase hand soap, it is not until after the offset of hand that it becomes clear that the utterance was not handsome. Yet our interpretation system does not fall behind, suggesting that we do not wait until a word has become unambiguous before assigning meaning. Since our interpretation system does manage to keep pace with the input despite the rampant temporary ambiguity in the lexicon, models of spoken word recognition assume that as a given word unfolds, words that start with the same sounds become partially active (i.e., hearing the ham of hammer triggers phonologically related words like hammock; e.g., Marslen-Wilson & Welsh's 1978 Cohort model; McClelland & Elman's 1986 TRACE model; Norris' 1994 Shortlist model; and Luce & Pisoni's 1998 Neighborhood activation model). Furthermore, since clear word boundaries are largely absent from running speech, some models of spoken word recognition also assume that we remain open to the possibility that what we are hearing at any given time could map onto any part of a word. Consequently, if there is sufficient subsequent overlap with the input, words whose onsets do not match the input (e.g., rhyme competitors) can become active as well (McClelland & Elman, 1986; Norris 1994; Luce & Pisoni, 1998).

Most models of spoken word recognition do not specifically address access to meaning (but cf. Gaskell & Marslen-Wilson, 1997 and McNellis & Blumstein, 2001). Nevertheless it is generally assumed that when a word’s form is accessed, its meaning is also automatically accessed (but c.f. Connine, Titone, Deelman & Blasko, 1997). If it is true that as we hear a word phonologically related words are partially activated, and also that a word’s form and meaning are activated together, this leaves open the possibility that we access the meanings of multiple unintended candidates before finally settling on the intended one. While context (linguistic and extra-linguistic) may often help to reduce this risk, there will still be times when context does little if anything to narrow down the choices. Clearly, all this “spurious” semantic activation has the potential to cause listeners a great deal of confusion. Yet we are very rarely aware of considering candidates that turn out to be incorrect. This absence of conscious confusion may appear to cast doubt on the theory that the semantic representations of unintended candidates become active. However, there is ample evidence that as we hear a given spoken word we do temporarily access semantic information about words with the same onset (henceforth onset competitors). The evidence that we also access semantic information about rhyming words (henceforth rhyme competitors) is much weaker.
The first part of this dissertation explores the activation of the uttered word’s semantic representation, and also the activation of the semantic representations of its onset and rhyme competitors. The question of whether we activate the semantic representations of rhyme competitors will be of particular interest because the evidence to date suggests that their semantic representations do not become active.

Most of the evidence concerning whether the meaning of a word’s onset and rhyme competitors become partially active comes from experiments using the cross-modal semantic priming paradigm\(^2\). In experiments investigating onset competitors, written target words are presented before the offset of auditory primes – just before the prime would have become unambiguous (e.g., if the prime were *hammer* or *hammock*, the target would be presented at the end of *ham*). Participants are asked to make lexical decisions on the targets. They make faster lexical decisions when the targets are related to possible continuations of the prime’s onset (e.g., *nail* or *bed*) than when targets are unrelated to the prime. Since words related to *both* the prime and its onset competitors appear to become active, these results suggest that we initially activate both the form and the meaning of multiple potential candidates (e.g., Marslen-Wilson, 1987; Moss, McCormick & Tyler, 1997; Zwitserlood, 1989).

A number of studies have also used the cross-modal semantic priming paradigm to ask whether hearing a word activates the meaning of rhyme competitors. In these studies the written targets are presented at the offset of auditory primes. While results of these studies do suggest that *non-words* activate rhyming words (e.g. “nister” primes “man”, via “mister”, Connine, Blasko, & Titone, 1993), there is little evidence from this paradigm that *real words* activate rhyming words. For instance, in one study, rhyme primes that were one segment away from words semantically related to a target (e.g., if the prime were *money* which shares all but its initial segment with *honey*, the target could be *bee*) did not speed lexical decisions on the target\(^3\) (Marslen-Wilson & Zwitserlood, 1989; Marslen-Wilson, Moss & van Halen, 1996). Thus, results of cross-modal semantic priming studies suggest that we activate the meanings of onset, but not rhyme competitors of an uttered word.

Intra-modal semantic priming has also been used to explore whether the semantic representations of words that rhyme with an uttered word become active. In a preliminary experiment of a study investigating the effect of VOT shortening on potential rhyme competitor

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2 Gating (Grosjean, 1980) and phonological priming tasks (also known as “form priming”; Słowiackz & Pisoni, 1986) have also been used to investigate whether a word’s phonological competitors become active. However, while results from these paradigms can indicate whether a word’s form has been activated, they do not tap meaning.  
3 However, in a post-hoc analysis Marslen-Wilson & Zwitserlood (1989) found that when two-syllable primes had no competitors other than the source word (competitors were defined as words that differed from the prime by only their initial segment), a small facilitative priming effect did emerge.
activation, Misiurski, Blumstein, Rissman and Berman (submitted) investigated whether words that rhyme with an unmodified presented word would speed lexical decisions on targets semantically related to the rhyme (i.e., would lexical decisions on penny be speeded if the prime were time, providing evidence that dime became active). While the effect was not statistically significant, they did find that lexical decisions were faster when a prime rhymed with a word related to the target. In their main experiment they shortened the prime’s VOT so that while it was still clearly identifiable, it was closer to its rhyme competitor. With this modification they found that lexical decisions on targets related to the rhyme competitor were significantly speeded. Although these findings suggest that only modified primes activate their rhyme competitors enough to reliably facilitate lexical decisions on semantically related words, the direction of the effect for unmodified primes was consistent with rhyme competitors becoming active.

The absence of an observable semantic priming effect for unmodified words that rhyme with the uttered word can be interpreted as evidence that no aspect of a word’s rhyme competitors becomes active. Yet it could also be that we activate the phonological forms, but not the meanings of rhyme competitors. Phonological form priming is one method that has been used to detect whether a word’s phonological form is active. In this paradigm, subjects hear a prime word and then are asked to name or make a lexical decision on a phonologically related target. The logic is that recognizing the target should be influenced by prior recognition of a phonologically related prime. Since obtaining a form priming effect for a word is a result of a phonological, not semantic relationship, if only the forms of a word’s rhyme competitors become active, form priming may be able to detect this activation.

Numerous form priming studies have shown that subjects are faster to respond to targets that share only their offsets with a prime than to phonologically unrelated targets (e.g., Slowiaczek, Nusbaum & Pisoni, 1987; Radeau, Morais, Segui, 1995; Monsell & Hirsch, 1998; Dumay et al., 2001). These findings would seem to indicate that not only do an uttered word’s rhyme competitors become partially active, but rhyme competitors also remain partially active after the word has been successfully recognized. Thus, the evidence seems to indicate that the forms, but not the meanings of rhyme competitors are activated when we hear a word.

However, this interpretation is complicated by the fact that form priming studies have found that when a target shares its onset with the prime, responses are delayed rather than speeded (e.g., Slowiaczek & Pisoni, 1986; Goldinger, Luce, Pisoni, & Marcario 1992; Monsell & Hirsch, 1998). This delay has been attributed to the prime being easily activated (since it was just recognized and is therefore likely to still be partially active) when the target is presented. Thus, the prime competes strongly with the target thereby delaying target recognition. However, if this
account is correct, an explanation is still needed for why it is that when the target is an onset competitor of the prime, competition from the prime overwhelms residual lexical activation of the target (from when the prime was presented and the target was considered but rejected), whereas when the target is a rhyme competitor of the prime, residual lexical activation of the target overwhelms competition from the prime.

Results from studies using eye tracking, a methodology that provides information about the time course of lexical activation during spoken word recognition, may help us to understand the form priming data. In these studies participants' eye movements are recorded as they follow spoken instructions to point to or manipulate an object that is part of a visual display in front of them. It has been found that there is a close time-locking between an unfolding referring expression and eye movements to a potential referent, making eye movements a valuable indicator of which lexical candidates participants are considering (Tanenhaus, Spivey-Knowlton, Eberhard & Sedivy, 1995; Allopenna, Magnuson & Tanenhaus, 1998; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Spivey & Marian, 1999; Dahan, Magnuson, & Tanenhaus, 2001; Dahan, Magnuson, Tanenhaus, & Hogan, 2001). A significant benefit of this technique is that one can measure eye movements without disrupting the spoken input or requiring participants to make a metalinguistic judgment such as a lexical decision. This allows participants to engage in tasks that are more naturalistic than those used in standard psycholinguistic paradigms. More importantly, eye movements provide a continuous measure of processing as participants listen to language input. Thus they supply information about the time course of word recognition as the word unfolds.

Several eye-tracking studies have shown that eye movements are preferentially drawn to onset competitors of a given spoken word (Allopenna et al., 1998; Dahan, Magnuson & Tanenhaus, 2001; Dahan et al., 2001; Tanenhaus et al., 1995). In these studies participants are presented with a four-picture display and asked to “pick up” (i.e., move with a computer mouse) one of the objects in the display (the target). It has been found that if the name of one of the objects is an onset competitor of the target word, participants are initially more likely to fixate on this onset competitor than on objects with phonologically unrelated names. For example, if asked to “Pick up the beaker,” participants are more likely to fixate on the onset competitor beetle than on objects with phonologically unrelated names before settling on the target. It has also been found (Allopenna et al., 1998; McMurray, Tanenhaus, Aslin, & Spivey, 2003) that eye movements are drawn to a rhyme competitor of the target word. That is, if asked to “Pick up the beaker,” participants are more likely to fixate on the rhyme competitor speaker than on phonologically unrelated objects. This rhyme competitor effect emerges later than the onset competitor effect and peaks lower. However, it also lasts longer. Intriguingly, Allopenna et al.
also showed that as a word unfolds, the likelihood that a participant will fixate on the corresponding picture – and also on its onset competitor and rhyme competitor – closely matches the word’s lexical activation as predicted by simulations using the TRACE model of spoken word recognition. This correspondence suggests that in these tasks, participants’ fixations are tightly linked to lexical activation.

These eye tracking results suggest that the position of the acoustic overlap critically affects when a competitor will be active. Thus, the position of the acoustic overlap most likely accounts for why it is that in form priming studies, when the target is an onset competitor of the prime, competition from the prime overwhelms residual lexical activation of the target, while when the target is a rhyme competitor of the prime, residual activation of the target overwhelms competition from the prime. Accounts of these form priming findings are given below, and following each account is a concrete example.

By definition, onset competitors overlap with the beginning of an uttered word and then become inconsistent with it. Consequently, the acoustic signal at the end of the prime is not consistent with the onset competitor and therefore no longer contributes to its activation. Thus, by the offset of the prime, there is likely to be little, if any, residual activation of onset competitors. When one of the prime’s onset competitors is later presented as the target, its onset is perfectly consistent with the prime, whose representation (since it was, after all, overtly presented) is still likely to be residually active. Thus, hearing the beginning of the target easily activates the prime, making the prime a strong competitor for recognition, and thereby delaying target recognition. For example, if the prime hammer is presented, its onset competitor hammock, will initially become active. However, since the end of hammer is not consistent with the end of hammock, by the offset of hammer, hammock will no longer be active. If hammock is then presented as the target, its onset will easily activate hammer since hammer is still residually active from when it was presented. Thus, hammer is a strong competitor for the target hammock, delaying recognition of hammock.

Rhyme competitors on the other hand, are inconsistent with the onset of the uttered word but overlap with the remainder of it. Thus, the acoustic signal at the end of the prime is consistent with the rhyme competitor and does contribute to its activation. As a result, at the offset of the prime, there is likely to be some residual activation of rhyme competitors. When a target that is a rhyme competitor of the prime is presented, its onset is inconsistent with the prime and thus initially the prime is not activated. The target can, however, activate its own representation, which (as explained above) may be residually active from when the prime was presented. Although the offset of the target is consistent with the prime, by the time this acoustic input is encountered, the target may be active enough that the prime does not become a significant
competitor. To give an example, at the onset of the prime *candle*, its rhyme competitor *sandal* will not be activated. However, by the offset of *candle*, enough acoustic input consistent with *sandal* will have been encountered to activate it. When the target *sandal* is presented, its onset will not immediately activate *candle* since the onsets of the two words do not overlap. However, the target will activate its own representation which is likely to still be residually active from when *candle* was recognized and *sandal* was partially activated. Thus, the target *sandal* is easily activated. By the time the prime *candle* becomes consistent with the acoustic input, *sandal* may already be active enough to withstand competition.

Thus, in the form priming paradigm, competition from the prime works against residual activation of the target (from when the prime was recognized and the target was a candidate for recognition). The strengths of these two forces differ depending on the position of the overlap between the prime and the target, with competition from the prime overwhelming residual activation of the target in onset form priming, and residual activation of the target overwhelming competition from the prime in rhyme form priming.\(^4\)

The time course of the eye tracking results are consistent with the interpretation of the form priming data provided above. That is, they suggest that onset competitors become active earlier than rhyme competitors but that they do not remain active for as long. The eye tracking data also appear to indicate that we activate *semantic* information about potential competitors—otherwise we would not recognize their pictorial representations. Yet in this respect, the eye tracking results are inconsistent with the results of cross-modal semantic priming studies which suggest that we activate the semantic representations of onset, but not rhyme competitors. This discrepancy between the results of the cross-modal semantic priming studies and the eye tracking studies regarding rhyme competitors needs to be explained. One possibility is that because eye movements are physiologically cheap and/or because of the time course information that the paradigm provides, eye movements are better able to reveal subtle or transient effects. In other words, it may be that eye movements are simply a more accurate measure of lexical activation.

\(^4\) As the discussion above makes obvious, form priming is quite complicated. Unfortunately, form priming is further complicated because other factors are likely to affect the results as well. For instance, when the prime is recognized it probably inhibits its phonological competitors (of which the target is one), which, depending on how long the inhibition lasts, could work to slow target recognition. On the other hand, it has also been argued that target recognition can be speeded from residual activation from sub-lexical representations that the prime and target share (Slowiaczek & Hamburger, 1992), and by facilitation from subject bias (e.g., noticing that when prime and target are related, the target is frequently a real word) (Goldinger et al., 1992; Hamburger & Slowiaczek, 1996; Goldinger, 1999). Since many different factors appear to be at work during auditory form priming, some of which would work to delay target recognition (e.g., inhibition of competitors) and some of which would speed target recognition (e.g., residual activation of sub-lexical representations and subject bias) interpreting results from this paradigm can be quite difficult.
It is also possible, however, that viewing a pictorial representation of an object automatically activates not only its semantic representation but also its name, and that once activated this semantic and phonological information becomes associated with the location of the picture. If true, then another possibility is that in the eye tracking paradigm, fixations on a word’s phonological competitors reflect the activation of their phonological forms, but not necessarily the activation of their meanings. For example, it is possible that when participants view a picture of a candle, they automatically activate both its form (/c@ndL/) and its meaning (wax cylinder that provides light), and that this information is associated with the location of the picture. Then, when they hear the target sandal, although the acoustic input partially activates the phonological form /c@ndL/, it does not activate the meaning. Yet, since the form /c@ndL/ is associated with a location in the display, eye movements to that location could be triggered via the activation of form, even without activation of meaning. Once visual attention is drawn to the picture of candle, the meaning would be activated. However, according to the scenario outlined above, this would be a consequence rather than a cause of eye movements to the location of the picture. Hence, if this scenario is accurate, the eye tracking paradigm might detect the activation of a word’s form even if its meaning is not active. Since a cross-modal semantic priming effect requires that meaning be active, then it could be that the two paradigms are consistent with respect to onset competitors because onset competitors become active enough that their forms and meanings are both triggered (so that both paradigms can detect their activation). They differ with respect to rhyme competitors because rhymes only become active enough for their forms to be triggered (so that only eye tracking can detect their activation).

One way to test whether eye movements reflect a word’s semantic as well as phonological activation would be to investigate a well-established lexical effect that does not depend on phonological overlap between the target and competitors. The semantic priming effect, in which words semantically related to an uttered word rapidly become active, is a good candidate. Specifically, if (given the task of identifying a spoken target) participants are presented with a display that includes an object that is semantically, but not phonologically related to the target, and if they are found to be more likely to fixate on the semantically related than the unrelated objects, then this would provide evidence that eye movements reflect the activation of full lexical-semantic representations rather than merely the matching of acoustic input to phonological form. Perhaps more interestingly, such a finding would also imply that words semantically related to the target become active enough for their pictorial representations to draw visual attention, despite the lack of any task-related motivation to attend to them. While a great deal of previous work has shown that words semantically related to uttered words are activated above baseline, these studies have required participants to name or make an overt judgment on
the semantically related item itself. They have not shown that the semantically related item becomes active enough to capture attention when it is not relevant to the task. Moreover, if words semantically related to the uttered word do in fact become active enough to draw visual attention, then since eye movements are measured continuously, it should be possible to obtain information about the time course of this activation.

In this section, three experiments are presented that explore spoken word recognition using eye movements to items semantically related to the uttered word or to its onset or rhyme competitors. Experiment 1 investigates whether eye movements will be drawn to an item semantically related to a spoken target word despite the absence of phonological overlap between the target and the semantically related item, as well as the lack of any task-related motivation to fixate on the related item. Experiment 2 explores whether the semantic effect that was obtained in Experiment 1 can be used to detect the activation of the semantic representation of an uttered word’s onset competitor – despite that the competitor itself is absent (e.g., will visual attention be drawn to *nail* when the uttered word is “hammock”, even though there is no *hammer* in the display?). Experiment 3 investigates whether the same semantic effect will reveal evidence that a rhyme competitor’s semantic representation is active, despite the absence of the rhyme competitor (will people fixate on *tiger* when the uttered word is “pear”, even though there is no *bear* in the display?).
EXPERIMENT 1: SEMANTICALLY RELATED ITEMS

Experiment 1 sought to determine whether eye movements would be sensitive to the activation of items semantically related to a given spoken target word. If they are, this would suggest that eye movements reflect the activation of a word’s semantic representation, not merely its phonological form. It would also indicate that even in the absence of any task-related motivation to attend to items semantically related to the uttered words, these words become active enough to capture visual attention.

Methods

Participants

Thirty male and female participants from the Brown University community were tested. All participants were native speakers of English and had normal or corrected-to-normal vision and no reported hearing deficits. They were paid a rate of $7/hour for participating.

Apparatus

An SMI EyeLink I head-mounted eye tracker was used to monitor participants' eye movements. A camera imaged the participant’s left eye at 250 Hz. Stimuli were presented with PsyScript, a freely available language for scripting psychology experiments (Bates & Oliveiro, 2003) on a 15 inch ELO touch-sensitive monitor.

Materials

Twenty-four pairs of semantically related stimuli were selected. To minimize the possibility that participants would mistake the picture of the related item for the target, only items that were visually dissimilar (according to experimenter intuition) were chosen\(^5\). Object names were 1-3 syllables long (1.6 syllables on average). See Appendix A for a full list of experimental items. The displays were created from color line drawings from a commercial clip art collection and from a collection of color line drawings based on the black and white Snodgrass picture library (Snodgrass & Vanderwart, 1980; Rossion & Pourtois, 2001).

To ensure that the pictures in critical trials clearly represented what they were intended to, picture-name correspondence pre-tests were conducted. Subjects who did not participate in any of the eye tracking experiments were presented with each picture and a label (either its intended name or a randomly selected name), and were asked to judge whether they matched. Two

\(^5\) The issue of visual similarity is explored further in the discussion.
criteria were used to ensure a high degree of picture-name correspondence. First, at least 15 of the 16 subjects had to agree that the intended name matched the picture. Second, for each picture the average amount of time it took for subjects to agree that the picture matched the name had to be within one standard deviation of the mean "agree" response time (650 ms) for all items. Pictures that did not meet these criteria were replaced with new pictures. These new pictures were presented to at least five subjects (who did not participate in the experiments) who were asked to name each picture. If more than one of the subjects did not provide the intended name for a picture it was replaced with a new picture that was normed in the same way.

A female speaker (E.Y.), in a sound-treated room, read each target word in isolation but with sentence-final intonation. Average target duration was 510 ms. The stimuli were recorded on a DAT tape and digitized at 20 kHz. Two lists, each 72 trials long, were created. Related word pairs appeared as target and competitor on one list and as unrelated items on the other. (See Appendix A.) Each participant was run on only one list so that no participant saw or heard any item more than once.

Figure 1 shows a sample display. In the semantically related condition (12 of the 72 trials on each list), one of the items in the display was semantically related to the target. This item will be referred to as the semantically related item. (Except where specified, none of the items in a display were semantically or phonologically related to any of the other items in the display.) The other two items were semantically and phonologically unrelated to both the target and the semantically related item. The name of one of these unrelated items was frequency matched with the semantically related item. This item will be referred to as the related item’s control. The name of the other unrelated item was frequency matched with the target.

The same displays that were used in the semantically related condition in one list also appeared in the control condition (12 of 72 trials) on the other list. This was accomplished by using one of the items that had served as an “unrelated” item in the semantically related condition as the target. Targets in the control condition were frequency matched with targets in the semantically related condition (log frequency = 1.53 vs. 1.52). Average number of syllables and duration were also similar (1.6 and 510 ms vs. 1.5 and 589 ms).

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6 In an effort to obtain accurate relative frequency information (i.e., to avoid floor effects) three corpora were utilized (essentially as one larger corpus). First, each word’s frequency count in the Brown corpus (Francis & Kucera, 1982), the Wall Street Journal corpus (Mitchell, Santorini & Marcinkiewicz, 1993), and the SWITCHBOARD corpus (Godfrey, Holliman & McDaniel, 1992) was obtained. Then, for each word the three counts were summed. Frequency matching was performed on the logged sums.
Figure 1.

Sample display from Experiment 1 (semantically related items). The target object, *(hammer)*, is semantically related to one of the other objects in the display (the semantically related item, *(nail)*). The other two objects are unrelated semantically and phonologically to the target and its competitor. One of the unrelated objects (the target’s control, *(monkey)*) is frequency-matched with the target. The other unrelated object (the competitor’s control, *(couch)*) is frequency matched with the competitor. This same display also appears (between subjects) in the control condition, with the target’s control *(monkey)* serving as the target.
Since the same displays were used (between subjects) in both the semantically related and the control conditions, one of the non-target items in the control condition had served as the semantically related item in the semantically related condition. This made it possible to determine whether the images that served as related items drew fixations regardless of their relationship to the target (e.g. because the pictures were more inherently interesting than the others in the display). Another benefit of this design is that in the control condition, although two of the objects in the display were semantically related to each other, neither one of these related items was the target. Thus, if any participants noticed that some of the items were related they could not then predict over the course of the experiment that the target would be one of the related items. Moreover, having two related items in the display would make it possible to determine whether semantically related items would draw participants' attention irrespective of the instructions. In filler trials (48 trials) no items in the display were related in any way. Item positions, including the positional relationship between the target and the semantically related item, were balanced so that each item type was equally likely to appear in each corner of the display. Trial order was randomized anew for each participant.

Procedure

Participants were presented a 3x3 array with four pictures on it, one in each corner (see Figure 1). Each cell in the array was approximately 2 X 2 in. Participants were seated a comfortable distance (about 18 inches) from a touch-sensitive monitor, with the monitor at eye height. Therefore, each cell in the grid subtended about 6.4 degrees of visual angle. (The eye tracker is accurate to less than one degree of visual angle.) Therefore, each cell in the grid subtended about 6.4 degrees of visual angle. (The eye tracker is accurate to less than one degree of visual angle.) One second after the display appeared, a red square appeared in the center of the screen. Participants were instructed to touch the red square when it appeared. Touching the red square both caused it to disappear and also triggered a sound file naming one of the objects in the display. After the subject selected one of the pictures by touching it on the screen, the trial ended and the screen went blank. At this point the experimenter could either press a key to go on to the next trial, or check the calibration before continuing. The experimenter continuously monitored the subjects’ performance and eye movements and suggested a break or validated the calibration as necessary. There were 4 practice trials.

Eye movements were recorded starting from when the array appeared on the screen and ending when the participant touched the screen to select a picture. Only fixations that were initiated after the onset of the target word were included in our analyses. Four regions were defined, each corresponding to a corner cell in the array. The SMI software parses the eye
movement data into fixations, blinks and saccades. A fixation to a particular region was defined as starting with the beginning of the saccade that moved to that region and ending with the beginning of the saccade that exited that region. In order for a fixation to a region to be counted it had to last at least 100 ms.

**Results**

Four trials (0.6%) were not included in the analysis because participants selected the wrong picture. Six percent of trials did not provide any data because there were no eye movements after the onset of the target word (most of these were trials in which the participant was already fixating on the picture of the target at the onset of the target word). For the remaining data, we computed the proportions (across trials) of fixations on each picture type (e.g., target, semantically related, unrelated) over time (in 32 ms time bins). Fixations anywhere inside the cell that contained a picture were counted as fixations on that picture. Outliers were treated as follows: fixation proportions more than 2.5 standard deviations from the mean (3% of fixation proportions) were replaced with the mean of the remaining fixation proportions for that bin of that condition.

**Figure 2** plots the mean proportion of trials over time that contained a fixation to the target, the semantically related item, and its control (from target onset to 1500 ms after onset) in the semantically related condition. For the purpose of analyzing the data, a “trial” is defined as starting at 200 ms after target onset (since it takes a minimum of about 180 ms to initiate a saccade to a target in response to linguistic input when the specific target is not known ahead of time, but the possible locations of the target are known, [Altmann & Kamide, 2004]) and ending at the point at which the probability of fixating on the target dropped below 50%. In these data the end of the trial occurred at about 900 ms after target onset. Averaging fixations over the entire trial shows that the semantically related item’s picture was fixated on more than its control, $t_1 (29) = 6.9, p < .01$, and $t_2 (23) = 5.3, p < .01$ for participants and items, respectively. The semantic effect was also measured by comparing fixations to the related item when it appeared in the semantically related condition, with fixations to the same item in the control condition. The related picture in the semantically related condition was also fixated on more than was the same picture in the control condition, where it was unrelated to the target, $t_1 (29) = 7.5, p < .01$ by participants, $t_2 (23) = 12.7, p < .01$ by items.

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7 Due to a computer error, on many trials the array was presented 1/4 inch lower than was intended. To adjust for this error, fixations within 1/4 inch of the lower boundary of each picture’s cell were also counted as fixations on that picture.
Figure 2.
Experiment 1, fixation on semantically related items in 30 subjects: Proportion of fixations over time on the target, the semantically related item, and the related item’s control. Standard error bars are shown for every other data point.
To obtain information about the time course of participants' fixations in the semantically related condition, the trial is divided into seven 100-ms windows (from 200-900 ms after target onset) and separate planned comparisons on each window were conducted. All differences reported below were reliable at $p < .05$ for both participants and items unless otherwise specified. First we sought to determine when the target started to become active by comparing fixations on the target picture with the average of fixations on the unrelated pictures. At the window beginning 200 ms after target onset, fixations on the target were significantly more likely than fixations on the unrelated pictures. This difference remained significant throughout the trial. Next we attempted to establish the time course of the semantically related item’s activation by comparing fixations on the semantically related picture with those on its control picture. At the window beginning 200 ms after the onset of the target, fixations on the semantically related item were more likely than fixations on its control. This difference also remained significant throughout the trial.

**Discussion of Experiment 1**

The results of Experiment 1 show that pictures of objects semantically but not phonologically related to the target draw more fixations than pictures of unrelated objects. Since these fixations cannot be attributed to participants’ simply matching the acoustic input with phonological forms, these results suggest that eye movements do reflect the activation of semantic information. Fixations on semantically related items began to increase in the window 200-300 ms after target onset, and they remained significantly above those on unrelated pictures until the end of the trial. The control condition ruled out two possible alternative explanations for the results. First, the same pictures were fixated on more frequently when they were semantically related to the target than when they were not related to the target, indicating that the pictures we used to represent the semantically related items were not inherently more interesting than other pictures in the display. Second, when two pictures were related to each other but unrelated to the target, they did not draw more fixations than the unrelated picture. This finding indicates that participants were not drawn to related pictures irrespective of the acoustic input (i.e., merely because they were related to each other).

However, there is still another explanation for the fixations on semantically related items that ought to be considered. It is possible that despite our efforts to select only visually dissimilar pairs, participants fixated on semantically related items because they temporarily mistook them for the target. To determine whether mistaking the related item for the target could account for the results, a visual similarity post-test was conducted. The hypothesis was that if the results were due to visual confusion, then the visual similarity of related pairs (the
target and the semantically related item, e.g., *hammer and nail* should be higher than those of unrelated pairs (the target and the related item’s control, e.g., *hammer and couch*). Twenty participants (who had not participated in Experiment 1) were presented with written words and asked to “picture the things that the words refer to and rate them according to how similar they are in shape”.

Ratings were done on a 1-7 scale with 1 being very different and 7 being very similar. Two lists were used so that no participant saw any word more than once. The presentation order was randomized for each participant. Visual similarity ratings for targets and semantically related items were quite low (mean = 2.4) indicating that the selected pairs of items were visually dissimilar. However, visual similarity ratings for targets and control pictures were even lower (mean = 1.5), and this difference was statistically significant \( t_1(19) = 9.4, p < .01 \), and \( t_2(23) = 3.9, p < .01 \) for participants and items, respectively.

To adjust for this disparity, we analyzed separately 12 items that had equivalent (mean of 1.5) average similarity ratings for the related item vs. the target and the control vs. the target. The pattern of results remained the same (Figure 3), with the semantically related item being fixated on significantly more often than its control. Averaged over the entire trial (recall that the trial was defined as the window 200-900 ms after the onset of the target word), this result was significant by both subjects \( t_1(29) = 4.1, p < .01 \), and items \( t_2(11) = 2.6, p = .01 \). While the time course of the semantic effect also appeared the same, in the bin from 500-600 ms after target onset the difference between the related item and its control object only approached significance by both subjects and items \( (p=.06 \) in both analyses). Likewise, in the bins from 600-800 ms after target onset, the difference between the related item and the control object did not reach statistical significance by items \( (p=.07 \) in both bins). Thus, fixations on semantically related items were not due to participants mistaking the related item for the target. Instead, the

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8 Another method would have been to ask participants to rate the pictures that were used in the experiment (this was done in a previous version of this experiment). However, these pictures were selected to be visually dissimilar and thus were unlikely to be visually confusable. Furthermore, despite the visual dissimilarity of the pictures that were used, if a participant’s mental image of a target object is similar to her mental image of the semantically related object, then she might confuse the two. In any case, the results of the two methods are likely to be similar.
Figure 3.

Experiment 1. The semantic effect in the 12 item pairs with equivalent average visual similarity ratings for the related item vs. the target and the related item’s control vs. the target.
Another possible explanation for the fixations on semantically related items is that they were not a consequence of semantic activation but instead a result of partial activation at the level of word form due to co-occurrence. For example, since “hammer and nail” so frequently co-occur, it is possible that there exists a single representation at a level of word form for the term “hammer-and-nail”. This possibility has been raised several times in the semantic priming literature (e.g., Fischler, 1977; Shelton & Martin, 1992), because of the concern that semantic priming effects could be due to associative factors such co-occurrence, rather than semantic relationships. However, a number of studies have showed that even unassociated pairs (as determined by word association tasks)\(^9\) will prime each other if they share enough semantic features (e.g., Perea & Gotor, 1997; McRae & Boisvert, 1998). When only the eight item pairs that were unassociated (forward and backward) according to published word association norms (Nelson, McEvoy, & Schreiber, 1998) were included in the analysis, the semantic effect remained (Figure 4). Averaged over the entire trial, this result was significant by both subjects \(t_1(29) = 4.2, p < .01\), and items \(t_2(7) = 2, p = .04\).

Therefore, with several alternative explanations ruled out, the results of Experiment 1 show that eye movements do reflect the activation of words semantically related to the target\(^{11}\). This

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\(^9\) Shape is, of course, a semantic feature, and it is possible that eye movements to objects similar in shape to the target are due to the activation of that semantic feature rather than confusion about the identity of the object. However, since the eye tracking paradigm requires that objects be identified by visual features such as shape, it may encourage subjects to place unusually strong weight on these visual features, complicating the interpretation of results that pertain to visual features. In an experiment (not described in this dissertation) specifically designed to investigate the time course of access to shape information during spoken word recognition, we provided subjects with a long preview (2 seconds) to inspect the display. The rationale for using such a long preview was that it would give subjects enough time to confidently identify all the objects in the display. Despite the long preview, subjects fixated significantly more on objects similar in shape to objects whose names were onset competitors of the target, than on unrelated objects. For example, given the target “hornet”, they fixated significantly more on a funnel, which is similar in shape to a horn (an onset competitor of hornet).

\(^{10}\) As McRae & Boisvert (1998) noted, however, the real concern of most of the researchers studying semantic, non-associative priming is whether primes and targets co-occur, not whether they are associatively related according to a word association task (i.e., whether subjects produce the target when confronted with the name of the prime). This is because word association tasks appear to reflect many relationships in addition to lexical co-occurrence (e.g., synonyms, antonyms, shared features, super/subordinate categories, etc.). Thus, while excluding associated pairs from one’s stimuli set will tend to exclude co-occurring pairs, this measure will also likely exclude some of the most strongly semantically related non co-occurring pairs (McRae & Boisvert, 1998). Instead of relying on association norms to eliminate co-occurring pairs, a better tactic would be to use a corpus to measure co-occurrence. Nevertheless, because association norm data are more readily available than co-occurrence data, in the current analysis, the former were used.

\(^{11}\) Whether this activation of semantically related words is a consequence of the spread of semantic information from target to related words or the distribution of semantic information over features that the target and related word share, is beyond the scope of this paper.
Figure 4.

Experiment 1. The semantic effect in the 8 item pairs that are unassociated (forward and backward) according to published free association norms (Nelson et al., 1998).
result shows that despite their lack of phonological overlap with the target and despite the lack of any task-related motivation to attend to them, semantically related words become active enough for their pictorial representations to draw visual attention. It should be noted, however, that since these words are semantically related to the intended word, diverting attention to them may not be problematic in terms of causing listeners confusion. On the contrary, since things that are semantically related are often used together or in the same contexts, partially activating semantically related words could assist the listener in understanding subsequent related utterances. What would be more striking is if items semantically related to unintended words became active enough to draw visual attention. Intriguingly, the time course results, namely that words semantically related to the target start to draw fixations 200-300 ms after target onset, indicate that the semantically related item may have been preferentially fixated on before the target word could be disambiguated from its onset competitors. If true, this suggests that eye movements might indeed be drawn to words semantically related to unintended candidates – specifically, to words semantically related to onset competitors of the target.

Such a finding would also show that the results obtained in the current experiment do not hinge on the visual co-presence of the pictures of the target and the semantically related object. For example, in the 1000 ms that participants had to view the display before they heard the target word, they could have processed the relationship between the related pictures, and thus pre-activated them. This pre-activation could have interacted with the acoustic input\textsuperscript{12}, reducing the amount of acoustic information needed for the semantically related to become active. If participants make eye movements to items semantically related to onset competitors of the target, even when the onset competitor itself is absent from the display, this would show that the results obtained in the current experiment do not depend on two semantically related objects being present in the display. More importantly, such a finding would also show that items semantically related to onset competitors become active enough to draw visual attention. Experiment 2 was designed to explore this question.

\textsuperscript{12} Acoustic input is required in this scenario – for if it were not, the related items should have drawn more fixations prior to target onset and/or in the distractor condition.
EXPERIMENT 2: SEMANTICALLY MEDIATED ONSET COMPETITION

Experiment 2 was designed to determine whether eye movements would be preferentially drawn to items semantically related to a phonological onset competitor of the target. If they are, then this would provide evidence from an independent paradigm that, as studies using the cross-modal semantic priming paradigm suggest, not only the forms but also the meanings of an uttered word’s onset competitors become partially active. Moreover, such a finding would also show that items semantically related to onset competitors become active enough to capture visual attention. Furthermore, it would also help alleviate any lingering concern that the semantic effect observed in Experiment 1 was an artifact due to the presence of two semantically related objects in the display.

As described above, previous studies have shown that eye movements reflect the activation of words phonologically related to the target (e.g., Allopenna et al., 1998). Importantly, Dahan et al. (2001) have also shown that lexical factors outside of the immediate visual context can affect fixations. In particular, their study showed that eye movements can be sensitive to the existence of non-displayed phonological neighbors: Participants were slower to fixate on a target picture if the onset of the target word was cross-spliced from an unpictured lexical competitor (e.g., the ne from neck cross-spliced into net) than they were if the onset was cross-spliced from a non-word (e.g., the ne from nep cross-spliced into net). This finding implies that eye movements reflect activation in the general lexicon, instead of merely reflecting the relative activation of potential referents in the display.

Based on these findings, and the early emergence of the semantic effect that appeared in Experiment 1, we reasoned that eye movements should reflect the activation of an item semantically related to an unpictured onset competitor of the target (this item will be referred to as the semantic onset competitor). For example, we predicted that when presented with a display like the one in Figure 5 and asked to “Point to the hammock,” participants should be more likely to fixate on the nail (which is semantically related to hammer, an onset competitor of hammock) than on an unrelated item – even when there is no hammer in the display.

Thus, if in Experiment 2 it is found that fixations are preferentially drawn to the semantic onset competitor, this would indicate that the meaning of the target’s onset competitor has become active enough to draw visual attention. Such a finding would also show that the semantic effect that was observed in Experiment 1 did not hinge on the co-presence of the target and the semantically related object.
Methods

The methods used in Experiment 2 were identical to those used in Experiment 1, with the exceptions described below.

Participants

Thirty male and female participants from the Brown University community were tested.

Materials

For 20 of the 24 items used in Experiment 1, the original target was replaced with a phonological onset competitor. For example, the target *hammer* was replaced with *hammock*. The four remaining items from Experiment 1 were not included in Experiment 2 because a suitable (i.e., picturable and relatively familiar) onset competitor with which to replace the target from Experiment 1 was not available. Three unrelated items (identified in Appendix B) were replaced to avoid introducing a semantic or visual relationship with the target. No other changes were made to the displays. Target names were 1-4 syllables long (2.0 syllables on average). Average target duration was 569 ms. Two lists, each 40 trials long, were created. Figure 5 shows a sample display. See Appendix B for a full list of Experiment 2’s stimuli. In the semantic onset competitor condition (10 of 40 trials), one of the pictures in the display was semantically related to an unpictured phonological onset competitor of the target. This item will be referred to as the semantic onset competitor. The other two items in the display were semantically and phonologically unrelated to both the target and the semantic onset competitor. The name of one of these unrelated items (the competitor’s control) was frequency matched with the name of the semantic onset competitor. In order to ensure that the change in the target would be the only way the displays in Experiment 2 differed from those used in Experiment 1, we did not change the targets in the control condition to frequency match them with targets in the semantic onset competitor condition. The average frequency of targets in the semantic onset competitor condition was slightly, but not significantly lower than the average frequency of targets in the control condition (log frequency = 1.33 vs. 1.58 respectively; \( t (20) = 1.1, p = .26 \)).

The same displays that were used in the semantic onset competitor condition in one list also served as displays in the control condition (10 of 40 trials) on the other list. Related word pairs appeared as target and competitor on one list and as unrelated (to the target) items on the other. (See Appendix B.) This was accomplished by using one of the items that had served as an “unrelated” item in the semantically related condition as the target. The twenty remaining trials were filler trials. There were 4 practice trials.
Figure 5.
Sample display from Experiment 2 (semantic onset competitors). The target object, (hammock), is an onset competitor of an unpictured object (hammer), which is semantically related to one of the other objects in the display (the semantic onset competitor, nail). The other two objects are unrelated semantically and phonologically to the target and its competitor. One of the unrelated objects (the competitor’s control, chocolate) is frequency matched with the competitor. This same display also appears (between subjects) in the control condition with the other unrelated object (monkey) serving as the target.
Results

Data were analyzed as in Experiment 1. Five percent of trials did not provide any data because there were no eye movements after the onset of the target word (most of these were trials in which the participant was already fixating on the picture of the target at the onset of the target word). Two percent of fixation proportions were replaced in the same way as in Experiment 1 because they were more than 2.5 standard deviations away from the mean.

Figure 6 plots the mean proportion of fixations on each picture type over time (from target onset to 1500 ms after onset) for the semantic onset competitor condition. As in Experiment 1, for the purposes of analyzing the data, a trial was defined as starting 200 ms after target onset and ending at the point at which the probability of fixating on the target dropped below 50%. In these data the end of the trial occurred at about 1000 ms after target onset. Comparing mean fixation proportions averaged over the entire trial revealed that the semantic onset competitor was fixated on slightly more than the competitor’s control. This difference was significant in the participants analysis, $t_1 (29) = 2.0, p = .02$ and in the items analysis, $t_1 (19) = 1.8, p = .04$. The semantic onset competitor effect was also measured by comparing fixations to the semantic onset competitor when it appeared together with the target, to fixations to the same object in the control condition. The related picture in the semantic onset competitor condition was also fixated on more than was the same picture in the control condition, where it was unrelated to the target, $t_1 (29) = 4.9, p < .01$, and $t_2 (19) = 5.5, p < .01$.

To obtain information about the time course of participants’ fixations in the semantic onset competitor condition, the trial was divided into eight 100-ms windows (from 200-1000 ms after target onset) and conducted separate planned comparisons on each window. All differences reported below were reliable at $p < .05$ for both participants and items unless otherwise specified. To establish when the target started to become active, fixations on the target were compared with fixations on the unrelated pictures. In the window from 200 to 300 ms after target onset, there were more fixations on the target picture than on unrelated pictures. Fixations on the target picture remained above those on unrelated pictures until the end of the trial. To determine when the semantic onset competitor became active, fixations on the semantic onset competitor were compared with fixations on the competitor’s control picture in the same display. There was no difference between fixations on the competitor and the control picture before 300 ms after the target onset. In the windows from 300 to 400 ms and from 400 to 500 ms after target onset there were significantly more fixations on the competitor than its control, with one exception: in items analysis of the window from 400-500 ms after target onset, the difference between the competitor and the control did not quite reach significance ($p = .07$). The competitor was also
Figure 6.
Experiment 2. Fixations on semantic onset competitors in 30 young normals: Proportion of fixations over time on the target, the semantic onset competitor, and the semantic onset competitor’s control. Standard error bars are shown for every other data point.
fixated on more than its control in the window from 500-600 ms after target onset but this difference only approached statistical significance both by participants ($p=.09$) and by items ($p=.11$).

**Discussion of Experiment 2**

The results of Experiment 2 show that words semantically related to phonological onset competitors of an uttered word become active enough to draw visual attention. These findings provide support for the hypothesis that not only the forms, but also the meanings of a word’s onset competitors become partially active during spoken word recognition. This finding also indicates that the pattern of eye movements to semantically related items that was observed in Experiment 1 was not due to the presence of two related pictures in the display. On the contrary, despite the fact that in Experiment 2 the target’s phonological onset competitor was not present in the display, participants still fixated on the semantic onset competitor more than on the competitor’s control picture.

Although visual similarity post-hoc analyses showed that visual similarity between the target and the related item did not cause the semantic priming effect of Experiment 1, it still remains conceivable that the results of Experiment 2 were affected by visual similarity. That is, because Experiment 1’s post test showed that the semantically related item (e.g., *nail*) was more visually similar to the target (e.g., *hammer*) than the control item (e.g., *couch*), it is possible that in Experiment 2, the fixations on the semantic onset competitor (e.g., *nail*) were due to participants confusing it for the (albeit unpictured) onset competitor (e.g., *hammer*). To adjust for the fact that the semantic onset competitors were more similar to the onset competitor than the unrelated items were (e.g., *nail* was more similar to *hammer* than *couch*), we analyzed separately the 8 items that had equivalent average similarity ratings for the semantic onset competitor vs. the onset competitor (e.g., *nail vs. hammer*) and the control vs. the onset competitor (e.g., *couch vs. hammer*). Both means were 1.55. Averaged over the entire trial (recall that the trial was defined as the window 200-1000 ms after the onset of the target word), this result was significant by both subjects $t_1(29) = 4.8, p < .01$, and items $t_2(7) = 3.0, p = .01$. The time course of the semantic onset competitor effect also remained essentially the same except that by subjects, the effect was significant in more time bins (300-800 ms).

It is interesting to note that the 200-300 ms duration of the semantic onset competitor effect is much shorter than the 700 ms duration of the semantic effect. The short duration of the semantic onset competitor effect is consistent with results from two early cross-modal semantic priming studies (Marslen-Wilson, 1987; Zwitserlood, 1989). In these studies it was found that if the target was presented before the prime’s uniqueness point, then as long as the target was
related to a possible continuation of the prime, lexical decisions were speeded. However, when it was presented after the point at which the prime became unambiguous, responses were only speeded if the target was related to the word actually uttered. Moreover, the semantic onset competitor effect’s short duration could explain why some investigators have not obtained priming for words semantically related to words embedded in the onsets of real words (Isel & Bacri, 1999; Vroomen & de Gelder, 1997). In these studies, visual targets related to onset embedded words were presented at the offset of the embedding words (e.g., they might have presented lock as a target at the offset of the prime keyboard). Although priming was not obtained, the authors of these studies did not interpret their result as indicating that onset embedded words were never active; rather they attributed the lack of priming to onset embedded words no longer being active at the time of the probe. Consistent with their account, no evidence of the semantic onset competitor's activation would have been found if only eye movements planned after the target's offset (which would begin to appear at 769 ms, 200 ms after the average target offset) had been measured.

Thus, Experiment 2 shows that words semantically related to not only the target, but also its onset competitors become active enough that their pictorial representations draw visual attention, despite the absence of any task demands related to these related items. In addition, the time course of the results of Experiment 2 may suggest why despite the fact that the semantic representations of unintended candidates become active enough to draw visual attention, we are not conscious of diverting attention to them: their activation is extremely short-lasting.

Experiment 2’s findings also imply that this experimental design could be used to investigate whether the semantic representations of an uttered word’s rhyme competitors become active. As described earlier, studies using the eye tracking paradigm (Allopenna et al., 1998; McMurray et al., 2003) have found visual attention is drawn not only to objects whose names start with the same sound as the uttered word, but also to objects whose names rhyme with the uttered word. However, studies using the cross-modal semantic priming paradigm have found no evidence that we activate the semantic representations of rhyme competitors (Marslen-Wilson & Zwitserlood., 1989; Marslen-Wilson et al., 1996). Taken together the data from these two paradigms could be interpreted as indicating that we activate the forms, but not the meanings of rhyme competitors. It is also possible, however, that eye movements are more sensitive to lexical activation than is cross-modal semantic priming. If true, and if the semantic representations of words that rhyme with an uttered word do in fact become active, then this activation might be reflected in eye movements to pictures of objects semantically related to the rhyming word.
EXPERIMENTS 3A & 3B: SEMANTICALLY MEDIATED RHYME COMPETITION

The goal of Experiments 3a and 3b was to investigate whether eye movements would be preferentially drawn to items semantically related to a word that rhymes with the target. Specifically, in light of the results obtained in Experiment 2 and the Allopenna et al. (1998) result for rhyme competitors, it was predicted that when presented with a display like the one in Figure 7 and asked to touch the *pear,*” participants should be more likely to fixate on the tiger (which is semantically related to *bear,* a rhyme competitor of *pear*), than on an unrelated item – even though there is no bear in the display. Such a finding would lend support to the hypothesis that the semantic representations of words than rhyme with an uttered word do in fact become active.

Methods 3a & 3b

The methods used in Experiments 3a and 3b were identical to those used in Experiments 1 and 2, with the exceptions described below.

Experiment 3a

Participants

Twenty nine male and female participants from the Brown University community were tested.

Procedure

Participants were presented with a 2x2 array with four pictures on it, one in each cell (see Figure 7). Each cell was approximately 2.25 x 2.25 in. Since participants were seated approximately 18 inches from the monitor, each cell in the display subtended approximately 7.2 degrees of visual angle. A 2x2 (instead of 3x3) array was used in this experiment so that the pictures would be closer together (about 7.2 degrees apart, as opposed to about 12.8 degrees apart). This was done because it was suspected that any semantic rhyme competitor effect would be quite subtle. Since larger saccades take longer to make, with the pictures closer together, participants might have time to make a greater number of small eye movements during the course of recognizing the target, which would potentially make the task more sensitive.
Figure 7.
Sample display from Experiment 3a (semantic rhyme competitors: voice and place items). On one list, the target is (*pear*), a rhyme competitor of an unpictured object (*bear*), which is semantically related to one of the other objects in the display (*tiger*). The other two objects are unrelated semantically and phonologically to the target and its competitor. On the other list (between subjects), the target is (*gold*), a rhyme competitor of an unpictured word (*cold*), which is semantically related to an object in the display (*snowman*).
Materials

Thirty two stimulus pairs were created. Target names were all one syllable, consonant initial, picturable nouns. Average target duration was 437 ms. For each target word there existed a rhyme competitor that differed only in either the voicing (16 items) or the place of articulation (16 items) of the initial consonant. One of the pictures in the display (the semantic rhyme competitor) was semantically related to this (unpictured) rhyme competitor of the target. For example, if the target were *pear* (which rhymes with *bear*), the semantic rhyme competitor would be *tiger*. Two lists, each 64 trials long, were created. Figure 7 shows a sample display. As in Experiments 1 and 2, each participant was run on only one list so that no participant saw or heard any item more than once. See Appendix C for a full list of Experiment 3a’s stimuli.

In the semantic rhyme competitor condition (16 of 64 trials on each list), one of the pictures in the display was semantically related to an unpictured rhyme competitor of the target. This item will be referred to as the semantic rhyme competitor. The other two items in the display were semantically and phonologically unrelated to both the target and the semantic rhyme competitor. In the other list, however, one of these items served as the target and the other as the semantic rhyme competitor (see Appendix C.) Since one of the unrelated items in each display served as the semantic rhyme competitor for another display, the average frequency of the semantic rhyme competitors perfectly matched the average frequency of one of the unrelated items. This unrelated item was used as the competitor’s control. The remaining 48 trials were filler trials. There were also three practice trials.

Results

Data were analyzed as in Experiment 1 and 2. Because the cells that contained each picture were adjacent, fixations were not counted as being on a picture unless they were more than 1/4 inch away from the line separating two cells (to avoid counting a fixation on the wrong object if the eyetracker was not perfectly calibrated). Five percent of trials did not provide any data because participants did not make any saccades after the onset of the target (most of these were trials in which the participant was already fixating on the picture of the target at the onset of the target word). Two percent of fixation proportions were replaced in the same way as in Experiment 1 and 2 because they were more than 2.5 standard deviations away from the mean. One item (*palm*) was excluded from the analysis because several participants reported difficulty understanding the word and because response times to this item were more than 3 standard deviations greater than the mean of the rest of the items.
Figure 8 plots the mean proportion of fixations on each picture type over time (from target onset to 1500 ms after onset) for the semantic rhyme competitor condition. As in Experiment 1 and 2, for the purposes of analyzing the data, a trial was defined as starting 200 ms after target onset and ending at the point at which the probability of fixating on the target dropped below 50%. In these data the end of the trial occurred at about 900 ms after target onset. When mean fixation proportions averaged over the entire trial, were compared it was found that the semantic rhyme competitor was fixated on slightly more than the competitor’s control. This difference was significant in the participants analysis, \( t_1 (28) = 2.4, p = .01 \) and in the items analysis, \( t_1 (30) = 1.7, p = .05 \).

To obtain information about the time course of participants' fixations, the trial was divided into seven 100-ms windows (from 200-900 ms after target onset) and separate planned comparisons on each window were conducted. To establish when the target started to become active, we compared fixations on the target with fixations on the unrelated pictures. In the window from 200 to 300 ms after target onset, there were significantly more fixations on the target picture than on unrelated pictures. Fixations on the target picture remained significantly above those on unrelated pictures until the end of the trial. To determine when the semantic rhyme competitor became active, we compared fixations on the semantic rhyme competitor with fixations on the competitor’s control picture in the same display. In the windows from 500 to 600 ms and from 600 to 700 ms after target onset, there were more fixations on the competitor than the control pictures. This difference was significant in the participants analysis (\( p=.03 \) in both bins), and approached significance (\( p=.07 \) in both bins) in the items analysis.

To assess whether the voicing and place of articulation feature contrasts differently affected the activation of the items semantically related to the rhyme competitor, we analyzed separately competitors that differed from the target in place from those that differed in voice. Figures 9 and 10 plot the mean proportion of fixations on each object type over time (from target onset to 1500 ms after onset) for the place and voice items respectively. As in previous analyses, the trial was defined as starting 200 ms after target onset and ending at the point at which the probability of fixating on the target dropped below 50%. In both of these data sets the end of the trial occurred at about 900 ms after target onset. When mean fixation proportions averaged over the entire trial were compared, it was found that for the place items, the semantic rhyme competitor was fixated on slightly more than the competitor’s control. However, this difference only approached significance in the participants analysis, \( t_1 (28) = 1.5, p=.08 \) and in the items analysis, \( t_1 (15) = 1.1, p=.15 \). For the voice items the semantic rhyme competitor was also fixated on slightly more than the competitor’s control. This difference was significant in the
Figure 8.
Experiment 3a. Fixations on semantic rhyme competitors (all items) in 29 young normals: Proportion of fixations over time on the target, the semantic rhyme competitor, and the semantic rhyme competitor’s control. Standard error bars are shown for every other data point.
Figure 9.
Experiment 3a. Fixations on semantic rhyme competitors (place items) in 29 young normals: Proportion of fixations over time on the target, the semantic rhyme competitor, and the semantic rhyme competitor’s control. Standard error bars are shown for every other data point.
Figure 10.
Experiment 3a. Fixations on semantic rhyme competitors (voice items) in 29 young normals: Proportion of fixations over time on the target, the semantic rhyme competitor, and the semantic rhyme competitor’s control. Standard error bars are shown for every other data point.
participants analysis, \( t_{1} (28) = 1.9, p=.03 \) and approached significance in the items analysis, \( t_{1} (14) = 1.0, p=.16 \).

To determine the time course of the semantic rhyme competitor’s activation for the place and voice items, we compared fixations on the semantic rhyme competitor with fixations on the competitor’s control picture in each bin from 200-900 ms after target onset. For the place items, the difference between the competitor and the control in the two bins from 500-700 ms after target onset was significant by participants \( (p<.05) \) and was either significant or approached significance by items \( (.03<p<.09) \). For the voice items, in the two bins from 200 to 400 ms after target onset the difference between the competitor and the control approached significance by participants \( (.07<p<.10) \) and by items \( (.09<p<.16) \).

**Discussion of Experiment 3a**

The results of Experiment 3a suggest that words semantically related to a rhyme competitor of the target are fixated on slightly more than unrelated words. However, overall, this is a small effect and furthermore, its significance depends upon the removal of an item \( (palm) \) that was judged to be poor – with that item included, the effect approaches significance by participants \( (p=.06) \), but is not significant by items \( (p=.22) \). Since this was the first demonstration that we do have access to the semantic representations of words that rhyme with an uttered real word, and because the effect was so small, a replication of this result was attempted.

**Experiment 3b**

**Participants**

Fifty male and female participants from the Brown University community were tested.

**Procedure**

Because the smaller array used in Experiment 3a did not appear to have an effect on the sensitivity of the procedure (participants did not make more eye movements than they did in Experiments 1 and 2), in Experiment 3b, we used the same array used in Experiments 1 and 2. The amount of time that the display was present on the screen prior to the appearance of the red square was reduced from 1000 ms to 500 ms. This adjustment was made because in post-test
questionnaires from Experiments 1, 2, and 3a participants occasionally reported attempting to produce labels for the images in the display prior to the onset of the acoustic input.

**Materials**

All of the stimuli in Experiment 3b consisted of target words for which there exists a rhyme competitor that differs only in the voicing of the initial consonant. Only voice items were used because in Experiment 3a, the semantic rhyme competitor effect appeared slightly larger in the voice than the place items. Furthermore, in a previous study (not described elsewhere in this dissertation) that used the same stimuli as Experiment 3a a small \(p=.04\) by subjects, \(p=.23\) by items) semantic rhyme effect appeared for the voice items, but no effect emerged for the place items. Twenty four stimulus pairs were created. Target names were all one syllable, consonant initial, picturable nouns. Average target duration was 524 ms. Two lists, each 72 trials long, were created. Related word pairs appeared as target and competitor on one list and as unrelated items on the other (See Appendix D.) As in Experiments 1, 2, and 3a, each participant was run on only one list so that no participant saw or heard any item more than once. See Appendix D for a full list of Experiment 3b’s stimuli.

Figure 11 shows a sample display. As in Experiment 3a, in the semantic rhyme competitor condition (12 of the 72 trials on each list), one of the pictures in the display (the semantic rhyme competitor) was semantically related to an unpictured rhyme competitor of the target. The other two items were semantically and phonologically unrelated to both the target and the semantic rhyme competitor. The name of one of these unrelated items was frequency matched with the semantic rhyme competitor. This item will be referred to as the competitor’s control. The name of the other unrelated item was frequency matched with the target.

The same displays that were used in the semantic rhyme competitor condition in one list also appeared in the control condition (12 of 72 trials) on the other list. This was accomplished in the same way as in Experiments 1 and 2 (by using one of the items that had served as an “unrelated” item in the semantically related condition as the target). Targets in the control

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13 The questionnaire explicitly asked participants whether they had attempted to label the images during the preview period. A few subjects reported doing this in Experiments 1, 2, and 3a. For each experiment the data were analyzed with these subjects excluded. Excluding these subjects had no effect on the pattern of results. However, we suspected that any pre-naming might make an effect as subtle as the semantic rhyme competitor effect even more difficult to detect because pre-naming would pre-activate the target’s representation (but not the rhyme competitor, as it was not present in the display), reducing competition from phonological competitors. Thus we attempted to minimize pre-naming by shortening the preview time. Post-test questionnaires from Experiment 3b showed that the reduction in the preview time was successful at preventing pre-naming.

14 This study used the same stimuli as Experiment 3a but did not allow any preview of the display prior to the onset of the target. This procedure appeared to add noise as well as a slight delay to the data because most participants looked at each picture before touching the screen, even if they had already identified the target (as evidenced by their finger hovering over the target).
Figure 11.
Sample display from Experiment 3b (semantic rhyme competitors: all voice items). The target object, \textit{(pear)}, is a rhyme competitor of an unpictured object \textit{(bear)}, which is semantically related to one of the other objects in the display \textit{(the semantic rhyme competitor, tiger)}. The other two objects are unrelated semantically and phonologically to the target and its competitor. One of the unrelated objects \textit{(the competitor’s control, sword)} is frequency matched with the competitor. This same display also appears (between subjects) in the control condition with the other unrelated object \textit{(lock)} serving as the target.
condition were frequency matched with targets in the semantically related condition. The remaining 48 trials were fillers. There were also four practice trials.

**Results**

Data were analyzed as in Experiments 1, 2 and 3a. Five percent of trials did not provide any data because participants did not make any saccades after the onset of the target (most of these were trials in which the participant was already fixating on the picture of the target at the onset of the target word). Two percent of fixation proportions were replaced in the same way as in previous experiments because they were more than 2.5 standard deviations away from the mean. **Figure 12** plots the mean proportion of fixations on each picture type over time (from target onset to 1500 ms after onset) for the semantic rhyme competitor condition. The trial length was defined as in previous experiments. In these data the end of the trial occurred at about 1000 ms after target onset. When mean fixation proportions averaged over the entire trial were compared, it was found that the semantic rhyme competitor was fixated on slightly more than the competitor’s control. This difference was significant by participants, \( t_1(49) = 1.9, p = .04 \) but not by items, \( t_1(23) = .7, p = .26 \). The semantic rhyme competitor effect was also measured by comparing fixations to the semantic rhyme competitor when it appeared together with the target, to fixations to the same object when it appeared in the control condition. The related picture in the semantic rhyme competitor condition was also fixated on slightly more than was the same picture in the control condition, where it was unrelated to the target. This difference was significant by participants \( t_1(49) = 2.1, p = .02 \), and approached significance by items \( t_2(23) = 1.1, p = .15 \).

To obtain information about the time course of participants' fixations, the trial was divided into eight 100-ms windows (from 200-1000 ms after target onset) and separate planned comparisons were conducted on each window. To establish when the target started to become active, fixations on the target were compared with fixations on the unrelated pictures. In the windows from 200 to 300 ms after target onset, there were significantly more fixations on the target picture than on unrelated pictures. Fixations on the target picture remained significantly above those on unrelated pictures until the end of the trial. To determine when the semantic rhyme competitor became active, fixations on the semantic rhyme competitor were compared with fixations on the competitor’s control picture in the same display. In the two windows from 200 to 400 ms after target onset, there were more fixations on the competitor than on control pictures. This difference was significant in the participants analysis (\( p<.05 \) in both bins), and approached significance in the items analysis (\( .11<p<.13 \)). The competitor was also fixated on
Figure 12.
Experiment 3b. Fixations on semantic rhyme competitors (all voice) in 50 young normals: Proportion of fixations over time on the target, the semantic rhyme competitor, and the semantic rhyme competitor’s control. Standard error bars are shown for every other data point.
more than the control in the bin from 400-500 ms after target onset. This difference approached significance both by participants ($p=.10$) and by items ($p=.11$).

**Discussion of Experiments 3a & 3b**

By showing that items semantically related to an uttered word’s rhyme competitors draw fixations, the results of Experiment 3 provide support for the hypothesis that not only the phonological but also the semantic representations of words that rhyme with an uttered word become active. The semantic representations of these rhyming words are activated despite the initial inconsistency between the acoustic input and their phonological forms, and also despite the existence (and the visual presence) of a real word that is completely consistent with the input.

The time course of the semantic rhyme competitor effect helps explain the differences between the findings of Experiment 3 and the cross-modal semantic priming studies on rhyme competition (Marslen-Wilson & Zwiterlood, 1989; Marslen-Wilson et al., 1996). Specifically, the semantic rhyme competitor effect that was obtained in Experiments 3a and 3b was short-lived (lasting 200-300 ms) suggesting that by the offset of the target word, the semantic rhyme competitor was no longer active. In each of the cross-modal semantic priming studies on rhyme competition, the target was presented at the offset of the spoken prime, at which point it may have been too late to detect the rhyme competitor’s activation. Thus, because eye movements are tracked continuously over time the eye tracking paradigm may be more sensitive to subtle lexical activation than paradigms that only provide a single data point per trial, such as cross-modal semantic priming.

A second factor may also contribute to making the eye tracking paradigm more sensitive to lexical activation than the cross-modal semantic priming paradigm. Although both paradigms use an item semantically related to the word of interest to detect that word’s activation, in the cross-modal semantic priming paradigm the semantically related item is presented as a letter-string, whereas in the eye tracking paradigm, the semantically related item is presented as a picture. It seems likely that a pictorial representation is closer to the mental representation of a word’s meaning than is a letter string, and thus responses to pictures better reflect the activation of that meaning than do responses to letter strings. Evidence that this may be true comes from two studies that found that the magnitude of semantic priming (in a naming task) was larger when the targets were pictures than when the targets were letter strings (Carr, McCauley, Sperber & Parmelee, 1982; Vanderwart, 1984).

Thus, although the discrepancy between the findings of studies using the cross-modal semantic priming paradigm and prior studies using the eye tracking paradigm seemed to suggest
that we activate the forms, but not the meanings of words that rhyme with an uttered word, Experiment 3’s results indicate that not only the phonological but also the semantic representations of words that rhyme with an uttered word can become active. It is important to acknowledge, however, that not only is the semantic rhyme competitor effect that appeared in Experiment 3 quite small, but also that the targets and their rhyme competitors were extremely similar acoustically – differing only in the voicing of the initial consonant. It remains to be seen, therefore, whether semantic information about other types of rhyme competitors also becomes active. As noted above, we have obtained some evidence suggesting that this same pattern may not hold true for place of articulation. However, it seems plausible that the proportion of acoustic overlap with the uttered word interacts with the type or extent of initial mismatch. For example, longer rhyming competitors that still differ from the target only in the voicing of the initial consonant may elicit a stronger semantic rhyme competitor effect.

Regardless of the answers to these questions, the findings of Experiment 3 are significant in that they demonstrate that the semantic representation of a word that rhyme with an unmodified real word can, in fact, become active.
GENERAL DISCUSSION: PART 1

In three experiments it has been shown that during spoken word recognition, items semantically related to both the intended word and also items semantically related to unintended lexical candidates become active enough to capture visual attention. These findings show that eye movements reflect more than just the degree of phonological match between the acoustic input and the phonological forms of potential referents in the display. They also reveal the activation of semantic information about candidates that are considered as a spoken word is processed.

These results also highlight the limitations of experimental paradigms that probe activation at only discrete time points. In particular, in the form priming paradigm, responses to targets that were onset competitors of primes were delayed rather than speeded because the probe occurred at a point after the onset competitors had already been rejected. On the other hand, cross-modal semantic priming studies that did detected the activation of onset competitors presented the target prior to the offset of the auditory prime, when the onset competitors were still active (Marslen-Wilson, 1987; Moss et al., 1997; Zwitserlood, 1989). Studies using the cross-modal semantic priming paradigm to explore rhyme competition, however, may have been unable to detect the activation of rhyme competitors because they failed to probe during the short period in which rhyme competitors are detectably active (Marslen-Wilson & Zwitserlood, 1989; Marslen-Wilson et al., 1996).

Thus, the time course information that eye movements provide, coupled with the semantic eyetracking paradigm’s sensitivity to semantic activation, appears to make this paradigm particularly well-suited for investigating the fine details of lexical and semantic activation during spoken word recognition. For example, although the experiments reported in this dissertation made no attempt to control for the way in which semantically related items were related to the target or its phonological competitors, explicitly controlling these semantic relationships could supply valuable insight into how semantic representations are organized. In particular, it has been proposed that we do not access all types of semantic information about a word at the same time, but rather that different kinds of semantic information (for example perceptual and functional) become active on different time courses. By varying these semantic relationships between the target and the semantically related item, we (together with colleague Jason Taylor) have conducted preliminary studies using this paradigm to procure information about the time course of access to function and shape information during spoken word recognition. Furthermore, another colleague, Jong-Yoon Myung, has recently used the paradigm introduced
here to show that information about how an object is manipulated is accessed during spoken word recognition.

Due to its simplicity and the time course information that it provides, the eye tracking paradigm may also be useful for investigating the time course of lexical and semantic activation in brain damaged populations. For example, the theories that have been proposed to account for the lexical processing deficits in Broca’s and Wernicke’s aphasia make predictions that relate to the time course of lexical activation (e.g., Hagoort, Brown & Swaab, 1996; Prather, Zurif, Love & Brownell, 1997; Milberg, Blumstein & Dworetzky, 1988). Although numerous studies have explored the time course of lexical activation in aphasic patients by varying the ISI in a semantic priming paradigm (e.g., Prather, Zurif, Stern & Rosen, 1992; Hagoort, 1993; Milberg, Blumstein, Katz, Gershberg & Brown, 1995; Prather, Zurif, Love & Brownell, 1997; Utman, Blumstein & Sullivan, 2001) information about the time course of lexical activation in Broca’s and Wernicke’s aphasics remains spotty because in the semantic priming paradigm, activation is probed at discrete points. A more direct and continuous measure of lexical activation, such as the eye movement paradigm, could provide further insight into the lexical processing deficits of these patients. That the eye tracking paradigm has been shown to be sensitive to semantic information is crucial if the studies using the eye tracking paradigm with Broca’s and Wernicke’s aphasics are to be interpreted in the context of previous work using the semantic priming paradigm.

To conclude this section, the results of Experiments 1-3 suggest that during spoken word recognition, semantic information about not only the uttered word, but also words similar in sound, becomes active enough to draw visual attention. Our visual attention is diverted despite that we are rarely aware of considering candidates that turn out to be incorrect, and even though attending to these candidates does not help (and in fact may hinder) task performance. These findings highlight the delicate balance between activation and deactivation that our word recognition system has to maintain in order to keep pace with the input – we have to constantly make hypotheses about what is being said in order to keep up with the input, but we also need to constantly deactivate the meanings of unintended candidates to avoid confusion. How does the system maintain this balance? The short duration (~200 ms) of both the semantic onset and the semantic rhyme competitor effects suggests that candidates either quickly decay when the input is no longer consistent with their representations, or that more active candidates inhibit less active candidates. Studying aphasic patients who are known to have lexical processing deficits may not only illuminate the disorders themselves, but could also provide clues as to how a properly functioning system resolves competition. The second part of this paper will describe four experiments investigating spoken word recognition in Broca’s and Wernicke’s aphasics.
PART 2: SPOKEN WORD RECOGNITION IN BROCA’S AND WERNICKE’S APHASIA

For over a century, studying the language impairments displayed by individuals with brain damage has provided us with clues about the functional and anatomical organization of language. The second part of this dissertation investigates lexical access in patients with Broca’s and Wernicke’s aphasia in an effort to better understand normal lexical processing and better characterize the language deficits displayed by these patients.

Broca’s aphasia is associated with language production problems, but relatively spared comprehension. In particular, the speech of Broca’s aphasics is non-fluent, agrammatic and effortful. Function words are often omitted, resulting in a telegraphic quality. Articulation is often poor. Object naming is often impaired. Comprehension, while relatively good compared to production, is not unaffected. Broca’s aphasics have difficulty with some function words, with more complex syntactic structures, and also with lexical access (see Damasio, 1998 for a review). Anatomically, Broca’s aphasia often results from a lesion to the left inferior frontal gyrus (in particular Brodmann areas 44 and 45), which is also called Broca’s area. However, the borders of Broca’s area are not clearly defined. Broca’s aphasia can also result from damage to premotor and motor regions behind and above these areas (Damasio, 1989). White matter deep to Broca’s area, as well as the basal ganglia and the insula are also often damaged, and it has been argued that such sub-cortical damage is essential for permanent Broca’s aphasia (see Dronkers, Redfern & Knight, 2000 for a review).

Wernicke’s aphasia is often thought of as the complement of Broca’s aphasia because it has been associated historically with language comprehension problems but comparatively spared production. Although it is true that productions of Wernicke’s aphasics are typically fluent, grammatical, and generally well-articulated, their speech output is far from normal. Productions often lack coherence or seem completely devoid of content. Novel words (jargon or neologisms) are often produced, related words are frequently substituted for one another, and words may be produced with one or more phonemes added, substituted or omitted (see Damasio, 1998 for a review). Anatomically, Wernicke’s aphasia is often associated with damage to the posterior portion of the left superior temporal gyrus (Brodmann area 22). However, adjacent parietal regions and the middle temporal gyrus are also often affected. Thus, as with those of Broca’s area, the boundaries of Wernicke’s area are unclear (Damasio, 1989).
Lexical access in Broca’s and Wernicke’s aphasia

The evident dissociation between the language comprehension abilities of Wernicke’s and Broca’s aphasics, together with demonstrations that Wernicke’s aphasics perform poorly in tasks requiring explicit access to semantic information, while Broca’s aphasics perform quite well (e.g., Goodglass & Baker, 1976; Zurif, Caramazza, Myerson & Galvin, 1974), led a number of researchers to believe that the semantic lexicon was impaired in Wernicke’s, but not Broca’s aphasia (e.g., Grober, Perecman, Keller & Brown, 1980). However, a pair of studies by Blumstein and colleagues (Milberg & Blumstein, 1981; Blumstein, Milberg & Shrier, 1982) showed that the distinction between the lexical-semantic processing capabilities of the two groups is not as clear as was previously thought.

These latter researchers noted that because prior studies exploring lexical-semantic processing in Broca’s and Wernicke’s aphasics required that the patients make explicit semantic judgments about whether words “go together”, these studies confounded damage to semantic representations with problems accessing those representations. In order to probe semantic representations without requiring conscious access to those representations, Milberg and Blumstein (1981) used an implicit measure of lexical-semantic processing: visual semantic priming as measured by reaction times in a lexical decision task. They found that, despite their problems with explicit access to semantic information, Wernicke’s aphasics did exhibit semantic priming in this task. But surprisingly, while the group of Broca’s aphasics that they tested showed the same pattern of results, their semantic priming effect was not statistically reliable. In order to determine whether these results were limited to the visual modality, the authors carried out a second, analogous experiment in the auditory modality (Blumstein, Milberg & Shrier, 1982). This time, both Wernicke’s and non-fluent aphasics (3 Broca’s and 4 Transcortical Motor) exhibited semantic priming. Several later studies provided further evidence that, like normals, Wernicke’s aphasics show semantic priming (Swinney, Zurif & Nicol, 1989; Hagoort, 1993; Prather, Love, Finkel & Zurif, 1994; Tyler, Ostrin, Cooke & Moss, 1995; Baum, 1997; Prather et al., 1997; Milberg, Blumstein, Sullivan, Giovanello & Misiurski, 2003). Furthermore, a number of later studies (which will be described below) also failed to obtain semantic priming for Broca’s aphasics in circumstances in which normals did show priming (e.g., Milberg,

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15 The data from one conduction aphasic, was included with the 5 Broca’s aphasics in this group “since neither has been found to have significant deficits in semantic processing and both groups have generally good language comprehension.” (Milberg & Blumstein, 1981, p. 373). Conduction aphasia is characterized by spared comprehension and fluent speech, but difficulty with repetition (see Damasio, 1998).

16 Transcortical Motor aphasia is similar to Broca’s aphasia in that patients produce non-fluent, agrammatic speech. It differs in that verbal repetition is spared in Transcortical Motor aphasia, and in that lesions are typically anterior or superior to Broca’s area (Damasio, 1989).
Several theories have been developed to account for the dissociation between the abilities of Broca’s and Wernicke’s aphasics to make explicit semantic judgments and their patterns of semantic priming. The first proposal, put forth by Blumstein and colleagues (1982), took as its starting point the idea that there are two distinct components underlying word processing: one process that automatically activates a word’s semantic information without conscious effort on the part of the hearer, and a second process that relies on conscious processing (e.g., Posner & Snyder, 1975). Blumstein and colleagues hypothesized that Wernicke’s and Broca’s aphasics each are impaired at one of these processes. Specifically, they proposed that Wernicke’s aphasics are unable to consciously control semantic information, but have spared automatic access to it, and that Broca’s aphasics are unable to automatically access semantic information, but are still able to consciously control it.

Because later studies showed that Broca’s aphasics do retain automatic access to semantic information and that Wernicke’s aphasics’ access to automatic information is not normal (e.g., Milberg et al., 1988), this original theory is no longer considered plausible. Nevertheless, because each of the three currently prominent theories about lexical-semantic processing in Broca’s and Wernicke’s aphasias were inspired by results of studies conducted to evaluate this original theory, it is still quite pertinent. These three theories are briefly summarized here, with more details about each one given below. Each theory implicates a (slightly) different mechanism, and each theory proposes that the mechanism that it implicates is affected in both patient groups. The three theories are:

1. Normal activation (but a deficit in lexical-semantic integration): Broca’s and Wernicke’s aphasics do not have problems with automatic lexical activation. Instead, both have problems integrating lexical-semantic information into context. Wernicke’s aphasics also have difficulty consciously operating on lexical-semantic information (Hagoort et al., 1996).

2. Delayed lexical activation/deactivation: Broca’s aphasics are delayed in activating lexical representations, while Wernicke’s aphasics are delayed in deactivating lexical representations (Prather et al., 1997).

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17 The authors usually refer to the deficit that they propose for Broca’s aphasics as slowed activation. However, although the term slowed suggests that the entire activation process is drawn out, Prather et al.’s (1992) description (“Broca’s aphasics should show a rise-and-fall time curve similar to the elderly subjects” [p. 339]) implies that what is meant is that the activation process starts later, but once it starts, activation proceeds normally. We therefore refer to this theory as delayed activation.
3. Reduced/increased activation: Compared to normals, Broca’s aphasics have reduced levels of lexical activation, while Wernicke’s aphasics have increased levels of lexical activation\(^\text{18}\) (Milberg et al., 1987).

In the next sections, each of these theories will be described in more detail. Then relevant behavioral data will be evaluated. To preview what follows, a review of data relevant to these theories suggests that some aspects of the hypothesis that both Broca’s and Wernicke’s aphasics have normal activation are difficult to reconcile with recent results. The delayed activation/deactivation and the reduced/increased activation hypotheses, in contrast, are both consistent with much of the available data. Unless otherwise specified, all of the experiments described below used auditorily presented stimuli.

**Normal activation (but a deficit in lexical-semantic integration)?**

This first hypothesis contends that neither Broca’s nor Wernicke’s aphasics have problems with automatic lexical activation. Instead, both groups are hypothesized to have difficulty integrating lexical-semantic information. This argument was first put forth by Hagoort (1993) who observed that in the initial studies in which Broca’s aphasics failed to display semantic priming (Milberg & Blumstein, 1981; Milberg, Blumstein & Dworetzky, 1987; Milberg et al., 1988), there were relatively long delays (over 500 ms) between the prime and target. It has been argued that at longer inter-stimulus intervals (ISIs) processes which occur after recognition of the prime and target play a larger role in semantic priming than does automatic lexical activation (Neely, Keefe & Ross, 1989). Hagoort reasoned, therefore, that the failure of Broca’s aphasics to exhibit semantic priming might not be due to impaired automatic lexical activation. Instead, he argued that it could be due to post-lexical *semantic matching*, which is hypothesized to occur when a subject consciously detects the relationship between the prime and target and uses the fact that they are related to bias a yes response (e.g., Koriat, 1981).

Evidence for normal activation in Broca’s aphasics came from a study investigating semantic priming in both Broca’s and Wernicke’s aphasics at ISIs ranging from 100-1250 ms (Hagoort, 1993). In this study both aphasic groups, like normals, exhibited semantic priming at ISIs shorter than 1250 ms, but unlike normals, they failed to exhibit priming at 1250 ms. Thus, since both groups exhibited semantic priming at short ISIs (when automatic activation was presumed to account for semantic priming), but not later (when semantic matching was hypothesized to drive semantic priming), Hagoort suggested that automatic lexical activation is normal in Broca’s and Wernicke’s aphasics, but that both groups have difficulty with semantic

\(^{18}\) This theory has also been characterized as Broca’s aphasics having an abnormally high *threshold* for lexical activation while Wernicke’s aphasics have an abnormally low threshold (Milberg, Blumstein & Dworetzky, 1988).
matching. He went on to argue that semantic matching requires “the integration of accessed lexical information into a higher order semantic representation” (Hagoort, 1993, p.222), and that, consequently, the source of the semantic matching problem is a deficit in lexical-semantic integration.

Since making explicit semantic judgments requires consciously detecting the relationship between the prime and target, Hagoort’s proposal seems incompatible with Broca’s aphasics’ good performance at making explicit semantic judgments. Hagoort (1997) claimed, however, that when making explicit semantic judgments, Broca’s aphasics are able to dedicate additional, general processing resources that are not usually tapped for making lexical decisions.

**Delayed lexical activation/deactivation?**

Like Blumstein et al.’s (1982) original hypothesis, this second theory highlights deficits in automatic processing. The part of the theory that pertains to Broca’s aphasia suggests that automatic access is delayed, but that eventually Broca’s aphasics should “show a rise-and-fall time curve similar to the elderly [control] subjects” (Prather et al., 1992, p. 339). The first suggestion that Broca’s aphasics may be delayed in activating lexical information came from a study by Swinney et al. (1989). When presented with ambiguous words in sentence contexts, Broca’s aphasics displayed semantic priming only for the dominant meaning of the ambiguous words, regardless of which meaning the sentence context biased. However, since Broca’s aphasics were able to successfully paraphrase sentences that used the ambiguous word’s subordinate meaning, the authors concluded that they must have accessed the appropriate meaning of the ambiguous word at some point after the ISI used to test for priming.

Further evidence that Broca’s aphasics may have delayed lexical activation comes from two studies that investigated auditory semantic priming using a list priming paradigm (Prather, Zurif, Stern & Rosen, 1992; Prather et al., 1997). In this paradigm, the prime and target are not paired but instead are presented in a list context for a lexical decision on each item. It has been argued that this format reduces the likelihood that processes other than automatic lexical activation (e.g., semantic matching) will contribute to semantic priming (Prather & Swinney, 1988; McNamara & Altarriba, 1988). The two studies showed that when tested at ISIs that ranged from 300-1800
ms, normals exhibited semantic priming only at a 500 ms ISI. The single Broca’s aphasic who was tested, on the other hand, only displayed semantic priming at 1500 ms\(^9\).

A Wernicke’s aphasic for whom semantic priming lasted 600 ms longer than it did for normals (appearing at ISIs ranging from 300-1100 ms, instead of only at an ISI of 500 ms) led Prather et al. (1997) to hypothesize that Wernicke’s aphasics may be delayed at deactivating lexical information. Prather et al. (1997) pointed out that delayed deactivation could be due to problems with mechanisms involved in inhibition. Furthermore, because comprehending language may require the ability to “focus in” on precise meanings by inhibiting the activation of weakly related representations in the lexical-semantic network, inhibition deficits could help explain the comprehension deficits of Wernicke’s aphasics. An earlier study by Prather et al. (1994) also produced evidence consistent with the hypothesis that Wernicke’s aphasics have delayed deactivation. In this study, Broca’s and Wernicke’s aphasics were presented with ambiguous words in sentence contexts that biased the dominant meaning of the ambiguous word (e.g., “I deposited the check in the bank yesterday.”). The task was to make a lexical decision on a visually displayed probe word related to the subordinate meaning of the ambiguous word (e.g., river). This probe word was presented 1500 ms after the offset of the ambiguous word, at a point when normals no longer exhibit facilitation for the unbiased (in this case subordinate) meaning of the probe (Swinney et al., 1989). Wernicke’s, but not Broca’s aphasics, exhibited semantic priming for the probe word. Since normals no longer have access to the unbiased meaning of an ambiguous word at 1500 ms, Prather et al. (1994) interpreted the data from the Wernicke’s aphasics as reflecting delayed deactivation of the incongruous meaning of the ambiguous word.

**Reduced/increased activation?**

The third hypothesis proposes that Broca’s aphasics have reduced lexical activation, and that Wernicke’s aphasics have increased lexical activation. It was inspired by the general finding that semantic priming in Broca’s aphasics is more “fragile” than it is in normals (Milberg & Blumstein, 1981; Milberg et al., 1987; Milberg et al., 1988; Utman et al., 2001) and that semantic priming in Wernicke’s aphasics emerges in more circumstances than it does in normals (Milberg et al., 1988). Reduced activation could result in Broca’s aphasics requiring a better than normal match between the acoustic input and a stored lexical representation in order to activate it, while increased activation could lead to Wernicke’s aphasics activating a lexical

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\(^9\)Although the finding of semantic priming only at 500 ms for normals appears to conflict with Hagoort’s (1993) demonstration of semantic priming in normals at ISIs up to 1250 ms, and also with numerous other studies that have reported auditory semantic priming in normals at other ISIs (e.g., Blumstein & Milberg, 1982; Milberg et al., 1988; Ostrin & Tyler, 1993), the majority of these studies used paired prime and target presentation, rather than the list priming paradigm. Prather would therefore probably argue that the results of these studies were contaminated by controlled processing.
representation even when the match between it and the acoustic input is less precise than is normally required.

A number of studies have provided evidence suggesting that Broca’s aphasics may have reduced activation (e.g., Milberg & Blumstein, 1981), but only a few have also suggested that Wernicke’s aphasics have increased activation. In a study that provided evidence for both, both normals and Wernicke’s aphasics responded faster to target words related to lexically ambiguous prime words, regardless of whether the meaning related to the target was concordant with the context (e.g., normals and Wernicke’s aphasics exhibited priming for money, regardless of whether the ‘monetary institution’ meaning of the word bank had previously been made salient by presenting the prime word coin, or whether the ‘sloped earth’ meaning of the word bank had previously been made salient by presenting the prime word river [Milberg et al., 1987]). Broca’s aphasics, in contrast, showed no priming in either context

Furthermore, Wernicke’s aphasics exhibited equal priming regardless of whether the target was related to the discordant or the concordant meaning of the prime. For example, they exhibited equal priming for coin-bank-money and river-bank-money), while normals appeared to exhibit less priming when the target was related to the discordant meaning of the prime word. However, the difference between the amounts of priming that normals displayed for targets related to concordant versus discordant meanings of the ambiguous word was not statistically significant.

Another study providing evidence that both Broca’s and Wernicke’s aphasics have abnormal levels of lexical activation showed that compared to normals, semantic priming in Broca’s aphasics is less robust to changes in the phonetic features of a prime word’s initial phoneme (Milberg et al., 1988). In contrast, compared to normals, semantic priming in Wernicke’s aphasics appears to be more robust to such changes. Specifically, for normals, a one phonetic feature change in a prime's initial phoneme reduced, but did not eliminate priming, (e.g., for normals, gat primed dog less than cat primed dog), but when more than one feature was changed priming was eliminated (e.g., wat did not prime dog). Unlike normals, Broca’s aphasics showed no priming at all when the prime’s initial phoneme was changed (e.g., cat primed dog, but neither gat, nor wat primed dog). Wernicke’s aphasics, on the other hand, showed the same, significant amount of priming regardless of whether the prime was changed by one or multiple features (e.g., cat, gat, and wat all primed dog). The use of modified primes may make this

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20 This study differed in a number of ways from the Swinney et al. (1989) study found that Broca’s aphasics did exhibit semantic priming for the dominant meaning of ambiguous words when presented in context. Importantly, the Milberg et al., 1987 study did not control for meaning dominance. Other factors that differed were the context in which the stimuli were presented (triplet vs. sentence), the modality of the target (auditory vs. visual), and/or the ISI between the prime and the target (0 ms vs. 500 ms). Any of these factors may account for the difference between the results of the two studies.
approach acutely sensitive to lexical activation abnormalities, for an unmodified prime may activate its lexical representation strongly enough to prime related words even if baseline levels of lexical activation are low. A slightly modified prime (e.g., one feature changed), in contrast, may not be able activate its lexical representation strongly enough to prime related words if baseline levels of activation are low. A more dramatically modified prime (e.g., two or more features changed) might only activate its lexical representation strongly enough to prime related words if baseline levels of lexical activation are abnormally high.

Although the two studies described above constitute the primary evidence that Wernicke’s aphasics have increased lexical activation, there exists additional evidence that Broca’s aphasics have reduced lexical activation. For example, Utman et al. (2001) found that like normals, who were tested in a separate study by Andruski, Blumstein and Burton (1994), Broca’s aphasics showed a reduced priming effect when presented with a prime that had had the voice onset time (VOT) of its initial consonant shortened by 2/3. However, for Broca’s aphasics, the reduction in priming appeared both at a 50 ms ISI and at a 250 ms ISI (for normals, there was no reduction in priming at the 250 ms ISI\(^{21}\)).

Like normals in Andruski et al. (1994), the reaction times of Broca’s aphasics were slower overall when the prime had a lexical counterpart that differed only in voicing, implying that competition from the lexical competitor delayed recognition of the prime. When the prime was altered, however, the existence of lexical competitors appeared to have more of an effect on Broca’s aphasics than normals; for Broca’s aphasics, semantic priming was reduced but not absent for altered primes with no voiced lexical competitors, while no semantic priming emerged for those with competitors (in contrast, for normals, the existence of a voiced lexical competitor reduced, but did not eliminate priming). For example, when \(p^{2/3}eace\) (whose competitor \(beace\) is not a real word) was presented, Broca’s aphasics showed semantic priming at both the 50 ms ISI and the 250 ms ISI. But, when \(p^{2/3}ear\) (which has the lexical competitor \(bear\)) was presented, unlike normals, Broca’s aphasics did not show semantic priming at either ISI.

Utman et al. (2001) accounted for the failure of Broca’s aphasics to show semantic priming by hypothesizing that altering the VOT of a prime with a lexical competitor has two consequences. First, because the match between the acoustic input and the stored representation is poor, the prime becomes only weakly activated. Second, the altered prime’s increased similarity to its lexical competitor causes that lexical competitor to become active. Because the prime is only weakly active, it will be unable to inhibit its competitor, and as a result it will be

\(^{21}\) Since both Utman et al. (2001) and Andruski et al. (1994) used paired prime-target presentation, their results are not inconsistent with Prather et al.’s (1992 & 1997) findings that in the list priming paradigm, normals did not show priming at a 300 ms ISI.
more difficult for the lexical processing system to clearly establish which lexical candidate is most compatible with the input. This lack of stability can further reduce the prime’s activation and consequently the activation of semantically related words. Thus, VOT-altered primes with lexical competitors do not prime semantically related words.

Utman et al.’s (2001) explanation for the difference between the pattern of results they obtained for Broca’s aphasics and normals hinges on the prime’s activation being reduced for Broca’s aphasics. Since the prime is weakly active it has difficulty inhibiting its lexical competitor. This suggests that the lexical competitor should be unusually active for Broca’s aphasics (either remaining active for longer than normal, or becoming more highly active than normal). The activation of the lexical competitor was not directly tested in the Utman et al. study, however. Thus, it was the contrast between the absence of semantic priming for words with lexical competitors, and the presence of semantic priming for words without lexical competitors, that let Utman et al. to infer that the prime’s lexical competitor became unusually active.

It might seem difficult to reconcile Milberg et al.’s, (1988) finding that Broca’s aphasics showed no priming at all when the prime’s initial phoneme was changed (e.g., cat primed dog, but neither gat, nor wat primed dog), with Utman et al.’s (2001) finding that for Broca’s aphasics reaction times are slower when a prime has a potential lexical competitor; for Milberg et al.’s finding implies that Broca’s aphasics do not activate rhyming words (e.g., gat does not activate cat), while Utman et al.’s finding suggests that Broca’s aphasics do activate rhyming words (e.g., pear does activate bear). If it is assumed that lexical activation is graded, however, instead of all-or-none (all current models of spoken word recognition make this assumption), the results of these two studies are compatible. For it is possible that in the Milberg et al. study Broca’s aphasics did partially activate real words that rhymed with the prime, but these real words did not become active enough to prime semantically related words (e.g., it is possible that gat did partially activate cat, but that cat did become active enough to prime dog). Likewise, it is possible that in the Utman et al. study, while the prime’s lexical competitor appeared to become active enough to interfere with recognition of the acoustically modified prime (in that no semantic priming was obtained when lexical competitors existed), it was not active enough to prime semantically related words (e.g., it is possible that while p*ear did partially activate bear, bear would not have been active enough to prime tiger). Only one of these scenarios would have to be true to accommodate the findings of the two studies.

A recent study by Misiurski et al. (submitted) directly tested whether for Broca’s aphasics, the uttered word’s lexical competitor becomes active enough to prime semantically related words (e.g., whether when presented with t^{33}ime, Broca’s aphasics activate dime enough to speed
lexical decisions on *penny*). They found that Broca’s aphasics did not exhibit semantic priming for lexical competitors of acoustically modified primes. Thus it appears that if, as Utman et al. (2001) suggest, the prime’s lexical competitor does become unusually active for Broca’s aphasics, it does not become active enough to prime semantically related words. (It is worth noting that in light of the fact that in the Utman et al. study Broca’s aphasics did not show priming for words related to the acoustically modified prime itself, it would be somewhat surprising if words related to the acoustically modified prime’s lexical competitor were primed.)

One finding obtained by Misiurksi et al., however, does not fit neatly into this account: Normal participants *did* exhibit semantic priming for lexical competitors of acoustically modified primes. If lexical competitors are unusually active for Broca’s aphasics but not for normals, why do normals, but not Broca’s aphasics exhibit semantic priming for these competitors? One possibility is that for Broca’s aphasics the lexical competitor is unusually active relative to the uttered word, but not necessarily active enough to cause detectable semantic priming. A second possibility is that rhyming words do become unusually active for Broca’s aphasics but that because only discrete time points were probed, the semantic priming task failed to detect this activation.

**Comparing the theories**

It is difficult to reconcile the claim that both Broca’s and Wernicke’s aphasics have normal activation (Hagoort, 1993) with the results of the Milberg et al. (1988) study. In the Milberg et al. study, Broca’s and Wernicke’s aphasics both displayed abnormal semantic priming, but in different ways. Thus, even though it could be argued that the ISI used in Milberg et al. was long enough (500 ms) for controlled processing to be a concern, because the two patient groups displayed *different* patterns of abnormal semantic priming, it would be difficult to attribute their deficits to the same source.

The claim that activation is normal in Broca’s aphasics is also inconsistent with the results of the Utman et al. (2001) study. In that study even at ISIs (50 and 250 ms) that have been claimed to be too short for controlled processes (such as semantic matching) to come into play (Neely, 1977), Broca’s aphasics did not exhibit normal semantic priming. Nevertheless, in the majority of studies that have been taken as evidence that activation is abnormal in Broca’s aphasia, ISIs were longer than 250 ms, so it is possible that any lack of priming could have been due to problems with semantic matching rather than problems with automatic activation. Furthermore, Prather et al. (1997) have argued that even ISIs less than 300 ms may not be sufficient to restrict priming to automatic effects if the prime and target are paired. Thus it
would be constructive to obtain a measure of automatic lexical activation in these patients using a task that is not susceptible to controlled processes such as semantic matching.

It is worth noting that it would certainly be possible for Broca’s and/or Wernicke’s aphasics to have both abnormal activation and a deficit in lexical-semantic integration. However, Hagoort and colleagues explicitly hypothesized that Broca’s and Wernicke’s aphasics have a deficit in lexical-semantic integration only, and that any appearance of a lexical activation deficit is due to problems with lexical-semantic integration. Therefore, evidence that Broca’s and Wernicke’s aphasics do have a problem with lexical activation will be taken as evidence against the instantiation of the lexical-semantic integration deficit hypothesis put forth by Hagoort and colleagues.

A second reason to use a task that is not influenced by controlled processing to investigate automatic activation in Broca’s aphasics is to evaluate the claim that Broca’s aphasics have delayed activation. Although this claim seems to be inconsistent with semantic priming effects at short ISIs (Hagoort, 1993; Utman et al., 2001), as noted above, Prather et al. (1997) have argued that even at short ISIs priming effects may be contaminated by controlled processing. Prather et al. go on to argue that when, by using the list priming paradigm, “strategy driven effects are minimized to provide the clearest assessment of automatic lexical activation, Broca’s patients show abnormal – and more specifically, abnormally slow – priming” (p. 393). Thus, to test the claim that Broca’s aphasics have delayed activation, the time course of lexical activation should be examined using a paradigm that is unlikely to be contaminated by strategy driven effects.

Because both the delayed and the reduced activation hypotheses predict that semantic priming will be delayed in Broca’s aphasics, it is difficult to obtain data in support of one but not the other. For example, the absence of observable lexical activation at a particular ISI could be interpreted as evidence that lexical activation was too low to be measured because of either delayed or reduced activation. Similarly, if Broca’s aphasics display a smaller priming effect than normals at a particular ISI, this could be because lexical activation was still increasing at that point, or it could be due to reduced activation overall. Thus, to help distinguish between delayed and reduced activation, i.e., between whether a priming effect would have emerged later or not at all, it is necessary to continuously observe a lexical item’s activation over time.

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22 It should be noted that the majority of studies that have been interpreted as supporting reduced activation in Broca’s aphasics used paired primes and targets. For this reason proponents of the delayed activation hypothesis would have to regard most of the priming obtained as strategic rather than automatic, and consequently irrelevant to delayed (automatic) activation. Nevertheless, most of the results that have been interpreted as support for Broca’s aphasics having reduced activation could also be interpreted as evidence that they have delayed activation.
As described above, the only direct evidence that Wernicke’s aphasics have delayed deactivation comes from two studies by Prather et al. (1994 and 1997). The only two other studies to probe semantic priming in Wernicke’s aphasics over a range of ISIs provided no evidence that they have delayed deactivation. In the first study (Milberg et al., 1995), it was not possible to directly compare the size of the semantic priming effect for Wernicke’s aphasics and normals\(^{23}\) to determine whether Wernicke’s aphasics exhibited a larger semantic priming effect at the later ISIs. In the second study (Milberg et al., 2003), Wernicke’s aphasics showed semantic priming in fewer conditions than normals. However, this study was unusual in that two primes were used to prime the target, and although there was a strong association between the two primes together and the target (e.g., meal-morning-breakfast), the relationship between each of the primes and the target (e.g., meal-breakfast and morning-breakfast) was quite weak. Priming in these circumstances may require the ability to selectively activate the semantic fields where the representations of the two prime words overlap – potentially a more complex process than the automatic activation of a lexical item. Since there exists so little evidence regarding time course of lexical activation in Wernicke’s aphasia, more information is necessary to evaluate the hypothesis that Wernicke’s aphasics have slowed deactivation.

Three studies have reported that Wernicke’s aphasics exhibited priming in circumstances in which normals did not (Milberg et al., 1988; Prather et al., 1994; Prather et al., 1997). Because increased activation would delay the point at which activation returns to baseline, the results of all three of these studies are equally compatible with delayed deactivation and increased activation. However, in other studies, either the Wernicke’s aphasics did not exhibit larger priming effects than the normals or the priming effects exhibited by the two populations were not directly compared (Blumstein et al., 1982; Swinney et al., 1989; Hagoort, 1993; Tyler et al., 1995; Baum, 1997; Milberg et al., 2003). Therefore, it is far from uncontroversial how, and even if, automatic lexical activation is affected in Wernicke’s aphasia. Additional data, preferably measuring lexical activation continuously over time, is needed to distinguish between the hypotheses that Wernicke’s aphasics have normal activation, delayed deactivation, or increased activation.

The goal of the four experiments presented in this section is to explore the time course of lexical activation in Broca’s and Wernicke’s aphasics via the eye movement paradigm used in Experiments 1-3. Since the eye movement paradigm allows lexical activation to be monitored continuously over time, these studies will provide a significant amount of information about lexical activation in Broca’s and Wernicke’s aphasia, and thus should help to discriminate between the three theories described above. Experiments 4 and 5 investigate the extent to which

\(^{23}\) Due to lack of homogeneity of variance.
Broca’s and Wernicke’s aphasics experience competition from words that share their onsets (Experiment 4) or that rhyme (Experiment 5) with the uttered word. Experiment 6 investigates whether items semantically related to the uttered word elicit preferential eye movements from Broca’s and Wernicke’s aphasics, as they did for normals in Experiment 1. Experiment 7 explores the extent to which Broca’s and Wernicke’s aphasic experience competition from words semantically related to an onset competitor of the uttered word. In each experiment, unimpaired, college-aged controls are tested to establish baseline effects, and unimpaired age-matched controls are tested to determine whether normal aging influences competitor effects.
Methods: Experiments 4-7

This section describes methods common to Experiments 4-7. Methods specific to each experiment will be described in a separate section for each experiment.

Subjects

Twelve young control subjects were recruited from the Brown University community. All were over 18. They were paid $7 for participating. Twelve older control subjects were recruited from the Brown University community and the surrounding area via word of mouth and the elderly control subject database of psychology professor W. Heindel. The older control subjects were matched in age to the aphasic subjects (average age 67). They were paid $15 for participating.

Six subjects with Broca’s aphasia and five subjects with Wernicke’s aphasia were recruited from the current patient database of S. E. Blumstein under the auspices of her research program in speech and language processing deficits in aphasic patients at Brown University. The aphasic subjects all had unilateral lesions, and did not have an associated dementia or memory (e.g., Korsakoff) deficit. None had a significant history of other neurological or psychiatric illness or drug/alcohol abuse. All were literate in English, had English as the native language, and had normal hearing in the speech frequencies. All were several years post-stroke. With the exception of one Wernicke’s subject who had right visual field neglect (discussed in more detail below), all had normal or corrected to normal vision and no known oculomotor deficits.

Two of the aphasic patients, one Broca’s aphasic and one Wernicke’s aphasic, had a great deal of difficulty with the task. Each of these patients’ response times was more than three standard deviations longer than the mean of the rest of the patients in his group. Each also had an error rate more than two standard deviations higher than the means of the rest of the patients in his group. As a result, these two aphasic subjects were not included in the analyses. In contrast, the Wernicke’s aphasic with right visual field neglect had no difficulty with any part of the task (including the calibration which required him to fixate on a dot that appeared in each quadrant of the screen in a random sequence), and his response times were well within the normal range. To further assess whether this subject’s visual impairments affected his performance, trials in which the target appeared on the right were analyzed separately from those in which the target appeared on the left side of the screen, and the subject’s performance was then compared to that of the other three Wernicke’s aphasics. For the subject with neglect, fixations on the target peaked about 450 ms later when targets appeared on the right than on the left. For the other three Wernicke’s aphasics, fixations on the target peaked about 335 ms later.
when the targets appeared on the right than on the left. The advantage for targets on the left is probably a consequence of the fact that the vast majority of subjects start scanning the display in the upper left hand corner (scanning either in a left to right pattern as if reading, or clockwise starting in the upper left). Since the Wernicke’s aphasic with visual neglect appeared able to perform the task without difficulty despite his visual impairment, his data were included with the data from the other three Wernicke’s aphasics. However, to be conservative, each analysis was also conducted with his data excluded, and any differences that emerged are reported.

All of the subjects who were included in the analyses were able to understand the experimental task and performed significantly better than chance on 5 practice trials. The average age of the aphasic subjects was 67. Aphasic subjects were paid $20/hour for participating.

**Apparatus**

The apparatus was the same as in Experiments 1-3. One Broca’s and one Wernicke’s aphasic were tested at Brown University. The rest of the aphasic patients were tested in their homes. The young and older control subjects were tested at Brown University.

**Materials**

The testing session was kept short in order to allow testing to be completed without a break that would require removal of the eye tracker. This was accomplished by using critical trials from one experiment as “filler” trials for the other experiments. Since each critical trial served a dual purpose, the ratio of each target-competitor relationship was kept quite low (each of the four target-competitor relationships appeared in 7% of trials). This prevented normals from noticing the experimental manipulations, without requiring lengthening the experiment by including a large number of trials that would serve as fillers only.

Because of the limited number of aphasic subjects who were available to test, a completely within-subjects design was used (i.e., unlike in Experiments 1-3, there was only 1 list). For each experiment there were 12 critical trials (Appendix E; these are described in greater detail in sections specific to each experiment). As in Experiments 1-3, each critical trial display included a target picture, a competitor picture, and two pictures that were phonologically unrelated to the target and semantically unrelated to the target and its phonological competitors\(^{24}\). In all critical

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\(^{24}\) The control conditions of Experiments 1 & 2 above, and a phonological onset and rhyme competitor study not described in this work established that when they were unrelated to the target, the pictures that served as competitors in competitor trials did not draw more fixations than other unrelated pictures. Thus it was possible to further shorten the experimental session by eliminating the control condition used in earlier experiments to assess whether the competitor pictures were particularly visually attractive.
trials, object positions, including the positional relationship between the target and the competitor, were balanced so that each object type was equally likely to appear in each corner of the display. The names of the unrelated pictures in each critical trial were frequency-matched with the name of the competitor picture. Picture-name correspondence pre-testing was conducted in the same way as in Experiments 1-3.

Average looking to the two unrelated pictures served as the baseline against which to compare looks to the competitor picture; the average of the two unrelated pictures was used in an effort to reduce the additional variance expected due to the small number of aphasic patients available for testing. In the onset (4), rhyme (5), and semantic (6) experiments, 12 distractor trials were included in which two of the objects in the display were related in the same way as in the critical trials in each experiment, but in which neither related object was the target. Thus, even if any subjects noticed that some of the objects were related, they could not then predict that the target would be one of the related objects. Such distractor trials were not necessary in the semantically mediated onset competitor experiment, since this relationship is so subtle that subjects never reported noticing it25. The testing session therefore included 185 trials, 48 critical trials (12 for each of the four experiments), 36 distractor trials, 96 (pure) filler trials, and 5 practice trials. Unimpaired subjects completed the testing in approximately 30 minutes and aphasics patients completed the session in approximately 45 minutes. Calibrating the eyetracker required an additional 15 minutes. Trial order was randomized anew for each subject.

**Procedure**

The procedure was identical to that used in Experiments 1-3 with the following exceptions. There were 5 practice trials, during and/or after which the instructions were repeated as necessary. Prior to any critical trials there were also 8 “warm-up” (filler) trials to accustom subjects to the task. After each quarter (45) of the trials, a message appeared on the screen indicating how many trials had been completed and prompting subjects to take a short break. After the half-way point, there were 4 more warm-up trials to allow subjects who had chosen to take a longer break to re-adjust to the task.

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25 Normal subjects filled out a post-test questionnaire that (in addition to asking whether they had attempted to label the images during the preview period) explicitly asked whether they “had any guesses as to what the experiment was about”.
EXPERIMENT 4: ONSET COMPETITION IN APHASIA

In the first study to use eye movements to explore spoken word recognition, Allopenna et al. (1998) showed that normal subjects were temporarily more likely to fixate on an onset competitor of an uttered word than on unrelated objects. This finding indicates that onset competitors temporarily became partially active. According to the normal activation hypothesis, (Hagoort et al., 1996), both Broca’s and Wernicke’s aphasics should show onset competitor effects similar to those of normals. The delayed activation/deactivation hypothesis (Swinney et al., 1989; Prather et al., 1992; Prather, 1997), predicts that for Broca’s aphasics, when an onset competitor effect does emerge, its size should be normal. For Wernicke’s aphasics, on the other hand, slowed deactivation should make the onset competitor remain active for longer than normal resulting in an abnormally large competitor effect. The reduced/increased activation hypothesis (Milberg et al., 1987) predicts that Broca’s aphasics will show an abnormally small onset competitor effect. This is because starting out with reduced activation means that for Broca’s aphasics, onset competitors will not become as active as they will for normals. In contrast, starting out with increased activation means that for Wernicke’s aphasics onset competitors will become more active than they will for normals, resulting in a larger competitor effect.

Methods

Materials

Twelve two-syllable pictureable nouns served as target words. For each of these target words, there existed a pictureable noun that was a phonological onset competitor (e.g., hammer-hammock). All of these onset competitors overlapped with the target by either their entire first syllable (10 of 12 items) or the onset and vowel of the first syllable (2 of 12 items). Average target duration was 527 ms. The competitor picture will be referred to as the onset competitor.

Results

Figures 13-16 plot the mean proportion of trials over time that contained a fixation to the target, to the onset competitor, and to the average of the two unrelated pictures (from target onset to 2500 ms after onset) in onset competitor trials for each of the four subject groups (young controls, age-matched controls, Broca’s aphasics and Wernicke’s aphasics, respectively). The results from each subject group will be discussed separately below. For the purpose of analyzing the data, a “trial” was defined as starting 200 ms after the onset of the target and ending at the
point at which the probability of fixating on the target dropped 50% from its peak (for the subject or item being analyzed). The difference between the competitor and the average of the two unrelated pictures at each 32 ms time bin of the trial was computed, and the differences obtained in each bin were summed. T-tests were conducted on the resulting scores to detect whether a competitor effect emerged. To obtain information about the time course of any competitor effects that emerged, the trial was divided into 100-ms windows, starting at 200 ms after target onset, and ending at the average trial end time for the subject group being analyzed. The difference between the target and competitor in each 100-ms time window was computed and t-tests were conducted on each window.

Young Controls:

Figure 13 plots the mean proportion of trials over time that contained a fixation to the target, to the onset competitor, and to the average of the two unrelated pictures (from target onset to 2500 ms after onset) in onset competitor trials for the young controls. The average trial end time for the young controls occurred in the 1000-1100 ms window. One trial (.7% of the 144 total trials for young normals) was excluded because the onset competitor was selected instead of the target (*pillow*->*pillar*). Seven trials (4.9%) did not provide any data because there were no eye movements after the onset of the target word (most of these were trials in which the subject was already fixating on the picture of the target at the onset of the target word).

Summing the difference between fixations on the competitor and the average of fixations on two unrelated pictures across the entire trial (hence the competitor effect) shows that fixations on the onset competitor’s picture were significantly more than the average of the fixations on the two unrelated pictures, $t_s(11)=2.8, p<.01$ by subjects, and $t_z(11)=3.3, p<.01$ by items. The time course analysis for the young controls showed that there was a significant difference between the competitor and the unrelated stimuli in the three windows from 200-500 ms after target onset at the $p<.05$ level for both subjects and items.

Age-matched controls

Figure 14 plots the data from the age-matched controls in onset competitor trials. The average trial end time for the age-matched controls occurred in the 1200-1300 ms window. One trial (.7% of the 144 total trials for age-matched controls) was excluded because the onset competitor was selected instead of the target (one instance of *basket*->*bathtub*). Eight trials (5.6%) did not provide any data because there were no eye movements after the onset of the target word.
Figure 13.
Experiment 4. Fixations on onset competitors in 12 young controls: Proportion of fixations over time on the target, the onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 14.
Experiment 4. Fixations on onset competitors in 12 older controls: Proportion of fixations over time on the target, the onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
The competitor effect shows that fixations on the onset competitor’s picture were significantly more than fixations on the two unrelated pictures, \( t_1(11)=2.8, p<.01 \) by subjects, and \( t_2(11)=2.5, p=.01 \) by items. The time course analysis for the age-matched controls showed a significant competitor effect in the three windows from 300-600 ms after target onset (\( p<.05 \) by subjects and items).

**Broca’s aphasics**

**Figure 15** plots the data from the Broca’s aphasics in onset competitor trials. The average trial end time for the Broca’s aphasics occurred in the 1500-1600 ms window. One of the 60 trials (1.7% of the 60 total trials for Broca’s aphasics) was excluded because the onset competitor was selected instead of the target (*penny*->*pencil*). Four trials (6.7%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that although fixations on the onset competitor’s picture were greater than fixations on the two unrelated pictures, this difference was not statistically significant either by subjects \( t_1(4)=.5, p=.31 \) or by items \( t_2(11)=1.1, p=.15 \). However, since a short-lived onset competitor effect appeared to emerge early in the trial, a time-course analysis for the Broca’s aphasics was conducted to gauge whether this apparent effect was statistically reliable. None of the windows showed a significant difference at the .05 level, but the difference approached significance in the 400-500 ms window (\( p=.05 \) by subjects and \( p=.06 \) by items).

**Wernicke’s aphasics**

**Figure 16** plots the data from the Wernicke’s aphasics in onset competitor trials. Average trial end time for the Wernicke’s aphasics occurred in the 2000-2100 ms window. In all trials, the correct picture was selected. Four trials (8.3% of the 48 total trials for the Wernicke’s aphasics) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that fixations on the onset competitor’s picture were significantly greater than the average of fixations on the two unrelated pictures, \( t_1(3)=2.8, p=.03 \) by subjects, and \( t_2(11)=2.0, p=.03 \) by items. The time course analysis for the Wernicke’s aphasics showed that in the five windows from 900-1400 ms after target onset, the difference between the competitor and the unrelated stimuli was either significant at the \( p<.05 \) level, or approached significance (\( .05<p<.15 \)) by both subjects and items.

The pattern remained the same when the subject with neglect was removed from the analysis, but the onset competitor effect appeared to emerge about 300 ms earlier (**Figure 17**). The difference between the competitor and the average of the two unrelated pictures across the
Figure 15.

Experiment 4. Fixations on onset competitors in 5 Broca’s aphasics: Proportion of fixations over time on the target, the onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 16.
Experiment 4. Fixations on onset competitors in 4 Wernicke’s aphasics: Proportion of fixations over time on the target, the onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 17.
Experiment 4. Fixations on onset competitors in the 3 Wernicke’s aphasics without hemifield neglect: Proportion of fixations over time on the target, the onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
entire trial remained significant by subjects, $t_1(2)=4.7$, $p=.02$, and by items $t_2(11)=2.2$, $p=.03$. In the time course analysis, the five windows from 600-1100 showed a difference between the competitor and the unrelated stimuli. This difference was either significant at the $p<.05$ level, or approached significance ($0.05<p<0.12$) by both subjects and items.

**Comparison of groups:**

The competitor effects from each of the four groups (the sum of the differences between the competitor and the average of the two unrelated pictures) were submitted to a 1-way ANOVA. The overall $F$ was not statistically significant by subjects $F(32)=2.1$, $p=.12$ or by items $F(47)=1.3$, $p=.29$. Planned paired comparisons of the aphasic groups with each other and the age-matched controls showed that the competitor effect was larger for the Wernicke’s aphasics than for the Broca’s aphasics ($p=.03$ by subjects and $p=.08$ by items). The Wernicke’s aphasics’ competitor effect was also larger than that of the age-matched controls ($p=.04$ by subjects and $p=.14$ by items). No other differences were found.

When the ANOVA was repeated without the Wernicke’s aphasic with neglect, the result was significant by subjects $F_1(31)=3.6$, $p=.03$. An ANOVA was not appropriate by items due to lack of homogeneity of variance between groups. Planned paired comparisons of the aphasic groups with each other and the age-matched controls showed that by subjects, the competitor effect was larger for the Wernicke’s aphasics than for the Broca’s aphasics ($p<.01$) and the age-matched controls ($p<.01$). Since traditional statistical comparisons by items were not appropriate due to the lack of homogeneity of variance, a test that does not assume homogeneity of variance, the permutation test (Good, 1994), was used to conduct the planned comparisons. The results showed that by items the Wernicke’s aphasics’ competitor effect was marginally significantly larger than that of the Broca’s aphasics ($p=.05$) and the age-matched controls ($p=.06$). No other differences were found.

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26 Note that it is possible for homogeneity of variance to be violated when the data are grouped by item even if it is not violated when the data are grouped by subject. One scenario in which this might happen is if the number of subjects differs across groups. In a group with fewer subjects, few observations go into each item, resulting in higher variance across items for that group.

27 In a permutation test, (also called a randomization test or a shuffle test) the difference between the means of two groups is calculated. Then the scores from the two groups are mixed together and randomly assigned to two new groups, each of which is the same size as one of the original groups. Then the difference between the means of these two new groups is calculated and this mean difference is stored. The previous two steps are repeated several thousand times, creating a distribution of mean difference scores. The original mean difference score can then be compared to this distribution, providing a measure of how often a difference score as extreme as the true difference would be obtained if all the scores came from the same group.

28 When permutation tests were conducted by subjects, the results were almost identical to that of the paired comparisons, with the Wernicke’s aphasics’ competitor effect being larger than that of the Broca’s aphasics at ($p=.05$), and larger than that of both the age-matched controls and the young controls at ($p=.01$). The results of the permutation tests continued to parallel the results of the traditional statistics in each experiment.
Discussion of Experiment 4

The results from Experiment 4 showed that like young controls, older controls and Wernicke’s aphasics fixate significantly more on pictures of objects that share their onsets with the uttered word than on unrelated objects. The onset competitor effect for the young and older controls appeared similar to each other and also similar to the results obtained for onset competitors in Allopenna et al. (1998). Although the Broca’s aphasics showed the same pattern of results (and their onset competitor effect was not statistically different from that of the controls), their onset competitor effect was not statistically significant. Importantly, the onset competitor effect in the Wernicke’s aphasics was significantly larger than the effect in the age-matched controls and the Broca’s aphasics.

These data do not establish whether the larger competitor effect exhibited by the Wernicke’s aphasics is due to a more active onset competitor (because of either delayed deactivation or abnormally high levels of activation) or whether it is due to generally slower eye movements in the context of linguistic input (since slower processing could prolong an onset competitor effect of normal size). However, although both accounts are consistent with longer duration fixations on the onset competitor, the general slowing account would be more difficult to reconcile with a larger number of saccades to the onset competitor. In an effort to distinguish between general slowing and a more active competitor, the number of saccades the Wernicke’s aphasics made to the onset competitor was compared with the number of saccades made by each of the other groups. While none of the comparisons were statistically significant (.17 < p < .21), the Wernicke’s aphasics did launch more saccades to the onset competitor (relative to the unrelated stimuli) than any of the other groups. Because the Wernicke’s aphasics also spend longer fixating on the onset competitor than do the other groups, it is likely that the onset competitor is unusually active in this population.

Although the Broca’s aphasics’ onset competitor effect was not statistically significant, a visual comparison of the competitor effects for older controls and Broca’s aphasics (Figures 14 and 15) suggests that the Broca’s aphasics’ competitor effect is similar in size to that of the age-matched controls. This apparent similarity raises the question of whether the smaller number of Broca’s aphasics tested may account for the difference between the non-significant result obtained for the Broca’s aphasics and the significant result obtained for the controls. As an informal measure of how likely it would be for an onset competitor effect of the size obtained for the 5 Broca’s aphasics to be obtained from a group of 5 of our control subjects, Monte-Carlo sampling was used to compute the average onset competitor effect (i.e., the sum of the difference between the competitor and the unrelated stimuli) for 10,000 samples of 5 randomly selected subjects from among the 12 age-matched control subjects. In 86% of these 10,000 randomly
selected control groups, the mean competitor effect was larger than it was for the Broca’s aphasics\textsuperscript{29}. While not definitive, this result suggests that the onset competitor effect observed in the Broca’s aphasics is abnormally small.

It is significant that the Broca’s and the Wernicke’s aphasics displayed different patterns of results. While the heightened onset competitor effect that appeared for the Wernicke’s aphasics could be explained by general slowing, no increased onset competitor effect appeared for the Broca’s aphasics, who also responded more slowly than the normal subjects. Similarly, although the diminished onset competitor effect that appeared for the Broca’s aphasics could be due to low power, the Wernicke’s aphasics group, which was even smaller, nonetheless showed an increased competitor effect.

The pattern of results obtained for Broca’s aphasics in this experiment, i.e., what appears to be an abnormally small onset competitor effect, cannot be explained by normal activation or by delayed activation. Instead, it is consistent with reduced activation, since starting out with reduced activation would mean that in order for a representation to become detectably active, more input that matches that representation would be required. Likewise, the abnormally large onset competitor effect obtained for Wernicke’s aphasics in this experiment is not consistent with Wernicke’s aphasics having normal activation. However, it is consistent with both the hypothesis that Wernicke’s aphasics have delayed deactivation, and with the hypothesis that they have abnormally high levels of lexical activation. Delayed deactivation could result in a large number of fixations on the onset competitor because it would cause abnormally long-lasting competition. High activation would also produce a large number of fixations on the onset competitor, which would be partially activated even when the match between the acoustic input and stored lexical representations is less precise than it needs to be for controls. Although for Wernicke’s aphasics’ the competitor effect is reliable in more time bins (the five bins from 900-1400 ms) than for age-matched controls (the three bins 300-600 ms) and Broca’s aphasics (the single bin from 400-500 ms), both delayed deactivation (for obvious reasons) and increased activation (due to a more highly active competitor taking longer to return to baseline) could have produced this longer-lasting onset competitor effect.

\textsuperscript{29} When the same simulation was done using each group’s effect size (t-statistic), rather than mean competitor effect, the results were even stronger, with the effect size for the Broca’s aphasics being smaller than 96% of the randomly selected groups.
Thus, while the absence of a significant onset competitor effect for Broca’s aphasics in Experiment 4 is consistent with reduced activation only, the heightened onset competitor effect for Wernicke’s aphasics is compatible both with delayed deactivation and with increased activation.
EXPERIMENT 5: RHYME COMPETITION IN APHASIA

In Experiment 4, the predictions of the reduced/increased activation hypothesis for Broca’s aphasics appeared to be borne out with respect to onset competitors. That is, Broca’s aphasics appeared to show a smaller than normal onset competitor effect. Wernicke’s aphasics, in contrast, showed a larger than normal onset competitor effect, a result that was equally compatible with the hypothesis that they have delayed deactivation and the hypothesis that they have increased activation. In addition to showing the time course of onset competitors’ activation during spoken word recognition, in their 1998 study Allopenna et al. also showed that normal subjects temporarily prefer to fixate on rhyme competitors of the uttered word than on unrelated objects. Exploring rhyme competition in Broca’s and Wernicke’s aphasics will provide a further test of the reduced activation hypothesis for Broca’s aphasics and may also make it possible to distinguish between the two hypotheses that are compatible with the Wernicke’s aphasics’ performance thus far.

As described in the introduction to Part 2, the results of a semantic priming study by Utman et al. (2001) were interpreted as support for the hypothesis that Broca’s aphasics have reduced activation. To review, Utman et al. found that for prime words with voiced rhyming lexical competitors (e.g., ‘pear’ has a voiced lexical competitor ‘bear’), Broca’s aphasics showed reduced (for unaltered primes) or absent (for altered primes) semantic priming. The authors explained this result by theorizing that because of reduced activation, the prime does not become active enough to inhibit the lexical competitor. As a result, the lexical competitor (e.g., bear) competes with the prime (e.g., pear), limiting the prime’s activation and therefore reducing the semantic activation of words related to the prime (e.g., the target fruit). In this study, however, the competitor’s activation was not directly measured; it was inferred from the fact that the prime either failed to activate the target or activated it less than did primes without lexical competitors. A later study (Misiurski et al., submitted) directly tested whether for Broca’s aphasics an altered prime activates its lexical competitor enough to speed responses to semantically related targets (e.g., they tested whether when presented with t ime, Broca’s aphasics activate dime enough to speed lexical decisions on penny). Although this study did not find evidence of priming, it is possible that rhyming words do become unusually active for Broca’s aphasics but that the semantic priming paradigm did not detect this activation because it probes only at discrete time points.

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30 Wernicke’s aphasics were not tested in this study.
Experiment 5 explored whether the eye tracking paradigm would provide evidence that for Broca’s aphasics, rhyming lexical competitors do indeed become abnormally active. This was accomplished by including in the display a picture of an object that rhymes with the target. Because the target and the rhyme competitor in the eye tracking paradigm correspond to the prime and its competitor (respectively) in the semantic priming paradigm, the eye tracking paradigm provides a way to directly test the hypothesized activation of the competitor. If Broca’s aphasics fixate on the rhyme competitor more than normals do, this would provide direct evidence that Broca’s aphasics have difficulty inhibiting competitors that rhyme with the uttered word. Such a finding would corroborate Utman et al.’s inference that rhyming lexical competitors become unusually active in Broca’s aphasia. Moreover, a large rhyme competitor effect would also be consistent with the hypothesis that Broca’s aphasics have reduced activation. This is because reduced activation would result in the target taking more time than usual to become active enough to successfully inhibit competitors, providing time for acoustic input that is consistent with the rhyme competitor to unfold in the absence of inhibition (thereby activating the rhyme competitor). Neither of the alternative hypotheses predicts a large rhyme competitor effect for Broca’s aphasics, for if Broca’s aphasics have normal or delayed activation, their rhyme competitor effect (once it emerges) should be of normal size.

For Wernicke’s aphasics, increased activation might be expected to lead to an unusually large rhyme competitor effect. However, if it is truly the case that the more active a word is the more easily it can inhibit its competitors, increased activation will allow Wernicke’s aphasics to successfully inhibit competitors early on. Thus, it is possible that the target will quickly become active enough to inhibit competitors – even before the unfolding acoustic input has become consistent enough with the rhyme competitor for it to become active. This would result in an unusually small rhyme competitor effect. Under the other two accounts, Wernicke’s aphasics should show a normal (normal activation account) or unusually large (delayed activation account) rhyme effect.

**Methods**

**Materials**

Twelve two-syllable pictureable nouns served as target words. For each of these target words, there existed a pictureable noun that was a rhyme competitor (e.g., carrot-parrot). All rhyme competitors shared everything but their initial consonant (11 of 12) or initial consonant cluster (1 of 12) with the target. Average target duration was 539 ms. The competitor picture will be referred to as the rhyme competitor.
Results

Figures 18-21 plot the mean proportion of trials over time that contained a fixation to the target, to the rhyme competitor, and to the average of the two unrelated pictures (from target onset to 2500 ms after onset) in rhyme competitor trials for each of the four subject groups (young controls, age-matched controls, Broca’s aphasics and Wernicke’s aphasics, respectively). The results from each subject group will be discussed separately below. For the purpose of analyzing the data, a “trial” was defined in the same way as it was in Experiment 4. The data were analyzed using the same procedures used in Experiment 4.

Young Controls:

Figure 18 plots the data from the young controls in rhyme competitor trials. The average trial end time for the young controls occurred in the 1000-1100 ms window. The correct picture was selected on all trials. Nine trials (6.3%) did not provide any data because there were no eye movements after the onset of the target word.

Summing the difference between the competitor and the average of the two unrelated pictures across the entire trial (hereafter the competitor effect) shows that the rhyme competitor was fixated on more than the average of the two unrelated pictures, but that this difference only approached statistical significance by subjects $t_1(11)=1.2, p=.12$ and by items $t_2(11)=1.4, p=.09$. Because the difference approached significance by both subjects and items, time course analyses were conducted to assess whether a small effect emerged in any part of the trial. The time course analysis for the young controls showed that while none of the windows showed a significant difference at the $p<.05$ level, the difference in the window from 400-500 ms approached significance both by subjects ($p=.08$) and by items ($p=.08$).

Age-matched controls

Figure 19 plots the data from the age-matched controls in rhyme competitor trials. The average trial end time for the age-matched controls occurred in the 1300-1400 ms window. Three trials (2.1%) were excluded because the incorrect picture was selected (each was jello--cello). In each of these trials, the rhyme competitor was selected. Nine trials (6.3%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the rhyme competitor’s picture was fixated on more than the average of the two unrelated pictures, but that the difference between the competitor and the unrelated stimuli only approached significance by subjects $t_1(11)=1.6, p=.07$, and was not significant by items $t_2(11)=.9, p=.19$. No difference emerged in any part of the trial.
Figure 18.
Experiment 5. Fixations on rhyme competitors in 12 young controls: Proportion of fixations over time on the target, the rhyme competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 19.
Experiment 5. Fixations on rhyme competitors in 12 older controls: Proportion of fixations over time on the target, the rhyme competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
**Broca’s aphasics**

Figure 20 plots the data from the Broca’s aphasics in rhyme competitor trials. The average trial end time for the Broca’s aphasics occurred in the 1600-1700 ms window. Two trials (3.3%) were excluded because the incorrect picture was selected (*jello*--*cello* and *honey*--*money*). In each of these trials, the rhyme competitor was selected. One trial (1.7%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the rhyme competitor’s picture was fixated on more than the average of the two unrelated pictures. This difference was very close to statistical significance by subjects $t_1(4)=2.0$, $p=.06$ and was statistically significant by items $t_4(11)=2.1$, $p=.03$. The time course analysis for the Broca’s aphasics showed that the difference approached significance in the two windows from 400-600 ms ($0.06<p<0.08$ by subjects and $0.07<p<0.10$ by items). The difference also approached significance in the window from 900-1000 ms ($p=0.07$ by subjects and $p=0.12$ by items).

**Wernicke’s aphasics**

Figure 21 plots the data from the Wernicke’s aphasics in rhyme competitor trials. Average trial end time for the Wernicke’s aphasics occurred in the 2200-2300 ms window. In two trials (4.2%), the rhyme competitor was selected instead of the target (*jello*--*cello* and *honey*--*money*). One additional trial (2.1%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the rhyme competitor’s picture was not fixated on significantly more than the average of the two unrelated pictures, $t_1(3)=.04$, $p=.49$ for subjects, and $t_2(11)=-.42$, $p=.66$ for items. Excluding the patient with right side neglect from the analysis had a negligible effect on the pattern and significance of the results.

**Comparison of groups:**

The competitor effects of each of the four groups were submitted to a 1-way ANOVA. The omnibus result approached significance by subjects $F_1(32)=2.1$, $p=.13$, but an ANOVA was not appropriate by items due to lack of homogeneity of variance. By subjects, planned paired comparisons of the aphasic groups with each other and the age-matched controls showed that as Figures 19-21 imply, the competitor effect was larger for Broca’s aphasics than for Wernicke’s aphasics ($p=0.04$) and age-matched controls ($p=0.05$). Permutation tests showed that by items the competitor effect was larger for Broca’s aphasics than for Wernicke’s aphasics ($p=0.04$), and age-matched controls ($p=0.08$). There were no other differences between the groups.
Figure 20.

Experiment 5. Fixations on rhyme competitors in 5 Broca’s aphasics: Proportion of fixations over time on the target, the rhyme competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Experiment 5. Fixations on rhyme competitors in 4 Wernicke’s aphasics: Proportion of fixations over time on the target, the rhyme competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Discussion of Experiment 5

The results from Experiment 5 show that Broca’s aphasics are significantly more likely to fixate on an object that rhymes with the target than on an unrelated object. While both the young and old control groups showed a small effect of rhyme competition, the effect only approached statistical significance in these control groups. In the Wernicke’s aphasics, on the other hand, there was no evidence of rhyme competition at all. A comparison of the rhyme competitor effect obtained in the Broca’s, Wernicke’s and age-matched control groups showed that the rhyme competitor effect in the Broca’s aphasics was larger than the effect in the Wernicke’s aphasics, as well as larger than the effect in the age-matched controls. The rhyme competitor effect obtained for the young and old controls in the current experiment appeared smaller than the effect obtained by Allopenna et al. (1998), which was statistically significant. Because we (in studies not reported in these pages), and others (e.g., McMurray et al., 2003) have obtained significant rhyme competitor effects previously, it is likely that the small effect obtained for control subjects the current experiment is due to low power (because of the small number of subjects and/or items tested).

The emergence of a significant rhyme competitor effect in the 5 Broca’s aphasics is particularly striking considering that the rhyme competition effect for both of the control groups only approached significance. This large rhyme competitor effect for Broca’s aphasics is consistent with Utman et al.’s (2001) explanation for why Broca’s aphasics showed reduced or absent facilitation for primes with voiced lexical competitors (e.g., pear-bear). Utman et al. argued that their findings indicate that for Broca’s aphasics, weakly activated targets do not become active enough to inhibit voiced lexical competitors. Thus, the competitors are active enough to compete with the target, reducing semantic priming from the target. The present study provides more direct evidence that Broca’s aphasics do, in fact, have difficulty inhibiting rhyme competitors. Furthermore, the results for Broca’s aphasics also replicate the finding of Yee, Blumstein & Sedivy (2000) in which 3 subjects with Broca’s aphasia were found to have a higher peaking rhyme competitor effect than did 12 young controls. The exaggerated rhyme competitor effect obtained in the Yee et al. study was also interpreted as evidence that because the target was weakly active, it had difficulty inhibiting the rhyme competitor.

Wernicke’s aphasics exhibited no sign of a rhyme competitor effect, suggesting that they are less susceptible to rhyme competition than are the other groups. This could be because the target rapidly becomes active enough to strongly inhibit competitors. Consequently, potential rhyme competitors are inhibited early, before enough acoustic input has been heard for them to become active enough to draw visual attention. Unfortunately, the Utman et al. study did not include
Wernicke’s aphasics. If it had, the current results suggest that for Wernicke’s aphasics the prime might have become active quickly enough to fully inhibit competitors, resulting in Wernicke’s aphasics showing a smaller difference between competitor-present and competitor-absent conditions than the other groups\footnote{However, note that according to the model outlined above, any rhyme competitor effect, or lack thereof, would depend entirely on how similar the rhyme competitor is to the target. Highly similar rhyme competitors (e.g., competitors that differ only in the voicing of the initial consonant) might rapidly become active enough to withstand inhibition from the target, or even to cross the inhibition threshold themselves and exert some inhibition on others. A computational model would be needed to explore the dynamics of competition and inhibition under different similarity conditions.}.

That the Wernicke’s aphasics did not exhibit a rhyme competitor effect in the present experiment may appear to be incompatible with Milberg at al.’s (1988) finding that for Wernicke’s aphasics, words that rhyme with the prime do become active. Specifically, in the Milberg et al., study priming was obtained for targets that were semantically related to words that rhymed with the prime (e.g., *gat* and *wat* primed *dog*, presumably via the activation of *cat*). A critical distinction between the two studies, however, is that in the Milberg et al. study all primes were non-words. Hence, the prime did not perfectly match any lexical representation, and thus no lexical representation quickly became active enough to inhibit its rhyme competitors. Consequently, unlike real word primes, which inhibit rhyming competitors that would otherwise become active, non-word primes do not inhibit rhyming real words. Likewise, although McNellis & Blumstein’s (2001) computational model of how sound structure contacts the lexicon demonstrated that increased baseline levels of lexical activation could result in increased activation of words semantically related to words that rhymed with the input, the input employed in their simulations was always a non-word. It would be quite interesting to test their model with increased baseline levels of lexical activation, a real word prime, and a target semantically related to a rhyme competitor of the real word prime.

In summary, in Experiment 5, Broca’s aphasics exhibited an abnormally large rhyme competitor effect and Wernicke’s aphasics failed to exhibit a rhyme competitor effect. The results are not consistent with the normal activation hypothesis, which predicts that both groups should show a normal rhyme competitor effect. They are also inconsistent with the delayed activation/deactivation hypothesis, which predicts that Broca’s aphasics should show a normal-sized rhyme competitor effect and that Wernicke’s aphasics should exhibit an unusually large
effect. However, under the assumption that the more highly active the target, the more successfully it can inhibit competitors, both groups’ effects are consistent with the reduced/increased activation hypothesis.
EXPERIMENT 6: SEMANTICALLY RELATED ITEMS IN APHASIA

Despite the abundance of studies showing that Broca’s aphasics exhibit semantic priming at much shorter intervals (e.g., Blumstein & Milberg, 1982; Milberg et al., 1988; Hagoort, 1993; Ostrin & Tyler, 1993), it has been maintained by Prather et al. (1992) and Prather et al. (1997) that it is not until 1500 ms after the offset of a word that Broca’s aphasics have automatic access to lexical representations. They claim that because studies showing priming at shorter intervals used paired presentation priming instead of list priming, controlled processing contaminated the results of these studies. Yet, it would be difficult to argue that controlled processing contaminates the results of Experiments 4 and 5. And still Figures 15 and 20 indicate that Broca’s aphasics have access to lexical information about the target and its competitors much earlier than 1500 ms after target offset. Thus the results of Experiments 4 and 5 appear to be inconsistent with Prather et al.’s findings. This suggests that the delayed semantic priming that Broca’s aphasics exhibit in the list priming paradigm may be due to some extra processing that is required to make lexical decisions on stimuli presented in lists, rather than being due to a lack of activation for the semantically related word.

Another possibility, though, is that the inconsistency between the two sets of studies could be a consequence of the fact that the Prather et al. studies measured the activation of words semantically related to the uttered word, while Experiments 4 and 5 measured the activation of the uttered word itself and words phonologically related to it. Thus it is still conceivable that for Broca’s aphasics, words semantically related to the target do not become active until 1500 ms after target offset. Given that Experiment 1 showed that for young normals, eye movements are sensitive to the activation of words semantically related to the target, it should be possible to use the same design to determine the time course over which aphasic patients activate words semantically related to the target. This would provide a more direct way of assessing the compatibility of Prather et al.’s findings and the results of Experiments 4 and 5.

A second reason to investigate eye movements to objects semantically related to the target is that the three theories that have been put forth to account for lexical processing deficits in Broca’s and Wernicke’s aphasia were all inspired by abnormal performance in semantic priming tasks. Demonstrating a semantic priming effect requires both activating the form and the meaning of the prime word. Therefore, semantic priming abnormalities could result from one or

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32 Presumably because semantic priming requires both phonological and semantic activation, Prather et al. do not attempt to make specific claims about whether access to phonological or semantic representations is delayed.
both of two sources: problems activating representations at the level of form, or problems activating representations at the level of meaning\textsuperscript{33}. Several studies have used the form priming paradigm in an effort to isolate any problems activating representations at the level of phonological form, but results have not been consistent or easily interpretable (Gordon & Baum, 1994; Baum, 1997; Blumstein, Milberg, Brown, Hutchinson, Kurowski & Burton, 2000). One reason that these studies did not provide clear cut results may be that (as argued in the discussion of form priming in Part 1) a number of different factors, some of which work in opposition to each other, may affect responses in the form priming paradigm, making data from this paradigm difficult to interpret.

Experiments 4 and 5 used an alternative method to detect abnormal activation of lexical form: eye movements to objects whose names overlap in form with the uttered word. The results of these studies suggest that both Broca’s and Wernicke’s aphasics access lexical form atypically. Specifically, Experiment 4 demonstrated that with respect to onset competition, Wernicke’s aphasics showed a larger than normal effect, while Broca’s aphasics appeared to show a smaller than normal effect. Experiment 5, on the other hand, demonstrated that with respect to rhyme competition, Broca’s aphasics showed a larger than normal effect, while Wernicke’s aphasics appeared to show an unusually small effect. Experiments 4 and 5 do not isolate activation at the level of lexical form since to fixate on an object whose name is phonologically related to the target, subjects must not only access the object’s name but also what it looks like. Nevertheless, the type of phonological overlap (onset or rhyme) affected each aphasic group differently. This difference suggests that the deficits of Broca’s and Wernicke’s aphasics are at least in part due to difficulty activating word forms. If their deficits were only at the semantic level, the two groups might still have responded differently from each other, but the two different types of phonological competitors should not have elicited a different pattern of results from each group. In other words, Broca’s and Wernicke’s aphasics might have exhibited different patterns from each other, but each group’s pattern should have remained similar for both types of phonological competitors. Thus, the results of Experiments 4 and 5 indicate that both Broca’s and Wernicke’s aphasics have a deficit with respect to activating word forms.

During spoken word recognition, activating a word’s lexical form is a pre-requisite for activating its meaning. Consequently, any problems activating a word’s lexical form would be expected to affect the activation of its meaning\textsuperscript{34} and as a result, should also affect the activation...

\textsuperscript{33} This assumes, as most researchers do, a model of lexical access that includes separate representations for form and meaning (e.g., McClelland & Rumelhart, 1986).

\textsuperscript{34} In so far as eye movements to a pictorial representation of an uttered word and its phonological competitors reflect the semantic as well as phonological activation of these words, Experiments 4 and 5 have already showed that abnormalities in activating phonological form result in abnormal activation of meaning.
of semantically related words. In Experiment 6, the semantic paradigm introduced in Experiment 1 is used to explore the activation of semantically related items in Broca’s and Wernicke’s aphasia. If Broca’s and Wernicke’s aphasics have reduced/increased activation (as Experiments 4 and 5 suggest) these deficits should produce abnormally small semantic effects in Broca’s aphasics and abnormally large effects in Wernicke’s aphasics. It is worth noting that while McNellis & Blumstein’s (2001) computational model predicts an abnormally small semantic effect for Broca’s aphasics as a consequence of reduced activation (the semantic facilitation of the target reaches a maximum of about .65 for Broca’s aphasics, compared to 1.05 for normals), their model does not predict an abnormally large semantic effect for Wernicke’s aphasics as a consequence of increased activation (like for normals, the semantic facilitation of the target reaches a maximum of 1.05 for Wernicke’s aphasics). However, as the maximum value of activation for lexical nodes was set to 1.05 (McNellis & Blumstein, p. 155), the lack of a larger semantic effect for Wernicke’s aphasics is likely due to a ceiling effect.

Methods

Materials

From the materials used in Experiment 1, eleven semantically related pairs were selected\textsuperscript{35}. One new pair (cherry-banana) replaced the pair mitten-glove because Experiment 1’s visual similarity post-test had showed that the average shape similarity rating for this pair was greater than 2 standard deviations above the mean of the rest of the pairs. With the exception of the new item pair, all auditory stimuli were taken from Experiment 1. Average target duration was 529 ms and average number of syllables was 1.8. As in Experiment 1, the related picture will be referred to as the semantically related item.

Results

Figures 22-25 plot the mean proportion of trials over time that contained a fixation to the target, the semantically related item, and the average of the two unrelated pictures (from target onset to 2500 ms after onset) in semantically related trials for each of the four subject groups (young controls, age-matched controls, Broca’s aphasics and Wernicke’s aphasics, respectively). The results from each subject group will be discussed separately below. For the purpose of analyzing the data, a “trial” was defined in the same way as it was in Experiments 4 and 5. The data were analyzed using the same procedures used in Experiments 4 and 5.

\textsuperscript{35} Only half of the items from Experiment 1 were used because we planned to use the other half of the items in an semantic onset competitor experiment that would be part of the bundle of experiments run in the same session.
**Young Controls:**

**Figure 22** plots the data from the young controls in semantically related trials. The average trial end time for the young controls occurred in the 1000-1100 ms window. Three trials (2.1%) were excluded because the incorrect picture was selected. In each of these cases, the semantically related item was selected (two wallet->purse and one battery->plug). Eight trials (5.6%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantically related item’s picture was fixated on significantly more than the average of the two unrelated pictures \( t_1(11)=2.8, p<.01 \) by subjects, and \( t_2(11)=3.3, p<.01 \) by items. The time course analysis for the young controls showed a significant difference between the related and the unrelated stimuli in the six windows from 500-1100 ms after target onset (\( p<.05 \) by subjects and items, with the exception of the window from 900-1000 ms, for which \( p=.06 \) by items).

**Age-matched controls**

**Figure 23** plots the data from the age-matched controls in semantically related trials. The average trial end time for the age-matched controls occurred in the 1200-1300 ms window. Three trials (2.1%) were excluded because the incorrect picture was selected (tepee->igloo, muffin->doughnut, pie->clover). In 2 of these trials, the semantically related item was selected. Eleven trials (7.6%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the related picture was fixated on significantly more than the average of the two unrelated pictures \( t_1(11)=2.5, p=.01 \) by subjects, and \( t_2(11)=2.3, p=.02 \) by items. The time course analysis for the age-matched controls showed a significant difference between the related and the unrelated stimuli in the three windows from 600-900 ms after target onset (\( p<.05 \) for subjects and items, with the exception of the 600-700 ms window, for which \( p=.07 \) by items).

**Broca’s aphasics**

**Figure 24** plots the data from Broca’s aphasics in semantically related trials. The average trial end time for the Broca’s aphasics occurred in the 1600-1700 ms window. Four trials (6.7%) were excluded because the incorrect picture was selected (wallet->purse, pie->clover, tepee->igloo, muffin->doughnut). In three of these trials, the semantically related item was selected. Two (3.3%) of trials did not provide any data because there were no eye movements after the onset of the target word.
Figure 22.
Experiment 6. Fixations on semantically related items in 12 young controls: Proportion of fixations over time on the target, the semantically related item, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 23.

Experiment 6. Fixations on semantically related items in 12 older controls: Proportion of fixations over time on the target, the semantically related item, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 24.
Experiment 6. Fixations on semantically related items in 5 Broca’s aphasics: Proportion of fixations over time on the target, the semantically related item, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
The competitor effect shows that the semantically related picture was fixated on significantly more than the average of the two unrelated pictures $t_1(4)=3.6, p=.01$ by subjects, and $t_2(11)=1.9, p=.04$ by items. The time course analysis for the Broca’s aphasics showed that in the five windows from 700-1200 ms after target onset, the difference between the related and the unrelated stimuli was either significant at the $p<.05$ level, or approached significance ($.05<p<.10$) for both subjects and items.

Wernicke’s aphasics

Figure 25 plots the data from Wernicke’s aphasics in semantically related trials. Average trial end time for the Wernicke’s aphasics occurred in the 2000-2100 ms window. Five trials (10.4%) were excluded because the incorrect picture was selected (two tepee-->igloo, robe-->slippers, saw-->axe, scissors-->knife). A single subject selected four of these incorrect pictures. In each of these trials, the semantically related item was selected. Three trials (6.3%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantically related picture was fixated on more than the average of the two unrelated pictures. This difference was significant by subjects $t_1(3)=3.4, p=.02$, and approached significance by items $t_2(11)=1.2, p=.13$. The time course analysis for the Wernicke’s aphasics showed that in the four windows from 1400-1800 ms after target onset the difference between the related and the unrelated stimuli was significant at the $p<.05$ level by subjects, and approached significance by items ($.05<p<.13$). Excluding the patient with right side neglect from the analysis had no effect on the pattern of results and negligible effect on the significance.

Comparison of groups:

The competitor effects from each of the four groups were submitted to a 1-way ANOVA. The omnibus result was not significant and planned paired comparisons of the two patient groups with each other and the age-matched controls revealed no differences.

Discussion of Experiment 6

Experiment 6 showed that like young controls, older controls, Broca’s aphasics and Wernicke’s aphasics all fixate more on pictures of objects semantically related to the target than
Figure 25.
Experiment 6. Fixations on semantically related items in 4 Wernicke’s aphasics: Proportion of fixations over time on the target, the semantically related item, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
on unrelated pictures. The results for the young controls appeared similar to the results of Experiment 1. Older controls also showed a semantic effect, though their effect was reliable in fewer time bins (the 3 bins from 600-900 ms) than was the effect for young controls (the 6 bins from 500-1100 ms). In light of arguments that strategic processing affects the outcome of semantic priming experiments, it is important to bear in mind that in the current experiment the task was merely to select the target. Thus, because semantic effects emerged in a task that required no overt response to the semantically related item, it would be difficult to maintain that controlled processing was the source of the effects.

The Broca’s aphasics’ semantic effect emerged 700 ms after target onset (or, allowing for eye movement programming time, in response to 500 ms of acoustic input). This time-frame is a far cry from the 1500 ms (that is 1500 ms after target offset) that Prather et al. (1992 & 1997) argued is required to activate lexical representations in the absence of controlled processing. This suggests that the delay in priming observed by Prather et al. may be due to some extra processing cost of making lexical decisions when stimuli are presented in lists, rather than delayed activation for the semantically related word.

Since there is no way to access a heard word’s meaning without first partially activating its lexical form, problems activating a word’s lexical form should affect the activation of its meaning and consequently also affect the activation of words semantically related to it. The apparent deficits exhibited by Broca’s and Wernicke’s aphasics for phonological competitors (in Experiments 4 and 5) were therefore expected to be reflected in the activation of words semantically related to the target. Thus it is somewhat surprising that both aphasic groups exhibited semantic effects that did not differ significantly from those of young or old normals. However, the result for Broca’s aphasics is consistent with most studies that have used paired (and unaltered) primes and targets to investigate semantic priming in Broca’s aphasia. For instance, while neither Ostrin & Tyler (1993), nor Tyler et al. (1995), nor Hagoort (1997) statistically compared Broca’s aphasics with normals, in each of these studies the magnitude of priming obtained for the two groups appeared similar. Other studies, while finding differences between the contexts (i.e., ISIs) in which Broca’s aphasics and normals showed priming when primes were non-words (Milberg et al., 1988) or acoustically modified words (Utman et al.,

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From the control condition of Experiment 1, which used the same target-competitor pairs used in this experiment, we know that the semantic effects obtained in the present experiment were not due to the pictures used to represent the semantically related items drawing attention irrespective of the instruction or due to related pictures drawing more fixations than unrelated pictures. To ensure that the semantic effect obtained in this experiment was not due to the subset of target-competitor pairs used in this experiment being visually confusable with each other, we used the visual similarity ratings from Experiment 1’s post-test to select the items from the present experiment whose visual similarity ratings were as low as the ratings for the control items in Experiment 1 (average of 1.5 on a 1 to 7 scale). When these items were analyzed separately, each group showed the same pattern as for the full set of items.
also found that when primes and targets were unaltered real words, Broca’s aphasics exhibited semantic priming in the same contexts as normals. Two studies did directly compare semantic priming (using paired and unaltered primes and targets) in Broca’s aphasics and normals (Baum, 1997; Milberg & Blumstein 1981). In one (Baum, 1997), no difference between the two groups was found, while in the other (Milberg & Blumstein 1981), a smaller priming effect for Broca’s aphasics than for normals was reported. Thus, most studies investigating semantic priming in Broca’s aphasia appear to indicate that Broca’s aphasics show normal semantic priming when primes and targets are paired and unaltered real words.

That Broca’s aphasics often exhibit what appears to be a normal-sized semantic priming effect, however, does not explain why abnormal activation at the level of lexical form does not appear to be reflected in an abnormal semantic effect in eye movements. In fact, if Broca’s aphasics have abnormally low levels of lexical activation, their normal semantic priming also needs to be accounted for. One possibility is that since both the semantic priming and the semantic eye movement effects measure the activation of words semantically related to the word of interest, both are one step removed from the level of impairment; consequently neither the semantic priming nor the semantic eye movement effect is sensitive enough to detect the impairment. This explanation seems unlikely however, since, even though the difference is not statistically reliable, in the current experiment the semantic eye movement effect for the Broca’s aphasics appears larger than it does for the normal controls. A second possibility is that part of Prather et al.’s (1992 & 1997) argument is correct: the semantic priming effects observed when primes and targets are paired are due to strategic, rather than automatic processing and thus do not reflect automatic activation. However, this account would not explain why Broca’s aphasics showed a normal semantic effect in the eye tracking paradigm, which is unlikely to be affected by controlled processing. Furthermore, if semantic priming effects are due to strategic processing, it is not clear why Broca’s aphasics exhibit abnormal priming when subphonetic alterations are made to primes with lexical competitors (Utman et al., 2001); there is no reason for a strategy-driven effect to be sensitive to such a subtle acoustic modification.

A third possibility is that because of their difficulties activating lexical form, Broca’s aphasics compensate by heavily weighting activation that reaches the semantic level, effectively amplifying the signal. Amplifying activation on the semantic level could give rise to apparently

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37 In these studies normal participants were not tested; it was in prior studies that normal participants exhibited priming in the same contexts.
normal semantic priming and semantic eye movement effects\textsuperscript{38}. Since any resulting increase in activation would likely be proportional to the original signal, this account is consistent with the sensitivity to acoustic modification of the prime that can be observed in Broca’s aphasics’ semantic priming effects. Evidence that this kind of increase in reliance on a higher level of processing can occur in Broca’s aphasia comes from a study on the role of lexical status on phonetic categorization (Blumstein, Burton, Baum, Waldstein & Katz, 1994) which showed that when making decisions about a phoneme’s identity, Broca’s aphasics rely more heavily than controls on the lexical status of the stimulus. The proposed compensation would need to operate automatically, however, to accommodate the fact that both the semantic priming and the semantic eye movement appear to reflect automatic processing.

A final explanation for Broca’s aphasics’ apparently normal semantic priming and semantic eye movement effects is that in addition to their abnormally low levels of lexical activation, Broca’s aphasics have a deficit at the semantic level that effectively increases the activation of semantically related items. One potential candidate for a semantic deficit is a problem selecting between competing semantic alternatives; it has recently been argued that the posterior portion of the left inferior frontal gyrus (i.e., Broca’s area) is involved in selecting between competing semantic alternatives (e.g., Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). A problem selecting from among competing semantic alternatives could increase competition from semantic representations related to the uttered word which, when coupled with a lower starting level of semantic activation (due to reduced activation), could result in a semantic priming or semantic eye movement effect that appears normal.

Thus, there are a number of potential explanations for why Broca’s aphasics would exhibit normal-sized semantic priming and semantic eye movement effects despite reduced activation. The two most plausible explanations seem to be that they heavily weight semantic activation or that they have an additional deficit at the semantic level\textsuperscript{39}.

In light of the abnormal phonological effects that they exhibited in Experiments 4 and 5, it is somewhat surprising that the Wernicke’s aphasics, like the Broca’s aphasics, exhibited a semantic effect of normal size. This is because, as argued above, in order to activate a heard word’s meaning, its lexical form must first be partially activated; as a result, problems activating

\textsuperscript{38} Increased activation for a target would not be predicted to result in inhibition of a semantically related item. This is because unlike the phonological level where there is a good reason for inhibition since activating related words will not aid and could instead impair comprehension, at the semantic level inhibiting related items is unnecessary since activating related words is unlikely to hinder and may even help comprehension.

\textsuperscript{39} The Broca’s aphasics’ normal-sized semantic eye movement effect is, of course, also consistent with their having normal or delayed activation. However, these two accounts are not consistent with the results of Experiments 4 or 5 or with semantic priming studies that altered the phonological form of the prime and consequently may have been particularly sensitive to reduced phonological activation (Milberg et al., 1988; Utman et al., 2001).
a word’s lexical form should affect the activation of its meaning, and in turn affect the activation of semantically related words. Since abnormalities in the timing or level of activation at the phonological level should both be reflected in the activation of words semantically related to the target, the delayed deactivation and increased activation hypotheses both predict an abnormally large semantic eye movement effect. Instead, the Wernicke’s aphasics’ normal-sized semantic effect is consistent with the hypothesis that they have normal activation. Yet, normal activation cannot account for the results of Experiments 4 or 5, or for the results of a number of semantic priming studies in which Wernicke’s aphasics exhibit semantic priming in more situations than normals (Milberg et al., 1988; Prather et al., 1994; Prather et al., 1997); increased activation, on the other hand, can account for all of these results.

This discrepancy suggests that a distinctive aspect of the Wernicke’s aphasics’ performance in Experiment 6 may be important: Wernicke’s aphasics selected the semantically related item instead of the target in 10.4% of trials, compared to 5.0% for Broca’s aphasics, 1.4% for older controls, and 2.1% for young controls. Although permutation tests showed that in this study Wernicke’s aphasics did not select the semantically related item significantly more than Broca’s aphasics ($p=.41$), age-matched controls ($p=.13$), or young controls ($p=.16$), semantic errors are common in Wernicke’s aphasia. Furthermore, another study using the same task (but without recording eye movements) found that Wernicke’s aphasics made almost twice as many semantic errors as Broca’s aphasics (Baker, Blumstein & Goodglass, 1981). Since trials in which the incorrect response was selected were not included in the analysis here, eye movements from these trials do not contribute to the semantic eye movement effect. However, when correct and incorrect trials are analyzed for each group, permutation tests show that the Wernicke’s aphasics’ semantic effect (Figure 26) is larger than that of the age-matched controls ($p=.03$), and marginally significantly larger than that of the young controls ($p=.08$), though not larger than that of the Broca’s aphasics ($p=.30$). It is therefore possible that for Wernicke’s aphasics increased activation occasionally caused the semantically related item to become so active that it was selected.

In summary, both Broca’s and Wernicke’s aphasics exhibited semantic eye movement effects of normal size. For Broca’s aphasics, these results are consistent with both the normal

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40 ANOVA could not be conducted on these data due to lack of homogeneity of variance.
41 Once again, ANOVA could not be conducted on these data due to lack of homogeneity of variance.
42 When data from incorrect trials were included in the analyses for Experiments 4, 5, and 7 the patterns were unchanged.
43 Note that while a delay in deactivating lexical information would also cause an abnormally large competitor effect, this effect should be larger than normal because it is long lasting, not because the competitor is highly active. Thus, assuming competitors have to be highly active to elicit selection errors, a competitor effect that is larger than normal because of a delay in deactivating lexical information would not be expected to cause selection errors.
Figure 26.

Experiment 6. Fixations on semantically related items including incorrect responses in 4 Wernicke’s aphasics: Proportion of fixations over time on the target, the semantically related item, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
and the delayed activation hypotheses, but not with the reduced activation hypothesis. However, the results of Experiments 4 and 5, like the results of semantic priming studies that may be particularly sensitive to reduced activation (i.e. with altered primes), were not consistent with the normal or the delayed activation hypotheses, but were consistent with the reduced activation hypothesis. Therefore, it is proposed that Broca’s aphasics might exhibit normal semantic priming despite having reduced activation because they either heavily weight activation that reaches the semantic level or because they have difficulty selecting between competing semantic alternatives, which effectively increases the activation of semantically related items, resulting in a semantic effect that appears normal. Similarly, although the semantic effect exhibited by the Wernicke’s aphasics is at first glance consistent with only the normal activation hypothesis, on several trials the semantically related item was selected instead of the target. These errors suggest that the Wernicke’s aphasics’ semantic effect is, in fact, larger than that of normals, but appeared deceptively small because eye movements from error trials were not included in the analysis. If true, the results of Experiment 6, like the results of Experiments 4 and 5, should be considered to be support for the hypothesis that Wernicke’s aphasics have increased activation.
EXPERIMENT 7: SEMANTICALLY MEDIATED ONSET COMPETITION IN APHASIA

Experiment 6 (semantically related items) showed that like normals, both Broca’s and Wernicke’s aphasic patients are more likely to fixate on an object semantically related to the target (e.g., hammer → nail) than on an unrelated object. Experiment 4 (onset competitors) suggested that like normals, Wernicke’s, but not Broca’s aphasics, are more likely to fixate on an object that shares its onset with the target (e.g., hammock → hammer) than on an unrelated object. Experiment 2, (semantic onset competitors) showed that for young normals, eye movements are sensitive to the activation of words semantically related to an onset competitor of the target (e.g., hammock → nail).

Taken together these three experiments suggest that Wernicke’s, but not Broca’s aphasics, should be more likely to fixate on an object semantically related to an onset competitor of a given target (i.e., a semantic onset competitor), than on an unrelated object. Furthermore, since Wernicke’s aphasics appeared to show a larger onset competitor effect than Broca’s aphasics and normals, they may also show a larger semantic onset competitor effect. Note that despite that Broca’s aphasics displayed a normal-sized semantic effect, it is predicted that they will show an abnormally small or absent semantic onset competitor effect. This is because there is no reason to activate something semantically related to an onset competitor of a target if the onset competitor itself has not been activated, and in Experiment 4 Broca’s aphasics did not appear to activate onset competitors.

Experiment 7 measures Broca’s and Wernicke’s aphasics’ eye movements to objects semantically related to onset competitors of the target. If Broca’s aphasics show an unusually small semantic onset competitor effect while Wernicke’s aphasics show an unusually large effect, this would parallel the data obtained in Experiment 4, thereby providing additional support to the reduced/increased activation hypothesis.

Methods

Materials

From the materials used in Experiment 2, the 12 semantically mediated onset competitor pairs that had no overlap with the pairs used in Experiment 6 were selected. All auditory stimuli were taken from Experiment 2. Average target duration was 615 ms and average number of syllables was 2.2. As in Experiment 2, the competitor picture will be referred to as the semantic onset competitor.
Results

Figures 27-30 plot the mean proportion of trials over time that contained a fixation to the target, to the semantic onset competitor, and to the average of the two unrelated pictures (from target onset to 2500 ms after onset) in semantic onset competitor trials for each of the four subject groups (young controls, age-matched controls, Broca’s aphasics and Wernicke’s aphasics, respectively). The results from each subject group will be discussed separately below. For the purpose of analyzing the data, a “trial” is defined in the same way as it was in Experiments 4-6. The data were analyzed using the same procedures used in Experiments 4-6.

Young Controls:

Figure 27 plots the data from the young controls in semantic onset competitor trials. The average trial end time for the young controls occurred in the 1000-1100 ms window. The correct picture was selected in all trials. Ten trials (6.9%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantic onset competitor’s picture was fixated on significantly more than the average of the two unrelated pictures by subjects $t_{1}(11)$=2.0, $p=.03$ and by items $t_{2}(11)$=2.1, $p=.03$. In the time course analysis, the three windows from 500-800 ms after target onset showed a significant difference at the $p<.05$ level by both subjects and items. The item analysis also showed a difference at the $p<.05$ level for the two windows from 800-1000 ms after target onset, but this difference was just short of statistically significant in the subjects analysis (.05$<p<.07$).

Age-matched controls

Figure 28 plots the data from the age-matched controls in semantic onset competitor trials. The average trial end time for the age-matched controls occurred in the 1200-1300 ms window. As was the case for the young controls, the correct picture was selected in all trials. Ten trials (6.9%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantic onset competitor’s picture was fixated on significantly more than the average of the two unrelated pictures. This difference was significant by subjects $t_{1}(11)$=2.1, $p=.01$ and by items $t_{2}(11)$=1.9, $p=.04$. The time course analysis showed that in the two windows from 500-700 ms after target onset the difference between the competitor and the unrelated stimuli was significant at the $p<.05$ level by both subjects and items. In addition, in the three windows from 200-500 the difference between the competitor and the unrelated stimuli approached significance (.06$<p<.10$ and $.05<p<.11$ by subjects and
Figure 27.

Experiment 7. Fixations on semantic onset competitors in 12 young controls: Proportion of fixations over time on the target, the semantic onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 28.

Experiment 7. Fixations on semantic onset competitors in 12 older controls: Proportion of fixations over time on the target, the semantic onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
items, respectively), with the exception of the window from 300-400 ms, in which the difference was statistically significant at the $p<.05$ level by subjects.

**Broca’s aphasics**

**Figure 29** plots the data from the Broca’s aphasics in semantic onset competitor trials. The average trial end time for the Broca’s aphasics occurred in the 1500-1600 ms window. The correct picture was selected in all trials. Seven trials (11.7%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantic onset competitor’s picture was not fixated on significantly more than the average of the two unrelated pictures, $t_1(4)=1.0, p=.18$ by subjects and $t_2(11)=-.61, p=.72$ by items.

**Wernicke’s aphasics**

**Figure 30** plots the data from the Wernicke’s aphasics. Average trial end time for the Wernicke’s aphasics occurred in the 1900-2000 ms window. Two trials (4.2%) were excluded because the wrong picture was selected (both were mattress --> lighter). One trial (2.1%) did not provide any data because there were no eye movements after the onset of the target word.

The competitor effect shows that the semantic onset competitor’s picture was fixated on more than the average of the two unrelated pictures. This difference was significant by subjects, $t_1(3)=3.3, p=.02$, and approached significance by items $t_2(11)=1.3, p=.11$.

The time course analysis showed that the semantic onset competitor was fixated on more than the unrelated stimuli in the window from 900-1000 ms after target onset. This difference was significant by subjects ($p=.02$), and approached significance by items ($p=.06$). The competitor was also fixated on more than the unrelated stimuli in the two windows from 1400-1600 ms after target onset. This difference approached significance by subjects ($0.05<p<.14$), and was either significant or approached significance by items ($0.04<p<.06$). The pattern remained similar when the subject with neglect was removed from the analysis, but the semantic onset competitor effect appeared slightly larger. The significance of the effect remained largely unchanged.

**Comparison of groups:**

The competitor effects from each of the four groups were submitted to a 1-way ANOVA. The omnibus ANOVA was not statistically significant by subjects ($F_{1}(32)=.9, p=.46$), and an ANOVA was not appropriate by items due to a lack of homogeneity of variance. By subjects, planned paired comparisons of the aphasic groups with each other and the age-matched controls
Figure 29.
Experiment 7. Fixations on semantic onset competitors in 5 Broca’s aphasics: Proportion of fixations over time on the target, the semantic onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
Figure 30.

Experiment 7. Fixations on semantic onset competitors in 4 Wernicke’s aphasics: Proportion of fixations over time on the target, the semantic onset competitor, and the average of the two unrelated control objects. Standard error bars are shown for every other data point.
showed that while the semantic onset competitor effect was larger for the Wernicke’s aphasics than for the other groups, this effect was not statistically significant. Permutation tests by items also failed to reveal a significant difference between the semantic onset competitor effect of the Wernicke’s aphasics and that of the age-matched controls (although for the Broca’s aphasics the difference approached significance at $p=.08$). No other differences emerged.

When the ANOVA was repeated without the Wernicke’s aphasic with neglect, the result was still not significant by subjects $F_1(31)=1.2$, $p=.32$, and homogeneity of variance was still violated by items. However, the differences between the Wernicke’s aphasics’ competitor effect and those of the Broca’s aphasics and the age-matched controls approached significance by subjects ($0.09<p<0.11$). By items, the permutation tests showed that the difference between the Wernicke’s and the Broca’s aphasics’ semantic onset competitor effects approached significance ($p=.05$), but the difference between the semantic onset competitor effects displayed by the Wernicke’s aphasics and the age-matched controls did not ($p=.18$).

**Discussion of Experiment 7**

The results from Experiment 7 show that like young and age-matched controls, Wernicke’s aphasics show a significant semantic onset competitor effect. That is, they are more likely to fixate on a picture of an object semantically related to an onset competitor of the target than on an unrelated object. Moreover, the semantic onset competitor effect for Wernicke’s aphasics appeared larger than the effect for the age-matched controls. This difference, however, only approached statistical significance by subjects when the patient with neglect was removed from the analysis. Broca’s aphasics, on the other hand, show no evidence of competition from the semantic onset competitor. The semantic onset competitor effect obtained in the current experiment for older controls appears similar to the semantic onset competitor effect obtained in Experiment 2. For young controls, the time course of the effect in the current experiment, however, is slightly later than it was in Experiment 2. This is surprising, and it would be interesting to test more subjects to determine whether this difference is reliable.

Activating the semantic onset competitor requires that the onset competitor be active. For this reason, it is reassuring that the pattern of results obtained in this experiment parallel the results obtained in Experiment 4 (onset competitors). Specifically, in the current experiment, as in Experiment 4, Wernicke’s aphasics showed a competitor effect while Broca’s aphasics did not. Furthermore, although the difference was not statistically reliable in the current experiment,
in both Experiment 4 and the current experiment the competitor effect was larger for the Wernicke’s aphasics than it was for the Broca’s aphasics and the age-matched controls.

The errors made by the Wernicke’s aphasics provide another piece of evidence that they experience more competition from the semantic onset competitor than do the other groups. Two of the Wernicke’s aphasics (once each) selected a semantic onset competitor instead of the target, whereas members of the other groups made no errors. Permutation tests\(^{45}\) show that the Wernicke’s aphasics selected the semantic onset competitor marginally significantly more than did the young controls (\(p=.05\)) and the age-matched controls (\(p=.05\)), but not the Broca’s aphasics (\(p=.17\)).

The findings obtained in the present experiment, specifically an absent semantic onset competitor effect for Broca’s aphasics, and what appears to be an abnormally large (though not statistically abnormal) semantic onset competitor effect for Wernicke’s aphasics, are consistent with the reduced/increased activation hypothesis. As explained previously, reduced activation could mean that Broca’s require a better than normal match between the acoustic input and a stored lexical representation in order to activate it. The results of the present experiment are consistent with words semantically related to the onset competitors failing to draw fixations from Broca’s aphasics because the onset competitors themselves failed to become active. For Wernicke’s aphasics on the other hand, increased activation may result in their activating a lexical representation even when the match between it and the acoustic input is less precise than is normally required. Therefore, for Wernicke’s aphasics onset competitors became more often and/or more strongly active, and as a result words semantically related to onset competitors drew more fixations.

The large semantic onset competitor effect displayed by the Wernicke’s aphasics is also compatible with delayed deactivation since delayed deactivation should cause longer duration fixations on the semantic onset competitor and/or more fixations on the semantic onset competitor. However, the results of Experiments 5, where Wernicke’s aphasics exhibited no hint of a rhyme competitor effect, let alone a larger than normal rhyme competitor effect, were incompatible with delayed deactivation but were compatible with increased activation. Therefore, together these experiments provide more support for the latter hypothesis.

In summary, the results of Experiment 7 parallel the results of Experiment 4, with Broca’s aphasics showing an absent semantic onset competitor effect and Wernicke’s aphasics showing a large semantic onset competitor effect. The results for Broca’s aphasics are consistent with reduced activation but not with the other two hypotheses. The results for the Wernicke’s

\(^{45}\) ANOVA could not be conducted on these data due to lack of homogeneity of variance.
aphasics are consistent with both increased activation and delayed deactivation, but not with normal activation.
GENERAL DISCUSSION: PART 2

Of the three hypotheses that have been proposed to account for the lexical processing deficits associated with Broca’s and Wernicke’s aphasics, the results of Experiments 4-7 are most compatible with the hypothesis that Broca’s and Wernicke’s aphasics have reduced/increased activation.

Consider first the Broca’s aphasics. In Experiments 4 (onset competitors) and 7 (semantic onset competitors), unlike normals, Broca’s aphasics did not display significant competitor effects. These findings are consistent with Broca’s aphasics having reduced activation since starting out with reduced activation would mean that for Broca’s aphasics, onset competitors (and therefore semantic onset competitors) will be less likely to become active. The results of Experiments 4 and 7 were not compatible with Broca’s aphasics having normal or delayed activation because both of these deficits would give rise to competitor effects of normal size.

The abnormally large rhyme competitor effect exhibited by the Broca’s aphasics’ in Experiment 5 is also consistent with their having reduced activation if it is assumed that a word can only successfully inhibit competitors once it has become sufficiently active. This is because reduced activation would result in the target taking more time than usual to become active enough to successfully inhibit competitors, allowing more acoustic input to be heard before the target can successfully inhibit competitors. Since this acoustic input matches the rhyme competitor, the rhyme competitor becomes abnormally active46. The Broca’s aphasics’ abnormally large rhyme competitor effect is not consistent with normal or delayed activation because both deficits would cause a normal-sized competitor effect.

The normal-sized semantic effect displayed by Broca’s aphasics’ in Experiment 6, however, is not consistent with reduced activation. Because it is necessary to at least partially activate a word’s form before its meaning can be activated, reduced activation should result in an abnormally small semantic effect. Although the normal-sized semantic effect is consistent with normal activation and delayed activation, the Broca’s aphasics’ results in Experiments 4, 5 and 7 were not consistent with these hypotheses. Thus, we suggest that Broca’s aphasics’ semantic effect may appear normal because activation at the semantic level is inflated, due to either heavily weighting information that reaches the semantic level to compensate for difficulty activating lexical forms, or due to difficulty selecting between competing alternatives. One way

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46 While a weakly activated target will also take longer than normal to become active enough to inhibit onset competitors, fewer onset competitors will overlap with the acoustic input enough to become active in the first place. Hence, a larger than normal rhyme competitor effect is consistent with an abnormally small onset competitor effect for Broca’s aphasics.
to distinguish between whether Broca’s aphasics heavily weight activation at the semantic level or instead have difficulty selecting between competing semantic alternatives would be to use a task which does not require accessing semantic representations via phonological input. This could be accomplished by presenting semantic representations visually (e.g., presenting pictures of objects) and asking subjects to perform a selection task (e.g., which pictures go best together). If Broca’s aphasics perform abnormally when the semantic alternatives are provided, this would suggest that what appears to be a normal semantic effect is actually due to increased competition from semantic alternatives, coupled with reduced activation. On the other hand, if the appearance of a normal semantic effect in Broca’s aphasics is due to their compensating for low activation at the phonological level by heavily weighting activation that reaches the semantic level, they would not be expected to perform abnormally on such a selection task.

In summary, the results for the Broca’s aphasics in Experiments 4, 5 and 7 are consistent with the hypothesis that Broca’s aphasics have reduced activation, but not consistent with the normal activation hypothesis or the delayed deactivation hypothesis. Because their semantic effect in Experiment 6 was not smaller than that of normals, the results of Experiment 6, in contrast, are not consistent with reduced activation, but were consistent with the other two hypotheses. In spite of Experiment 6, of the three proposals discussed, the hypothesis that Broca’s aphasics have reduced activation most consistently accounts for the data obtained.

Now consider the Wernicke’s aphasics. The large competitor effects they exhibited in Experiments 4 (onset competitors) and 7 (semantic onset competitors) are not consistent with normal activation. The results of these two experiments are, however, compatible with delayed activation since this would cause abnormally long-lasting competition and therefore give rise to numerous and/or long-lasting fixations on the competitor. The results are also compatible with increased activation, for starting out with increased activation means that for Wernicke’s aphasics onset competitors will become more active than they will for normals, resulting in a larger competitor effect.

Experiment 5’s results for Wernicke’s aphasics are not consistent with delayed deactivation since this should cause long-lasting competition from the rhyme competitor and consequently a large rhyme competitor effect. Nor are Experiment 5’s results consistent with Wernicke’s aphasics having normal activation since this should result in a rhyme competitor effect of normal size. The results of Experiment 5 are, however, compatible with the reduced/increased activation hypothesis if a word’s activation must reach a certain threshold of activation before it can inhibit competitors (as proposed above in reference to Broca’s aphasia). Increased activation would allow the target to quickly reach the threshold for inhibiting competitors, which would enable it
to inhibit potential rhyme competitors early on, before the unfolding the input is consistent enough with them for them to become active.

In Experiment 6, Wernicke’s aphasics exhibited a semantic effect that was not different from that of normals or Broca’s aphasics. While this normal semantic effect is consistent with the hypothesis that Wernicke’s aphasics have normal activation, the results of Experiments 4, 5 and 7 were not consistent with this hypothesis. Furthermore, in Experiment 6, Wernicke’s aphasics selected the semantically related item instead of the target more than twice as often as the other groups did. One way to account for these errors is to assume that the semantically related item became so highly active that it was selected. And in fact, when all trials were analyzed (instead of correct trials only), the Wernicke’s aphasics’ semantic effect was significantly larger than that of the age-matched controls. Thus, it could be that Wernicke’s aphasics exhibited a normal-sized semantic effect only because the trials in which the competitor was most active were not included in the analysis. If true, then the Wernicke’s aphasics’ results in Experiment 6 are most compatible with the hypothesis that they have increased activation.

Table 1 provides an overview of how well the data from Experiments 4-7 conform with the three theories that have been proposed to account for the lexical processing deficits displayed by Broca’s and Wernicke’s aphasics.

<table>
<thead>
<tr>
<th>Broca’s aphasics</th>
<th>Exp. 4 (onset)</th>
<th>Exp. 5 (rhyme)</th>
<th>Exp. 6 (semantic)</th>
<th>Exp. 7 (sem onset)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Activation</td>
<td>n</td>
<td>n</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>Delayed Activation</td>
<td>n</td>
<td>n</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>Reduced Activation</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>y</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wernicke’s aphasics</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Activation</td>
<td>n</td>
<td>n</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>Delayed Deactivation</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>y</td>
</tr>
<tr>
<td>Increased Activation</td>
<td>y</td>
<td>y</td>
<td>?</td>
<td>y</td>
</tr>
</tbody>
</table>

An abnormally large semantic effect for Wernicke’s aphasics is also consistent with the delayed deactivation hypothesis. Recall, however, that delayed deactivation should not cause the competitor to be selected more frequently.
As an extension of the studies described in these pages, it would be interesting to conduct an experiment analogous to Experiment 3 (semantic rhyme competitors) with Broca’s and Wernicke’s aphasics. According to the pattern of data obtained in Experiment 5 (rhyme competitors), Broca’s aphasics should exhibit an unusually large semantic rhyme competitor effect. However, as described earlier, Milberg et al. (1988), and Misiurski et al. (submitted) did not find evidence that Broca’s aphasics activate the semantic representations of rhyming words (e.g., *gat* did not prime *dog* and *t²ime* did not prime *penny*). It is possible, though, that these studies failed to obtain a semantic priming effect for Broca’s aphasics not because the semantic representation of the rhyming word was never active, but because activation was probed when the rhyme competitor was no longer active enough to prime semantically related items. It is also possible that rhyming words do not become active enough to speed lexical decisions on semantically related words, but do become active enough for visual attention to be drawn to pictures of related words – for, as discussed in Experiment 3’s discussion, pictures may better reflect meaning activation than do words.

For Wernicke’s aphasics, the results of Experiment 5 suggest that an unusually small semantic rhyme competitor effect will emerge (recall that while Milberg et al., 1988 found that Wernicke’s aphasics displayed priming for words semantically related to words that rhymed with the prime [e.g., *gat* and *wat* primed *dog*], in their study the prime was always a non-word, and thus would not have inhibited rhyming lexical competitors in the way that highly activated targets are hypothesized to have inhibited rhyme competitors for Wernicke’s aphasics in Experiment 5). If the predicted pattern of results are obtained in a study of semantic rhyme competitors in Broca’s and Wernicke’s aphasia, this would corroborate the results obtained in Experiment 5 (i.e., the large rhyme competitor effect for Broca’s aphasics and the small rhyme competitor effect for Wernicke’s aphasics). A semantic rhyme competitor effect for Broca’s aphasics would also confirm that, as the results of Experiment 3 indicated, the semantic representations of rhyme competitors can become temporarily active.

It is admittedly counterintuitive that in some instances reduced activation results in competitor effects while increased activation does not. One way this pattern can emerge is if a) a word can only successfully inhibit competitors once it is sufficiently active (e.g., once it reaches a certain level), and b) activation below that level can still be detected (e.g., is sufficient to draw visual attention). Thus, Broca’s aphasics, with initially reduced activation, require more input than normals do before a word becomes active enough to successfully inhibit competitors. Before the target reaches that level, the amount of overlap between the acoustic input and the rhyme competitor is already sufficient for the rhyme competitor to draw visual attention. For Wernicke’s aphasics, on the other hand, activation starts out high. Therefore the target is able to
successfully inhibit competitors before there has been enough acoustic input that matches the rhyme competitor for it to draw visual attention (recall that the mismatch is at the beginning for rhyme competitors). Consequently, Wernicke’s aphasics show no rhyme competitor effect despite starting out with increased activation.

To confirm that this account is at least internally consistent, we used a simple equation to model how a word’s lexical activation might change over time in response to unfolding acoustic input. In this equation, a word’s activation at any point in time is a function of:

1. The word’s activation at the previous time-step, plus
2. The word’s match with the input at the current time-step, minus
3. The weighted activation of any other words in the lexicon whose activation (at the prior time-step) has passed the level\(^{48}\) that must be reached in order to inhibit competitors.

Formalized, this amounts to:

\[
A_i(t) = A_i(t-1) + I_i(t) - \sum_{j, j \neq i}^k \text{threshold}(A_j(t-1), T) \cdot w_{ij}
\]

Where,

\[
\text{threshold} (x, T) = x, x > T
\]

\[
= 0, x \leq T
\]

Where \(A_i(t)\) is the activation of word \(i\) at time \(t\), \(A_i(t-1)\) is the activation of word \(i\) at time \(t-1\), \(A_j(t-1)\) is the activation of a potential inhibiting word \(j\) at time \(t-1\), \(I_i(t)\) is a value representing the match between the acoustic input and the representation of word \(i\) at time \(t\), and \(w_{ij}\) is the weight from word \(i\) to word \(j\)\(^{49}\). This equation was implemented in a simple model that takes “phonemes” (represented as 1s and 0s) as input, and represents words as strings of these phonemes. Each phoneme of the input (i.e., each 1 or 0) either unambiguously matches (1) or fails to match (0) the corresponding phoneme of a word.

This model clearly makes no pretense of being a fully specified model of lexical access (it incorporates no minimum or maximum levels of activation, there is no decay parameter, it makes no attempt to account for frequency, there is no accounting for graded activation within a phonetic category, it assumes that the input’s position is known, etc). Instead the goal is merely

\(^{48}\)This equation uses a threshold function in the interest of simplicity. However, the pattern of results should be the same if a similar non-linear function was used instead of a threshold.

\(^{49}\)All weights were set to .5 in this equation, but in a more realistic model of lexical access the weights between words would likely depend on a number of factors, including how similar words are to each other and their frequencies.
to assess whether the account put forth to explain the patterns of competition exhibited by Broca’s and Wernicke’s aphasics could in fact stem from abnormal baseline levels of lexical activation (at $t = 0$, i.e., before any input). In order to test this account, the baseline levels of activation were changed, with a reduced baseline used for the Broca’s aphasics, and an increased baseline for the Wernicke’s aphasics, such that:

$$A_i(t = 0) = 0, \text{ normals}$$

$$< 0, \text{ Broca’s}$$

$$> 0, \text{ Wernicke’s}$$

These choices were inspired by McNellis and Blumstein (2001) who used a self-organizing connectionist architecture to create a more sophisticated model of how sound structure contacts the lexicon. Their model simulated the effects that phonological and phonetic variation in the prime word would have on the activation of a target word over time. With their model, McNellis and Blumstein were able to successfully simulate how semantic facilitation changed in normal subjects in response to primes that were altered phonologically (Milberg et al., 1988) or phonetically (Andruski et al., 1994).

Furthermore, when they changed the value of just one parameter, (making the “lexical resting state” lower than normal for Broca’s aphasics and higher than normal for Wernicke’s aphasics) their model also successfully simulated semantic priming effects exhibited by Broca’s and Wernicke’s aphasics in response to phonologically (Milberg et al., 1988) and phonetically (Utman et al., 2001) altered primes. Unfortunately it was not possible to use McNellis & Blumstein’s model to test the validity and internal consistency of our account because their model only considers the period after the offset of the acoustic input. That is, it makes predictions about how a word’s activation will evolve over time in response to the overall match between the acoustic input and the word’s representation in the presence or absence of competitors; it does not provide a way to assess a word’s activation as it unfolds. It seems likely, however, that it would be possible to incorporate into their model a method of estimating how a word’s activation would change as the acoustic input unfolds.

**Figure 31** graphs the model’s output for the target, the onset and rhyme competitors and an unrelated word over time. The top panel shows the output for normal subjects, the middle panel shows the output for Broca’s aphasics, and the bottom panel shows the output for Wernicke’s
Figure 31.
The model’s output for a toy lexicon that includes a “target” (e.g., santa), an “onset competitor” (e.g., sandal), a “rhyme competitor” (e.g., candle), and an “unrelated” word (e.g., turkey). Top panel (normals) displays the output with a neutral starting level, middle panel (Broca’s) a reduced starting level, and bottom panel (Wernicke’s) an increased starting level. The inhibition threshold is set to 2, while the hypothetical threshold for making eye movements is set to 1.
aphasics. The inhibition threshold is set to 2, and the threshold for making eye movements is set to 1. As the figure illustrates, the model’s output is consistent with most of the qualitative patterns that emerged in Experiments 4 and 5. For onset competitors, Broca’s aphasics have less activity above a hypothetical eye-movement “threshold” (above the dotted line in 2 time-slices) than normals (3 time-slices) and Wernicke’s aphasics have more (4 time-slices), while for rhyme competitors, Broca’s aphasics have more activity above the hypothetical eye-movement threshold (2 time-slices) than normals (1 time-slice) and Wernicke’s aphasics (1 time-slice).

Although the model does not incorporate a means of making predictions about semantic activation, it may be reasonable to assume that in a word recognition task in which the meanings of the words are known, the activation of a word’s semantic representation is proportional to the activation of its phonological form. Since (in the current task) semantically related words should only become active via the uttered word’s activation, the activation of semantically related words should likewise be proportional to the activation of the word itself. Under these assumptions, the activation of the target can be taken as an indication of the activation of the related item, and the activation of the onset competitor can be taken as an indication of the activation of the semantic onset competitor.

Since the model predicts that for normals, the target is more active than it is for Broca’s aphasics, Broca’s aphasics’ results in Experiment 6 are not consistent with the model’s output. However, we have argued that in addition to reduced activation, additional factors (i.e., compensation or a selection deficit) may have an effect on the activation of semantically related items for Broca’s aphasics. These factors could account for the larger than predicted activation of semantically related items for Broca’s aphasics in Experiment 6. Under the interpretation that the semantic errors made by Wernicke’s aphasics in Experiment 6 indicate that the related item was unusually active, the model’s output is consistent with the rest of the results of Experiment 6 since it displays a more highly active target for Wernicke’s aphasics than for normals. Furthermore, assuming that the onset competitor’s activation indicates the activation of the semantic onset competitor, Experiment 7’s semantic onset competitor results are also consistent with the model’s output, since they parallel Experiment 4’s onset competitor results. Since the model’s output is qualitatively consistent with the patterns of data obtained in Experiments 4, 5, and 7 for onset, rhyme and semantic onset competitors, and is arguably consistent with the Wernicke’s aphasics’ semantic effect in Experiment 6, the simulation confirms that the patterns of data observed in these experiments are compatible with Broca’s aphasics having reduced activation and Wernicke’s aphasics having increased activation.

A recent study that used an artificial lexicon to study the time course of spoken word learning (Magnuson, Tanenhaus, Aslin & Dahan, 2003) also suggests that the onset and rhyme
competitor effects obtained in Experiments 4 and 5 for Broca’s and Wernicke’s aphasics may be related to the degree to which the target words are activated. This study used a paradigm almost identical to the one used in the current experiments except that participants were learning to associate novel CVCV words (e.g., pibu, dibu, dibo) with various geometric shapes. (Both onset and rhyme competitors shared three phonemes with the target. However, long vowels were used and the rhyme competitor and the target had two vowels in common, whereas the onset competitor and the target shared only one vowel. As a result, in this study, as in the current one, rhyme competitors shared more acoustic input with the target than onset competitors.) It was found that subjects displayed larger rhyme competitor effects early in the course of learning than they did later on. Magnuson et al. suggest that one way to account for rhyme effects that are larger early in learning would be to suppose that early in learning, words’ representations are weak. Consequently, even after hearing an entire word, that word may not be activated strongly enough to inhibit competitors that have significant overall similarity with it. This may be true, even if the competitors mismatch the input at onset. Thus, early in learning, rhyme competitors can become active. Later in learning, however, as words’ representations become stronger, hearing just the onset of a word can activate it strongly enough for it to inhibit words that mismatch at onset (e.g., rhyme competitors).

In an effort to determine whether the decrease in rhyme competition that they observed with learning could be captured by a learning-based model, Magnuson et al. (2003) modeled the behavioral effects they obtained using a simple recurrent network (SRN), and observed the network’s performance throughout training. Vowels were represented over a longer time period than consonants to approximate their acoustic differences. Early in the SRN’s training, rhyme competitors appeared to compete strongly with targets, but onset competitors did not. Interestingly, human learners also appeared to exhibit a slightly smaller onset competitor effect early vs. late in training (though this difference was far from statistically significant). Thus, the competitor effects exhibited by the SRN early in training, when lexical representations are weak, are similar to the small onset and large rhyme competitor effects exhibited by Broca’s aphasics.

As training continued and representations were better learned, targets became active more quickly, the rhyme competitor effect diminished and the onset competitor effect grew larger. At this point, both the onset and rhyme effects appeared similar to those exhibited by the young and old normals in Experiments 4 and 5. After further training, however, as representations became even stronger, the rhyme competitor effect continued to decrease and the onset competitor effect continued to increase. This pattern parallels the large onset and small rhyme competitor effects exhibited by the Wernicke’s aphasics in Experiments 4 and 5.
Thus, Magnuson et al.’s (2003) data and simulations suggest that the small onset and large rhyme competitor effects obtained for Broca’s aphasics in Experiments 4 and 5 are consistent with weak lexical representations, and that the large onset and small rhyme competitor effects obtained for the Wernicke’s aphasics in Experiments 4 and 5 are consistent with strong lexical representations. The SRN, similar to the model presented above, does not incorporate any means of making predictions about semantic activation. However, as argued above, if it is assumed that a word’s semantic representation is proportional to the activation of its phonological form, then the SRN’s output appears to be qualitatively consistent with the patterns of data obtained not only in Experiments 4 and 5, but also 7, and is also consistent with the results for Wernicke’s aphasics in Experiment 6 (when errors are included).

These models verify that the argument provided above to explain why in some instances (e.g., for rhyme competitors) reduced activation results in competitor effects while increased activation does not, is at least internally consistent. They also confirm that the results of Experiments 4-7 are compatible with the reduced/increased activation hypothesis. Furthermore, in both of these models, inhibition plays an important role in moderating the activation of lexical candidates. For example, in both our model with a “normal” baseline and in the SRN with well-learned but not over-learned representations, inhibition prevented rhyme competitors from becoming as active as the input alone would have warranted. One could speculate that in a properly functioning system, rhyme competitors become just active enough that they are still easily accessible if it turns out that the onset of the word was misheard, but not so active that they interfere with recognition of the target. The atypical patterns of activation and deactivation that emerge in aphasics patients, apparently in part because inhibition is unable to operate normally (since abnormal levels of activation affect when a lexical item becomes active enough to successfully inhibit competitors), suggest that lateral inhibition may also help maintain the delicate balance between activation and deactivation that is evident in normal subjects. This balance is vividly illustrated in the very brief activation of semantic onset and semantic rhyme competitors that was revealed in Experiments 2 and 3. If lateral inhibition is necessary to explain how it is that we are able to quickly and accurately settle on the correct word despite the partial activation of so many candidates, then this should constrain the structure of models of spoken word recognition.

Most implemented models of spoken word recognition do incorporate inhibition (e.g., McClelland & Elman’s 1986 TRACE model; Norris’ 1994 Shortlist model; and Luce et al.’s 2000 PARSYN model; but c.f. Gaskell & Marslen-Wilson’s 1997 distributed Cohort model).
CONCLUSIONS

The first part of this dissertation showed that during spoken word recognition, words semantically related to both the intended word and of onset and rhyme competitors of the intended word can become active enough to capture visual attention. It was argued that the time course of these effects helps to explain why results from the form priming paradigm and the cross-modal semantic priming paradigm differed with respect to whether onset and rhyme competitors become active. The time course of these effects (specifically their brevity), may also reveal why we are not consciously aware that we ever activate the meanings of unintended candidates.

The second part of this dissertation used eye movements to explore the time course of spoken word recognition in Broca’s and Wernicke’s aphasia, with the goals of better understanding the disorders themselves, and gaining insight into what is required for a spoken word recognition system to function properly. We first showed that Wernicke’s aphasics appear to be more sensitive to competition from words with the same onset as the uttered word than are normals or Broca’s aphasics. Then we demonstrated that Broca’s aphasics, like normals (but not Wernicke’s aphasics), experience competition from words that rhyme with the uttered word. Next we showed that like normals, both Broca’s and Wernicke’s aphasics experience competition from items semantically related to the uttered word. Finally we demonstrated that Wernicke’s aphasics appear to be more sensitive to competition from words semantically related to an onset competitor of the target than are normals and Broca’s aphasics.

These data are consistent with the hypothesis that the lexical processing deficits of Broca’s aphasics are due to reduced lexical activation, and that those of Wernicke’s aphasics are due to increased lexical activation. Using a simple equation to model how a word’s lexical activation might change over time in response to unfolding acoustic input, we demonstrated that by changing only the baseline levels of lexical activation (lowering the baseline for Broca’s and increasing the baseline for Wernicke’s aphasics), a version of the reduced/increased activation hypothesis that incorporates lateral inhibition can account for both groups of aphasics’ data.

Finally, we speculated that since the aphasics’ results imply that lateral inhibition plays a significant role in activating and deactivating lexical candidates, it may also help explain how it is that we are (usually) able to quickly and accurately settle on the correct word despite the partial activation of not only phonological but also semantic information about numerous other candidates. If true, this suggests that inhibition is a critical component of spoken word recognition.
REFERENCES


## APPENDICES

### APPENDIX A.

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(Unpictured onset competitor in parentheses)

*ghost and money were exchanged because they would have been related to the (new) target in their original positions.

**couch was replaced with chocolate because couch would have been related to the (new) target.
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(Unpictured rhyme competitor in parentheses)
### APPENDIX D.

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