Is Speech Recognition Automatic?

Lexical Competition, but not Initial Lexical Access, Requires Cognitive Resources

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Abstract

Current models of spoken word recognition suggest that multiple lexical candidates are activated in parallel upon hearing an utterance, with these lexical hypotheses competing with each other for recognition. The current project investigated the effect of cognitive load on initial lexical access and later lexical competition. In a set of priming studies, the lexicality of the primes (i.e., non-word vs. word) was manipulated to dissociate these two sub-processes. We tested performance on a semantic association task under conditions with no additional load, or with cognitive load that used cognitive resources that are either general or more specific to phonological processing. The results suggest that the initial access of lexical items is relatively automatic. In contrast, maintaining lexical candidates in competition requires cognitive resources, and these resources are specific to phonological processing. The overall result pattern provides insights into differences in the way that lexical activation and competition operate.

Keywords: speech recognition; lexical access; lexical competition; cognitive load; cognitive resources

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Understanding spoken language is one of the most fundamental cognitive skills human beings have. Speakers first formulate semantic information they would like to express, select proper lexical items, activate the phonological information for these items, and use the motor system to articulate sounds. Listeners map the acoustic-phonetic waveform of the unfolding speech signal to the lexical representations stored in long-term memory, find the right item in long-term memory, activate its semantic representation, and understand a spoken word. For normal adults, speech recognition is fast and seems effortless, but the underlying mechanism is complex. A critical question is whether speech recognition is as automatic as we subjectively feel. In the current study, we compare speech recognition under optimal vs. more difficult conditions to test which sub-processes during speech recognition really do operate relatively automatically, and which require cognitive resources.

Lexical Access and Competition

Decades of research have been devoted to the question of how spoken words are recognized with such remarkable efficiency. Most current models of spoken word recognition (Cohort: Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994) agree that when speech comes in, the signal first makes contact with sub-lexical representations, such as acoustic-phonetic features or phonemes. The processing at the sub-lexical level provides input codes for accessing lexical entries, where the form (e.g., abstract phonological information, morphological information), syntactic role, and semantic information of words are stored. Although different models make different claims about the dynamic properties of speech processing, there is a consensus that upon hearing the first few segments of an unfolding speech signal, multiple lexical entries are activated automatically in parallel if their phonological representations transiently match the incoming signal. This initial lexical access is thought to occur as early as the first 100-150 ms of a speech signal, and to occur obligatorily. The bottom-up activation of a lexical candidate depends merely on the goodness-of-fit between the speech signal and the phonological representation of the candidate.

There have been a large number of studies supporting rapid initial access of multiple lexical candidates. Various tasks have been used, including gating (e.g., Grosjean, 1980), shadowing (e.g., Marslen-Wilson, 1973), perceptual identification (e.g., Slowiaczek, Nusbaum, & Pisoni, 1987), lexical decision (e.g., Goldinger, Luce, Pisoni, & Marcario, 1992; Zwitserlood,1989), word spotting (e.g., McQueen, Norris, & Cutler, 1994), eye-tracking (e.g., Allopenna, Magnuson, & Tanenhaus, 1998), and ERPs (e.g., Friedrich, Felder, Lahiri, & Eulitz, 2013). There is also substantial evidence that multiple lexical access occurs obligatorily, regardless of contextual constraints. For instance, even when the semantic or syntactic context favors only one of the lexical hypotheses, all possible candidates are activated before the uniqueness point of a spoken word is heard (e.g., Dahan & Tanenhaus, 2004; Zwitserlood, 1989). Similarly, all possible meanings of a polysemous word and all possible interpretations of a homophone or ambiguous-sounding word are activated at the beginning of the speech, independent of the context (e.g., Connine, Blasko, & Wang, 1994; Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979).

The literature on visual word recognition provides additional evidence that mapping sensory information onto lexical representations occurs automatically, without intention and awareness (see Neely, 1991 for a review). For instance, words are activated to the level of meaning even when participants are instructed to ignore them (e.g., Fuentes, Carmona, Agis, &

Catena, 1994), when participants' attention is allocated to lower-level information rather than the meaning of the words (e.g., letters: Valdés, Catena, & Marí-Beffa, 2005; ink color: MacLeod, 1991, 1992; Stroop, 1935), and even when participants are not consciously aware of the presence of the words (e.g., Marcel, 1983). These results indicate that initial lexical access based on bottom-up activation functions in a relatively automatic way and may not require much attentional control.

According to current models of spoken word recognition (Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987; McClelland & Elman, 1986; Norris, 1994), once multiple lexical hypotheses are generated by the speech signal, a competition mechanism is necessary for the selection of the best candidate to be recognized. One type of competition depends on the degree of match or mismatch between the bottom-up signal and the phonological representations of lexical candidates. The Cohort model (Marslen-Wilson, 1987; Marslen-Wilson, Moss, & Van Halen, 1996) assumes that the activation level of a candidate is reduced when the unfolding speech input is no longer consistent with it. For instance, although for Dutch listeners, both "kapitein" and "kapitaal" are activated upon hearing "kapit", once the vowel after "t" is heard, responses to a probe associated with the other candidate are no longer facilitated (Zwitserlood,1989). However, this does not mean that the mismatching candidate is completely eliminated from the candidate set or is excluded from future processing. Dahan and Gaskell (2007) found that although fixations to a cohort competitor decreased after the recognition point of the target word, they were still greater than those to unrelated distracters. In addition, studies of embedded words have also shown robust priming for the embedded words (e.g., "cap" within "captain") at the offset of (Isel & Bacri, 1999; Luce & Cluff, 1998; Vroomen & de Gelder, 1997), 100 ms after (Macizo, van Petten, & O'Rourke, 2012), and 500 ms after the carrier words (Zhang

& Samuel, 2015), suggesting an extended time window of activation (Dahan & Gaskell, 2007; Friedrich, Felder, Lahiri, & Eulitz, 2013; Marslen-Wilson & Welsh, 1978).

Another type of competition comes from co-activated lexical candidates. The TRACE model (McClelland & Elman, 1986) assumes that activated candidates compete directly with each other via lateral inhibition. All activated candidates inhibit each other as a function of their bottom-up activation level, which depends on their similarity to the speech signal. At any time during perception, the activation level of a candidate is determined by the bottom-up activation received from the speech input and the lateral inhibition received from other activated candidates. The candidate that is most similar to the speech signal usually has the strongest activation and sends out the strongest inhibition to other candidates, and therefore will win the competition. Furthermore, short words usually have a disadvantage over long words because short words receive less bottom-up support from the speech input than longer words, and they receive more competition from similar sounding words (Bowers, Davis, Mattys, Damian, & Hanley, 2009).

No studies have explicitly examined whether lexical competition is as automatic as initial lexical access. However, some studies have suggested that distinguishing among lexical candidates and inhibiting inappropriate ones may take more time than activating those candidates (e.g., Marslen-Wilson, 1987; Swinney, 1979) and may be relatively costly in terms of processing resources (e.g., Connine, Blasko, & Wang, 1994). Moreover, research on language deficits has also indicated that processes such as inhibition might be more likely to vary between individuals than activation (e.g., McMurray, Samelson, Lee, & Tomblin, 2010). Across the different views of lexical competition, a common feature is the need to maintain the competing candidates themselves during the competition, which itself may be resource-dependent.

Collectively, the available evidence suggests that initial lexical access and later lexical competition -- two sub-processes involved in speech recognition -- may have different requirements for cognitive resources and attentional control. However, as noted, there has not been explicit investigation of the automaticity of lexical access versus competition. The current study addresses this issue by comparing initial lexical access and later lexical competition under both optimal and more complicated conditions. In the latter, cognitive resources were depleted by secondary cognitive load tasks.

Effect of Cognitive Load on Speech Processing

There has been a recent growth in work focusing on speech perception under more complicated situations. For instance, studies have examined speech perception under perceptual load due to background noise or changed speaking rates, or under cognitive load imposed by secondary tasks (see Mattys, Davis, Bradlow, & Scott, 2012 for a review). Cognitive load research has shown that speech is sometimes processed in the same way under optimal conditions as under cognitive load, while sometimes not, implying that some processes during speech perception depend on the availability of cognitive resources more than others. For instance, the speech system is able to adjust to atypical pronunciations (Eisner & McQueen, 2005, 2006; Kraljic & Samuel, 2005, 2006; McQueen, Norris, & Cutler, 2006; McQueen, Cutler, & Norris, 2006; Norris, McQueen, & Cutler, 2003) and to perceptually restore missing phonemes (Samuel, 1981, 1996; Warren, 1970) under optimal conditions, and these abilities remain almost intact under cognitive load conditions (Mattys, Barden, & Samuel, 2014; Zhang & Samuel, 2014). However, for speech segmentation, listeners' reliance on fine-grained acoustic detail is attenuated under cognitive load (Mattys, Brooks, & Cooke, 2009; Mattys, Carroll, Li, & Chan, 2010).

In addition, previous studies have found that under optimal conditions, carrier words are able to prime words that are associated with words embedded in them (Bowers, et al., 2009; Salverda, Dahan, & McQueen, 2003; van Alphen & van Berkum, 2010; Zhang & Samuel, 2015). However, when a cognitive load task is added, the carrier words (e.g., "napkin") no longer prime the associations (e.g., "sleep") of embedded words (e.g., "nap"), whereas the isolated embedded words (i.e., "nap") are still able to produce significant associative priming (Zhang & Samuel, 2015). These results indicate that cognitive load does not prevent the speech input from activating the meaning of a candidate, if its phonological representation perfectly matches the speech. The null effect for embedded words when hearing carrier words under cognitive load suggests that the consideration of lexical candidates that do not strongly match the speech is resource-dependent.

There are two possible explanations for this pattern. One is that cognitive load prevents alternative candidates from being accessed in the first place, which would occur if the initial lexical access based on bottom-up activation requires cognitive resources. Under optimal conditions, when there is no cognitive load, all possible candidates that match the speech signal to some degree can be activated at the same time. Although there is competition from the inconsistent bottom-up signal and/or from other candidates, the residual activation of some alternative candidates is still strong enough to be observed at the end of the speech input. In contrast, when processing demand increases, e.g., when listeners are working on a concurrent task, the speech system may not have enough cognitive capacity to activate multiple candidates as it does under optimal conditions. An alternative hypothesis is that all potential candidates are still activated under cognitive load, but their ability to compete with the strongest candidate (normally, the correct item) is limited. This would implicate a relatively automatic process of lexical access but a more resource-demanding process for competition.

The Current Study

The current study includes priming experiments designed to explore the effect of cognitive load on speech recognition. Our primary question is whether cognitive load impairs initial lexical access, lexical competition, both, or neither. If either of these sub-processes is constrained by cognitive load, the experiments allow us to test whether the load effect specifically involves phonological processing, or if instead more general cognitive resources are the limiting factor.

To address the primary question, we used non-word and word primes to tease apart the processes of lexical access and lexical competition. According to most (but not all) models of spoken word recognition, words are represented as localist units in long-term memory (cf. Page, 2000; for an alternative view see Gaskell and Marslen-Wilson, 1997; 1999). However, non-words do not have such representations in memory (Vitevitch & Luce, 1998). When a word prime is heard, it leads to access of the lexical entries of both itself and alternative candidates that sound similar to it. The activated representation of the prime itself competes with the representations of alternative candidates. In contrast, when a non-word prime is heard, although it also leads to the access of candidates that are partially consistent with it, there is no way for the non-word prime itself to compete with these alternative candidates directly at the lexical level (Shtyrov, Kujala, Pulvermuller, 2009; Vitevitch & Luce, 1998).

Of course, the non-word primes do not provide a pure index of lexical access, and word primes do not provide a pure index of lexical competition; it is a matter of degree. As shown by Zhang and Samuel (2015), the activation of an embedded word is eliminated under load only when the word is an alternative candidate (i.e., when presented within a carrier word – “nap” within “napkin”) but not when it is a full match to the input (i.e., when presented in isolation – “nap”). Thus, as noted, cognitive load may either impair the initial access of alternative candidates or impair their ability to compete at the lexical level with a fully-matching candidate. By manipulating the prime’s lexicality we can tease apart these two hypotheses. If cognitive load impairs initial access of alternative candidates, this should be true for both non-word and real word primes. In contrast, if cognitive load impairs only lexical competition (i.e., the ability of partially matched alternative candidates to compete with the fully-matching one), a non-word prime should be able to activate the target because there is no fully-matching lexical candidate to dominate the competition.

An additional question the current project aims to investigate is whether any of the sub-processes of speech recognition require cognitive resources that are specific to speech processing. To examine this question, two different types of cognitive load tasks were imposed. The participants needed to encode either (a) unnamable non-alphabetical (i.e., Chinese) characters or (b) a list of four letters, and to recognize them after performing a primary task. Since the participants were all native English speakers who did not know Chinese, they were unable to rehearse the Chinese characters as they could rehearse the letters. Although it is possible that a few participants might name a few characters (as symbols a character might look like), the character recognition task should mostly impose a non-phonological load and require speech-irrelevant resources. In contrast, because the participants had to rehearse the letters in order to keep them in mind, the letter recognition task should impose a phonological load and require cognitive resources that are primarily speech-related. If a speech recognition sub-process requires general cognitive resources, performance on the primary task should be impaired by both cognitive load tasks. However, if resources that are specific to speech are needed, the primary task should be impaired only by the letter recognition task.

The core of the current study includes three pairs of experiments. The first pair did not include a load task, while the second pair (non-phonological load), and third pair (phonological load) did impose cognitive loads. The two experiments within each pair used non-words and real words as primes, respectively, to provide a direct comparison between lexical access and lexical competition. Specifically, Experiments 1 and 2 were baseline experiments, in which only a primary task was tested, with no additional load task. Non-word primes were used in Experiment 1, while word primes were used in Experiment 2. The same sets of stimuli were used in the next two pairs of studies. In Experiments 3 and 4, a character recognition task was added to impose a non-phonological load. In Experiments 5 and 6, a letter recognition task was added to the primary task to impose a phonological load. If cognitive load affects only lexical access, the two experiments within each pair should show similar patterns under each type of cognitive load. If cognitive load instead affects lexical competition, only the experiments using word primes would show impairment under cognitive load. If cognitive load affects both, then we should see impairment in both experiments of each pair under cognitive load, but this effect should be more robust in the experiments using word primes. If any of the sub-processes requires cognitive resources that are specific to phonological processing, only the experiments under the phonological load condition should show impairment.

In addition to this core set of six experiments, we conducted two additional experiments. To make sure that the two cognitive load tasks had a similar level of difficulty and had a similar influence on a primary task, we conducted a preliminary study to compare participants' performance on these two load tasks while doing a lexical decision task. To follow up the core experiments, we ran a final study to provide a within-subject test of the difference between phonological and non-phonological loads (Experiment 7).

Preliminary Study

Method

Participants

Twenty-two undergraduate students from Stony Brook University participated in the Preliminary Study. All participants were native English speakers and were 18 years of age or older. They received research credit for their participation. None of them were tested in any of the following experiments.

Materials and Procedure

The primary task was auditory lexical decision, with 108 word-word pairs and 108 word-non-word pairs as stimuli. They were recorded by a speaker of American English in a sound shielded booth and were stored on a PC, sampled at 44 kHz. Each stimulus was isolated using Goldwave sound editing software and was saved as its own file.

For the primary task, participants listened to these stimulus pairs over headphones. Before each pair, a fixation cross was displayed at the center of a screen for 500 ms. Then, the participants heard a prime followed by an auditory target after a 300 ms inter stimulus interval (ISI) and decided whether the second member of each pair was a real English word or not as quickly and as accurately as possible. The next trial began 1000ms after the response. If the participant failed to respond within 3000ms, the next trial began.

To impose a Non-Phonological Load, a character recognition task was added to the primary task. The participants were asked to maintain a Chinese character in mind before hearing each word pair, and to judge whether a character presented after the word pair matched the initial character. One-hundred and twelve Uni-structure Chinese characters that have 3 to 5 strokes were selected for this load task (see Table 1 for stimulus samples of the Chinese characters). Since none of the participants knew Chinese, they were unable to name the characters. On each trial, a fixation cross was presented at the center of a screen for 500 ms, followed by a Chinese character at the same location for 2000 ms. The participants were asked to keep this symbol in mind during the trial. After the character disappeared, the participants heard a pair of spoken items with a 300 ms ISI and made a lexical decision on the second item. After they had responded, or if they failed to respond within 3000ms, a Chinese character was presented at the center of the screen. The participants were asked to decide whether the second character was the same as the first one. The next trial began 1000ms after the response. If the participant failed to respond within 3000ms, the next trial began.

Table 1

Stimulus samples for Chinese characters used in the Preliminary Study (with number of strokes in parentheses; these numbers were not shown to the subjects). The same set of Chinese characters was used in Experiments 3 and 4.

Same Trials		**Different Trials**	
First Character	**Second Character**	**First Character**	**Second Character**
丏 (4)	丏 (4)	开 (4)	干 (3)
五 (4)	五 (4)	无 (4)	云 (4)
车 (4)	车 (4)	犬 (4)	太 (4)

牙 (4)	牙 (4)	升 (4)	夭 (4)
少 (4)	少 (4)	午 (4)	矢 (5)

To impose a Phonological Load, a letter recognition task was added to the primary task. The participants were required to maintain four consonants in mind before hearing each word pair, and to judge whether a consonant presented after the word pair was from the set of four. The presentation method for the letter recognition task was the same as the character recognition task, except that four upper-case consonants were presented at the beginning of each trial, following the fixation cross. The strings were chosen so that they were unable to be pronounced as pseudowords. The letters R and L were never used since they could potentially be pronounced as vowels, making the letter strings pronounceable. The participants were asked to keep the consonants in mind during the trial. After the lexical decision response was made, a single upper-case consonant was presented. The participants were asked to decide whether this letter had been presented in the string they saw at the beginning of the trial.

Up to three participants were tested at the same time in a sound shielded booth. One third of the stimulus pairs were presented in the no-load condition, in which participants only did the primary task. One third of the stimuli were presented with the character recognition load, and the rest were presented with the letter recognition load. The trials were blocked across these three conditions. The stimuli were counterbalanced across conditions, and the order of the three conditions was counterbalanced across participants.

Results and Discussion

Analyses of Variance (ANOVA) were conducted on the reaction times and accuracies on the primary task under the three different load conditions, as well as on performance on the two cognitive load tasks. For the primary task, the accuracies were essentially identical across the three conditions (with the accuracies all being 0.92), $F < 1$. There was a significant effect of load condition on reaction times for the primary task (see Figure 1), $F(2, 42) = 8.59$, $p = .001$, partial $\eta^2 = .290$. The participants responded faster under the no-load condition (M = 924 ms, SD = 107, 95% CI = [876, 971]) than with the character recognition load task (M = 1011 ms, SD = 199, 95% CI = [923, 1099]) ($p = .032$), and the letter recognition load (M = 1033 ms, SD = 176, 95% CI = [955, 1111]) ($p = .003$), indicating that both types of cognitive load tasks affected performance on the primary task. Furthermore, the reaction times for the primary task under the two load conditions did not differ ($p = .998$), suggesting that the impact of the two cognitive load tasks on the primary task was comparable.

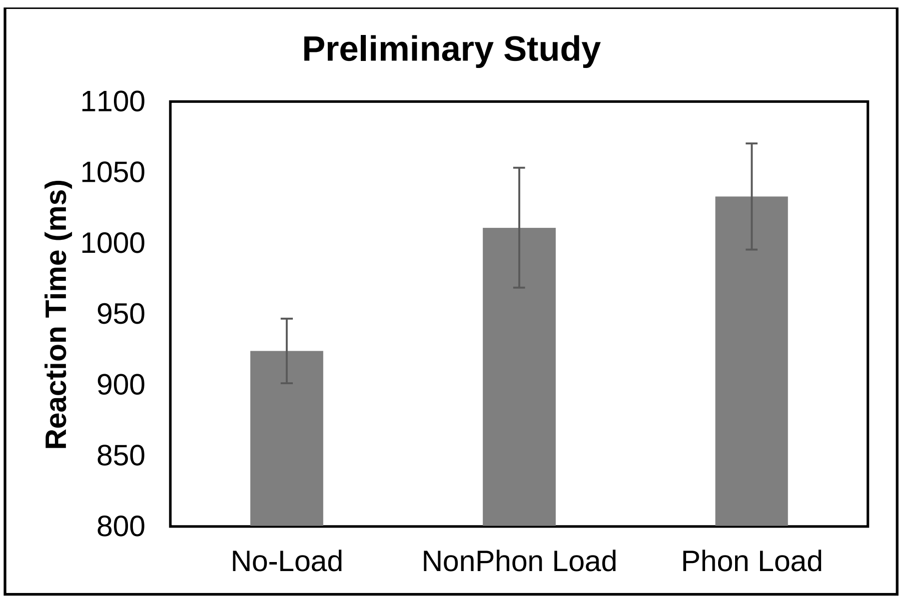

Figure 1. Reaction times on the lexical decision task under no-load, non-phonological load and phonological load conditions. The error bars represent the standard errors.

For the cognitive load tasks themselves, there was no significant difference in accuracy between the character recognition task (M = 0.90, SD = 0.07, 95% CI = [0.86, 0.93])) and the letter recognition task (*M* = 0.89, *SD* = 0.10, 95% CI = [0.85, 0.94], *t*(21) = -0.04, *p* = .966, suggesting that the two cognitive load tasks had similar levels of difficulty. The average reaction time on the letter recognition task (*M* = 842 ms, *SD* = 154, 95% CI = [773, 910]) was longer than that on the character recognition task (*M* = 776 ms, *SD* = 172, 95% CI = [700, 852]), *t*(21) = 2.70, *p* = .013. This difference does not necessarily mean that keeping four letters in mind is more difficult than keeping one Chinese character in mind. The reaction time difference is likely to be a result of a difference in the decision stages of the two load tasks. Specifically, making a letter recognition decision will typically require a serial search since there were four possible correct answers, whereas making a character recognition decision does not rely on such a serial process.

Overall, the results of the Preliminary Study demonstrate that the two cognitive load tasks have a similar level of difficulty, and critically, that they have a similar impact on the primary task. Therefore, they were used in the main experiments to impose either a primarily phonological or a primarily non-phonological cognitive load.

Main Experiments

Three pairs of experiments examined priming under No-Load (Experiments 1 and 2), Non-Phonological Load (Experiments 3 and 4), and Phonological Load (Experiments 5 and 6) conditions. The first experiment of each pair used Non-Word primes, while the second one used Word primes.

For the Non-Word priming test, each target word (e.g., **accent**) was preceded by three types of related Non-Word primes. One prime type was created by deleting the last one or two phonemes of the target (<u>Deletion</u>, e.g., *accen_*), the second type was created by replacing the last or the last two phonemes of the target (<u>Replacement</u>, e.g., *accen<u>d</u>*), and the third type was made by appending one phoneme to the target (Addition, e.g., *accenty*). Note that both Deletion and Replacement primes provided most of the phonological information of their targets, but there was no inconsistent phoneme in the Deletion primes. In contrast, the Addition primes contained all the phonemes of their targets, but also included extra signal.

For the Word priming test, target words were preceded by three types of Word primes. The construction of the primes in this set followed the same general principles as in the first set. For the first type, each prime (e.g., *nap*_ _ _) was an initial Embedded word of its target (e.g., **napkin**). For the second type, each prime (e.g., *access*) was a Cohort member of its target (e.g., **accent)**. For the last type, each prime (e.g., *fancy*) was a Carrier word of its target (e.g., **fan).** As in the first set of stimuli, both the Embedded and Cohort primes provided part of the phonological information of their targets, but there was no mismatch in the Embedded word primes. As in the Non-Word Addition primes, the Carrier word primes contained all the phonemes of their targets, but included inconsistent signal as well.

Although these overall parallels were imposed across the Non-Word and Word primes, there were also differences across the two sets. In particular, the targets for the Word primes were different across different prime types whereas a single target was kept constant within each Non-Word set. The elegance of the Non-Word design is not possible for the real Word primes because of the lack of English words that can have bits deleted, replaced, and added and still yield real words.

As noted above, the Non-Word primes (e.g., *accen*) were used to index the lexical access of a similar-sounding lexical target (e.g., **accent**) without direct lexical competition from the prime since it does not have a lexical representation. The Word primes (e.g., *access*) were used to index both the access of a similar-sounding target (e.g., **accent**) and competition with the prime. In both cases, there might also be phonological competition or lexical competition from other potential candidates, but any such additional competition should not vary systematically across the two cases. The difference between the two sets of stimuli allows us to tease apart the initial lexical access of the target and subsequent lexical competition between the target and the prime.

On each trial, participants listened to either a Non-Word prime or a Word prime, followed by an auditory target. Their primary task was a semantic association decision on a visual probe that was presented at the same time as the (auditory) target – they made a Yes-No choice as to whether the target word they heard was semantically related to the visual probe they saw. The association task was used to index processing of the semantic representation of the target, after hearing the prime. The rationale is that if the semantic representation of a target is supported by hearing a prime, there should be priming for the association response (i.e., semantic priming). We manipulated the proportion of the related trials and varied how the prime-target relationship mapped to the participants' responses in order to minimize expectancy-based strategies. Under these conditions, a priming effect on the association task for Non-Word primes should reflect the initial access of targets that support the bottom-up activation of their semantic representations, without direct lexical competition from the primes. In contrast, a priming effect for Word primes should reflect the activation of semantic representations of the targets as a result of the dynamic interaction between bottom-up activation and lexical competition.

In sum, the six experiments allow us to examine priming as a function of prime-target similarity (within-subject), prime lexicality (between-experiment), and cognitive load (between-experiment). Our design decisions for the primary task, prime lexicality, and load were based on the number of English words that match the requirements of our tests.

Experiments 1 and 2: No-Load

Methods

Participants

Each experiment recruited 27 undergraduate students from Stony Brook University. All participants were native English speakers and were 18 years of age or older. Each participant took part in only one experiment, and received research credit for participation.

Materials

Experiment 1. Seventy-two bi-syllabic English words were chosen as critical targets, and each target was paired with three types of Related primes and an Unrelated prime. Table 2 provides examples of the critical stimuli used in the primary task in Experiment 1.

Table 2

Stimulus sample for each type of Non-Word prime used in the primary task in Experiments 1, 3, and 5. Primes and targets were presented auditorily, whereas associated probes were presented visually.

Prime Type	Non-Word Prime	Target	Associated Probe
Deletion	*accen_*	**accent**	LANGUAGE
Replacement	*accend*	**accent**	LANGUAGE
Addition	*accenty*	**accent**	LANGUAGE
Unrelated	*bencil*	**accent**	LANGUAGE

Primes with a Deletion were created by deleting the last phoneme of each target. If the target ended with /ju/, /ən/, /əm/, or /əl/, the last two phonemes were deleted. Primes with a Replacement were created by replacing the last phoneme in the target; final consonants were replaced by another consonant, and final vowels were replaced by another vowel. For Addition primes, an additional phoneme was appended to the end of the target word. If the target ended with a consonant, a vowel was added. If the target ended with a vowel or with /ən/, /əm/, or /əl/, a consonant was added. Another 18 non-words were selected to be used as Unrelated primes. These primes did not share either semantic or phonological properties with their targets.

Four lists were created from the 72 target words, with each critical target preceded by one of the four types of non-word primes such that 18 pairs of critical stimuli were presented in the Deletion trials, 18 pairs were presented in the Replacement trials, 18 pairs were presented in the Addition trials, and the remaining 18 pairs were presented in the Unrelated trials. Different types of primes were counterbalanced across lists. For each critical target, a word that is associated with it was selected as the visual probe for the association decision task. Appendix A presents a full list of the critical primes, targets and probes used in Experiment 1.

In addition to the 72 critical trials, each list contained another 252 trials that were intended to dissociate "yes"-"no" responses from prime-target relatedness. There were 72 control pairs that mirrored the Deletion, Replacement, Addition and Unrelated structure of the critical stimuli, but each control target was paired with a visual word probe that was not associated with it. These control pairs resulted in "no" responses for the primary task, balancing the 72 "yes" responses for the critical trials. For an additional 180 trials (fillers), the non-word primes were unrelated to the targets. Half of the filler pairs had visual probes that were associated with the targets, leading to "yes" responses on the primary task, while the other half had unrelated visual probes, leading to “no” responses. No prime or target was presented to a given subject more than once.

All the primes and targets were recorded by a speaker of American English in a sound shielded booth and stored on a PC, sampled at 44kHz. Each stimulus was isolated using Goldwave sound editing software and saved as its own file. All of the visual probes were presented in capital letters. Ten undergraduate students who did not participate in the main experiments were asked to rate the strength of association between each target and its potential associated probe for the critical and control targets on a 4-point scale, with “1” indicating no association and “4” indicating a strong association. The average rating for the critical targets (M = 3.52, SD = 0.10, 95% CI = [3.45, 3.59]) was significantly higher than that for the control targets (M = 1.32, SD = 0.24, 95% CI = [1.15, 1.49]), $t(9) = 24.07$, $p < .001$.

Experiment 2. Experiment 2 used real Words as primes. Table 3 provides examples of the critical stimuli used in the primary task in Experiment 2. The critical stimuli included 18 Embedded-carrier word pairs, 18 Cohort word pairs, 18 Carrier-embedded word pairs and 18 Unrelated word pairs. All the Embedded words were monosyllabic, and were embedded at the beginning of the Carrier words. All the Carrier words were bi-syllabic and were stressed on the first syllable. The Cohort pairs included words that were both bi-syllabic and that shared their first syllable. The Unrelated pairs included words that matched the three Related pairs in frequency and number of syllables. Unlike Experiment 1, in which the same target word was paired with three types of Related primes and an Unrelated prime, the targets used in Experiment 2 were different across different prime types. As in Experiment 1, an associated word was selected for each critical target as the visual probe. Appendix B presents a full list of the critical primes, targets and probes used in Experiment 2.

Table 3

Stimulus sample for each type of Word prime used in the primary task in Experiments 2, 4, and 6. Primes and Targets were presented auditorily, whereas associated Probes were presented visually.

Prime Type	**Word Prime**	**Target**	**Associated Probe**
Embedded	*nap*_ _ _	**napkin**	WIPE
Cohort	*access*	**accent**	LANGUAGE
Carrier	*fancy*	**fan**	AIR
Unrelated	*collar*	**essay**	WRITE

Another 18 Embedded-carrier word pairs, 18 Cohort word pairs, 18 Carrier-embedded word pairs and 18 Unrelated word pairs were selected as control pairs. Each control target was paired with a visual word probe that is not associated with it in order to produce “no” responses. Another 180 unrelated word pairs that matched the critical stimuli in frequency and number of syllables were selected to be used as fillers. Half of the targets were paired with an associated probe, leading to “yes” responses, while the other half were paired with unrelated visual probes, leading to “no” responses.

All the primes and targets were recorded by the same speaker who produced the stimuli in the first experiment, and were edited in the same way. The same ten undergraduate students who rated the stimuli in Experiment 1 were asked rate the strength of association for each Word prime-target pair. The rating for the critical targets (M = 3.58, SD = 0.26, 95% CI = [3.39, 3.77]) was again significantly higher than that for the control targets (M = 1.22, SD = 0.11, 95% CI = [1.14, 1.30]), $t(9) = 24.39$, $p < .001$. The ratings for these Word pairs did not differ from the corresponding ratings for the Non-Word stimuli (critical targets: $t(18) = 0.68$, $p = .502$; control targets: $t(18) = 1.21$, $p = .241$) of Experiment 1.

Procedure

The procedures of the first two experiments were matched. The participants were tested only on the primary task – judging whether an auditory target was associated with a visual probe. In both experiments, the participants listened to prime-target pairs over headphones, with those in Experiment 1 receiving Non-Word primes and those in Experiment 2 receiving Word primes. Up to three participants were tested at the same time in a sound shielded booth.

Before each pair, a fixation cross was displayed at the center of a screen for 500 ms. Then, the participants heard a prime followed by an auditory target after a 300 ms inter stimulus interval (ISI). At the same time that the target started to play, a visual word was presented at the location of the fixation cross. The participants needed to decide whether the visual probe was associated with the auditory target by pressing one of two buttons (labeled "YES" and "NO") on a button board. They were asked to respond as quickly and as accurately as possible. The visual probe stayed on the screen until they had responded. The reaction time was recorded from the onset of the auditory target (which was also when the visual probe appeared). The next trial began 1000ms after the response. If the participant failed to respond within 3000ms, the next trial would begin.

Results

For each experiment, any participant who had an error rate over 30% on the primary task was not included in the analyses; two participants were eliminated in each experiment. Across the remaining participants, the average accuracies for the primary task are shown in Table 4. Because accuracy was generally high and did not vary in systematic ways, only the reaction time analyses are reported here and in the remaining experiments.

For each experiment, reaction times that were either faster or slower than 2.5 standard deviations from the mean were replaced by the cut-off values. The raw reaction times for all types of primes are shown in Table 5. For the sake of clarity, in the main text of the paper, we focus on the overall priming effects in each experiment, with reaction times collapsed across all three types of Related trials. Readers interested in detailed analyses that break the results down by the type of Related prime can find these in Appendix C.

Table 4

Average accuracies for participants on the primary and cognitive load tasks in all experiments. In Experiments 1, 3, and 5, the participants received Non-Word primes under No-Load (Experiment 1), Non-Phonological Load (Experiment 3) and Phonological Load (Experiment 5), respectively. In Experiments 2, 4, and 6, the participants received Word primes under No-Load (Experiment 2), Non-Phonological Load (Experiment 4) and Phonological Load (Experiment 6), respectively.

Experiments	**Association Task**			**Cognitive Load Tasks**					
				Character Recognition			**Letter Recognition**		
	M	*SE*	95% CI	*M*	*SE*	95% CI	*M*	*SE*	95% CI
Exp 1	.85	.02	[.82, .87]		-			-	
Exp 2	.90	.01	[.88, .92]		-			-	
Exp 3	.89	.03	[.84, .94]	.71	.01	[.69, .72]		-	
Exp 4	.90	.01	[.88, .91]	.71	.01	[.69, .73]		-	
Exp 5	.90	.01	[.88, .92]		-		.74	.01	[.72, .76]

Exp 6	.92	.02	[.89, .95]		-		.73	.01	[.71, .76]
Exp 7	.92	0.01	[.90, .94]	.75	.01	[.73, .77]		-	
	.93	0.01	[.91, .95]		-		.73	.01	[.71, .75]

Table 5

Raw reaction times on the association task for each type of prime in Experiment 1 (Non-Word primes) and Experiment 2 (Word primes). In both experiments, there was no cognitive load.

Experiments	**Prime Type**	***M***	***SE***	**95% CI**
Exp 1	Deletion	815	20	[775, 853]
	Replacement	822	19	[784, 859]
	Addition	803	22	[762, 848]
	Unrelated	863	21	[822, 902]
Exp 2	Embedded	843	19	[806, 881]
	Cohort	880	19	[842, 917]
	Carrier	856	29	[796, 911]
	Unrelated	928	23	[879, 970]

We index the priming effect by subtracting the average reaction times of all the Related trials from the reaction times of the Unrelated trials. Data of each experiment were modeled as a 2 Relatedness (Related vs. Unrelated) single factor design, with Relatedness as a within-subject factor. Reaction times for the correct responses in the primary task were analyzed using mixed linear modeling, via the *lmer* function within the *lme4* package (Bates, Maechler, & Dai, 2008) implemented in R (R Development Core Team, 2008). For each experiment, the maximal random factor structure was modeled by including raw reaction time as the dependent variable, and all the possible factors justified by the experimental design as random factors (Barr, Levy, Scheepers & Tily, 2013). The maximal random factor structure included by-subject and by-item intercepts, and by-Subject and by-Item slopes for Relatedness. However, the maximal model failed to converge for both experiments (and for the four subsequent ones). The maximal structure was then progressively simplified by excluding each random factor from the maximal structure. For all experiments, the first model that converged included the by-subject and by-item intercepts only, and this model was used as the base model. For each analysis, we report the model estimates (β), standard errors (*SE*), *t* values, and *p* values that were obtained from the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2014).

Figure 2 shows the overall priming effects for the primary task in Experiments 1 and 2, when there was no cognitive load. The two sets of primes produced similar result patterns. In Experiment 1 (Non-Word Primes), the main effect of Relatedness was significant, χ^2 (1) = 27.28, $p < .001$, with faster responses on Related trials (*M* = 813 ms, *SE* = 20, 95% CI = [773, 852]) than on Unrelated trials (*M* = 863 ms, *SE* = 21, 95% CI = [882, 902]), $\beta = 46.43$, *SE* = 8.85, $t = 5.25$, $p < .001$. In Experiment 2 (Word primes), the main effect of Relatedness was significant, χ^2 (1) = 11.12, $p < .001$, with faster responses on Related trials (*M* = 860 ms, *SE* = 23, 95% CI = [814, 903]) than on Unrelated trials (*M* = 928 ms, *SE* =23, 95% CI = [879, 970]), $\beta = 73.24$, *SE* = 21.32, $t = 3.44$, $p < 001$.

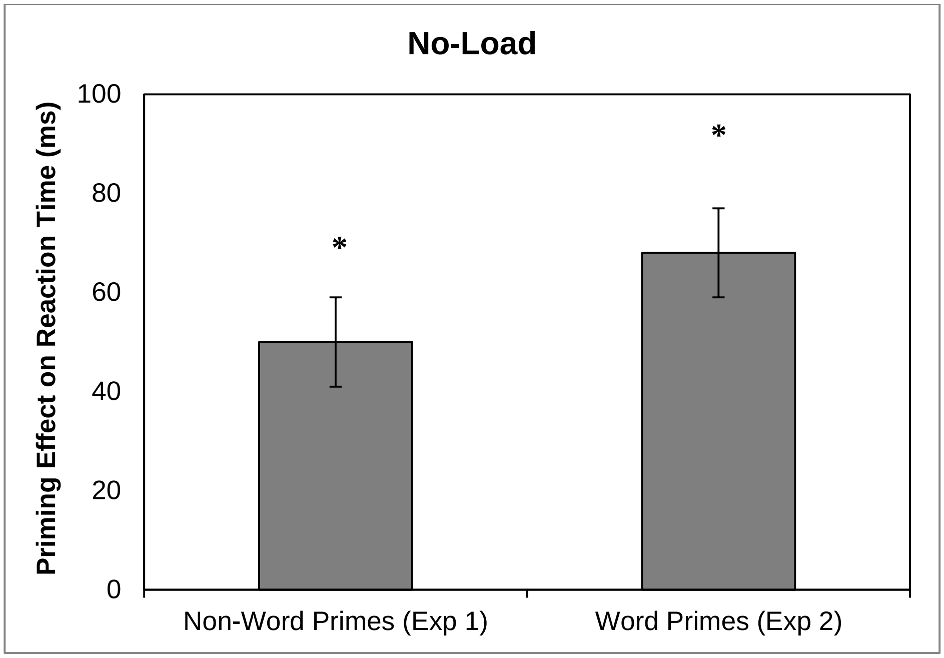

Figure 2. Overall priming effects for the Association task under No-Load (Experiments 1 and 2). The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

Discussion

The purpose of the first two experiments was to make sure that our primary tasks and stimuli were sensitive enough to produce robust priming effects when there was no cognitive load, and thus to provide a baseline pattern for the cognitive load conditions. We found significant semantic priming in both experiments, despite the lexical competition between the primes and the targets in Experiment 2. These results are consistent with the predictions of models of spoken word recognition (McClelland & Elman, 1986; Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987; Norris, 1994) that multiple lexical candidates will be activated if their phonological representations match the speech signal transiently. The priming effects replicate previous findings that the meanings of cohort competitors are activated after hearing the first few phonemes of a word (e.g., Zwitserlood,1989), and the meanings of embedded words are activated while hearing their carrier words (e.g., Isel & Bacri, 1999; Luce & Cluff, 1998).

Having established significant priming effects for both Word and Non-Word primes on the primary task, in the following experiments we impose different types of cognitive load by adding secondary tasks that vary in their resource demands. The resulting priming patterns will provide insight into which sub-processes of spoken word recognition require cognitive resources, and what type of cognitive resources are needed.

Experiments 3 and 4: Non-Phonological Load

Non-Phonological Load was imposed in Experiments 3 and 4 by adding a concurrent character recognition task to the primary task used in Experiments 1 and 2. In this pair of experiments, participants were asked to keep non-alphabetical characters (i.e., Chinese characters) in mind while performing the primary task. Since these Chinese characters were unnamable for native English speakers, the participants were unable to rehearse them in order to keep them in mind. Therefore, this task should primarily impose a cognitive load that is not specific to phonological processing. In Experiment 3, as in Experiment 1, the primes were non-words. In Experiment 4, as in Experiment 2, the primes were words.

Methods

Participants

Each experiment recruited 27 undergraduate students from Stony Brook University. All participants were native English speakers who did not know Chinese and were 18 years of age or older. Each participant took part in only one experiment and had not taken part in either of the first two experiments. They received research credit for their participation.

Materials

The primary task in Experiments 3 and 4 used the same prime-target pairs as those used in Experiments 1 and 2, respectively. A Non-Phonological Load was imposed by adding a character recognition task in both experiments, using the Chinese characters that were tested in the Preliminary Study.

Procedure

The procedures of Experiments 3 and 4 were similar. For each trial, a fixation cross was presented at the center of a screen for 500 ms, followed by a Chinese character presented at the same location for 2000 ms. The participants were asked to keep this character in mind during the trial. After the character disappeared, the auditory prime and auditory target were presented, with a 300 ms ISI between the prime and target. A visual probe was presented at the onset time of the auditory target. The participants were asked to decide whether the visual probe was associated with the target by pressing the “yes” or “no” button on the button board. After they responded for the primary task, or if they failed to respond within 3000ms, a Chinese character was presented at the center of the screen. The participants needed to decide whether the second character was the same as the first one or not, by making a YES-NO response. The next trial began 1000ms after the response. If the participant failed to respond within 3000ms, the next trial would begin. For half of the trials the same character was presented twice within a trial, while for the other half, the two characters were different.

Results

Participants with over 30% errors on the primary task, or who failed to respond on more than 30% of the trials on the character recognition task were removed from analyses. With these criteria, three participants were eliminated in each experiment. Across the remaining participants, the average accuracies for the primary task and for the character recognition task are shown in Table 4. Reaction times for each type of prime are shown in Table 6. Data were cleaned and analyzed using the same procedures as in the first two experiments.

Table 6

Raw reaction times on the association task for each type of prime in Experiment 3 (Non-Word primes) and Experiment 4 (Word primes) under Non-Phonological Load.

Experiments	**Prime Type**	***M***	***SE***	**95% CI**
Exp3	Deletion	950	28	[896, 1004]
	Replacement	933	25	[883, 983]
	Addition	933	29	[875, 991]
	Unrelated	973	28	[917, 1029]
Exp4	Embedded	943	31	[882, 1004]
	Cohort	967	28	[913, 1021]
	Carrier	954	26	[902, 1006]
	Unrelated	1001	30	[942, 1060]

Recall that without any cognitive load, both word and non-word primes were effective (Figure 2): Nonwords produced a 50 msec priming effect, and Words yielded a 68 msec priming effect. With the introduction of a non-phonological load, priming followed a similar pattern, but both priming effects were about a third smaller than before, 34 msec with Nonword primes and 46 msec with Word primes. Figure 3 shows the overall priming effects in Experiments 3 and 4. In Experiment 3 (Non-Word Primes), the main effect of Relatedness was significant, χ^2 (1) = 12.85, p <.001, with faster responses on Related trials (*M* = 939 ms, *SE* = 28, 95% CI = [885, 993]) than on Unrelated trials (*M* = 973 ms, *SE* =28, 95% CI = [917, 1029]), β = 38.80, *SE* = 10.80, t = 3.59, p < .001. In Experiment 4 (Word primes), the main effect of Relatedness was also significant, χ^2 (1) = 5.97, p = .015, with faster responses on Related trials (*M* = 955 ms, *SE* = 28, 95% CI = [899, 1011]) than on Unrelated trials (*M* = 1001 ms, *SE* = 30, 95% CI = [942, 1060]), β = 58.47, *SE* = 23.66, t = 2.47, p = .015.

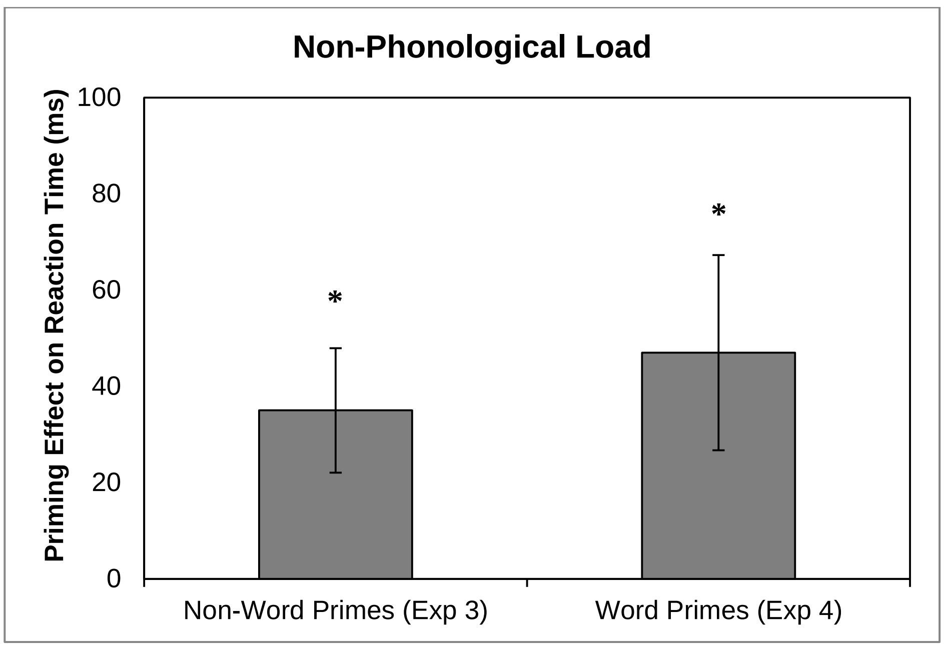

Figure 3. Overall priming effects for the Association task under Non-Phonological Load (Experiments 3 and 4). The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

Discussion

Overall, the priming in Experiments 3 and 4 was similar to the priming in Experiments 1 and 2, but somewhat smaller. For both the Word and Non-Word primes, participants made their semantic association judgments faster when the prime was related to the target word. The generally similar results in this pair of experiments to what we found in the No-Load experiments indicates that imposing a Non-Phonological Load did not produce much interference with the lexical activation that supports semantic priming.

Experiments 5 and 6 further examine whether the priming effects are affected by cognitive load. Unlike Experiments 3 and 4, the imposed load requires cognitive resources that are specific to phonological processing. Many prior studies have shown that two tasks that both engage phonological processing cause more mutual interference than two tasks that engage different types of processing (e.g., one task that involves phonological processing and one that involves spatial processing) (Baddeley, 1992; Baddeley & Hitch, 1974; Maehara & Saito, 2007). Therefore, some sub-processes that were not affected under Non-Phonological Load may be impaired under Phonological Load.

Experiments 5 and 6: Phonological Load

In Experiments 5 and 6, Phonological Load is imposed by adding a concurrent letter recognition task, in which participants keep letters in mind while performing the primary task. Because the natural way to maintain the letters is to rehearse them, this task should impose a load that recruits cognitive resources that are specific to phonological processing. Non-Word primes were tested in Experiment 5, and Word primes were tested in Experiment 6.

Methods

Participants

Each experiment recruited 27 undergraduate students from Stony Brook University. All participants were native English speakers and were 18 years of age or older. Each participant took part in only one experiment and had not participated in any of the previous studies. They received research credit for participation.

Materials

The primary task in Experiment 5 used the same prime-target pairs as those used in Experiments 1 and 3, and the primary task in Experiment 6 used the same prime-target pairs as those used in Experiments 2 and 4. A Phonological Load was imposed by adding a secondary letter recognition task, which used the consonant strings that had been tested in the Preliminary Study.

Procedure

The procedures of Experiments 5 and 6 were similar to those of Experiments 3 and 4, except that a letter recognition task was added to the primary task. Instead of seeing a Chinese character, the participants saw four upper-case consonants presented simultaneously after the fixation cross at the beginning of each trial, and were asked to keep these letters in mind during the trial. After making a decision for the primary task, the participant saw a single consonant, and decided whether this single letter had been presented in the four-letter string at the beginning of the trial. For half of the trials, the tested consonant had been presented in the string, while for the other half it had not been.

Results

Using the same criteria as before, three participants were eliminated in each experiment. The average accuracies for the primary task and for the letter recognition task for the remaining participants are shown in Table 4. Data of each experiment were analyzed in the same way as in the previous experiments. Reaction times for each type of prime are shown in Table 7.

Table 7

Raw reaction times on the association task for each type of prime in Experiment 5 (Non-Word primes) and Experiment 6 (Word primes) under Phonological Load.

Experiments	**Prime Type**	***M***	***SE***	**95% CI**
Exp5	Deletion	915	36	[844, 986]
	Replacement	910	32	[848, 972]
	Addition	902	31	[842, 962]
	Unrelated	950	46	[860, 1040]
Exp6	Embedded	956	26	[904, 1008]
	Cohort	984	23	[939, 1029]
	Carrier	983	18	[947, 1019]
	Unrelated	1004	27	[951, 1057]

Figure 4 shows the overall priming effects for the association task in Experiments 5 and 6. Comparison of these results to those shown in Figures 1 and 2 reveals a different impact of Phonological Load than Non-Phonological Load. In Experiment 5 (Non-Word primes), the main effect of Relatedness was significant, χ^2 (1) = 13.43, $p < .001$, with faster responses on Related trials (*M* = 909 ms, *SE* = 33, 95% CI = [845,973]) than on Unrelated trials (*M* = 950 ms, *SE* = 46, 95% CI = [860, 1040]), β = 46.44, *SE* = 12.64, *t* = 3.67, $p < .001$. In contrast, in Experiment 6 (Word primes), a different pattern was observed than in the previous experiments. There was no significant main effect for Relatedness, χ^2 (1) = 2.60, *p* = .111, with similar reaction times on Related (*M* = 974 ms, *SE* = 23, 95% CI = [930,1019]) and Unrelated trials (*M* = 1004 ms, *SE* = 27, 95% CI = [951, 1057]), β = 38.90, *SE* = 24.13, *t* = 1.61, *p* = .111.

The results of Experiments 1 – 6 can be looked at as comprising a 2 x 3 design, crossing the type of prime (NonWord vs Word) with the type of load (No-Load, Non-Phonological Load, and Phonological Load). We noted that for the NonWord primes, assumed to primarily tap lexical access, the load manipulation had little effect, with average priming effects of 50, 34, and 41 msec across the three load conditions. In contrast, for the Word primes that were designed to also affect lexical competition, priming did seem to be affected by load, dropping from 68 msec with No-Load, to 46 msec under Non-Phonological Load and to 30 msec under Phonological Load. The interaction of the two factors was in fact significant, χ^2 (11) = 86.71, $p < .001$. Moreover, for the NonWord primes, the overall priming effect in the No-Load condition was not significantly different from that under Non-Phonological Load (β = 7.30, *SE* =15.38 , *t* = 0.48, *p* = .633), or under Phonological Load (β = 0.59, *SE* = 15.38, *t* = 0.04, *p* =0.970). In contrast, for the Word primes, the overall priming effect in the No-Load condition was significantly stronger than that in the Phonological-Load condition (β = 34.03, *SE* = 14.98, *t* = 2.27, *p* = .023), but not different from the Non-Phonological Load condition (β = 16.79, *SE* = 14.95, *t* = 1.12, *p* = .261); the latter two were not significantly different (β = 17.25, *SE* = 14.85, *t* = 1.16, *p* = .246).

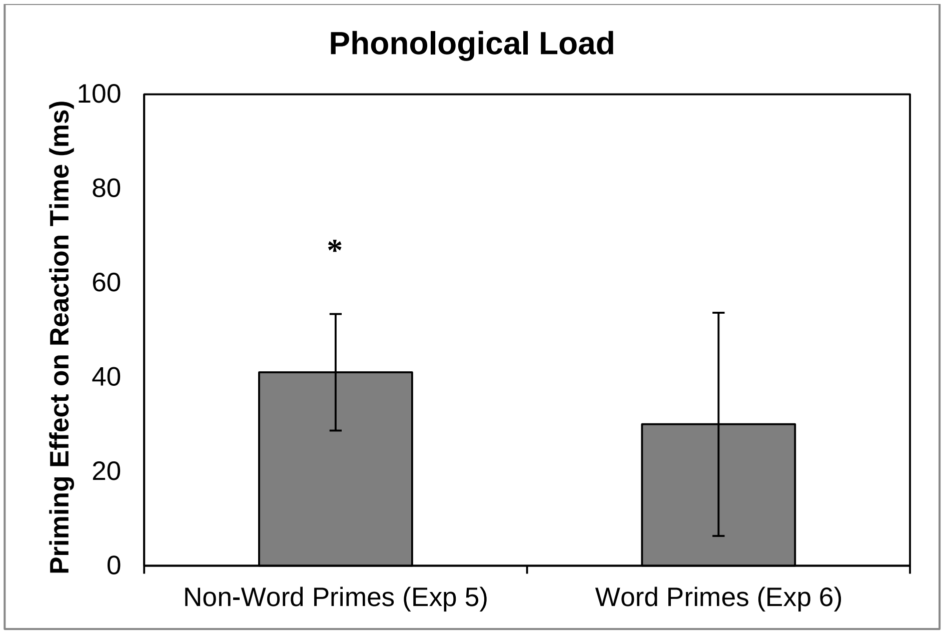

Figure 4. Overall priming effects for the Association task under Phonological Load (Experiments 5 and 6). The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

Discussion

The final two experiments produced a different result pattern than what we found under Non-Phonological Load (Experiments 3 and 4). Specifically, Phonological Load led to the loss of semantic priming for the Word primes (Experiment 6), whereas the Non-Phonological Load in Experiment 4 did not bring semantic priming down to a non-significant level. The different impact of the two cognitive load conditions demonstrates that different sub-processes of speech recognition have different needs for cognitive resources. In particular, when the primes were Non-Words, semantic priming remained robust, regardless of whether the load was phonological or not (Experiments 3 and 5). The results across the two types of cognitive load suggest that initial lexical access – the bottom-up activation of semantic representations – is relatively automatic, without much reliance on cognitive resources. Critically, however, when the primes were real Words, and thus expected to provide lexical competition for the target words from the primes, we observed disruption of the priming effects when the load was phonological (Experiment 6), but not when the load was non-phonological (Experiment 4). This implies that lexical competition is resource-demanding, and that the cognitive resources needed to sustain lexical competition are specific to phonological processing**.**

The testing conditions of Experiment 6 imposed multiple sources of possible disruption, and the combination was effective: Subjects were deprived of phonological resources by the Phonological Load manipulation, and target words were subject to lexical competition from the primes. These two factors were sufficient to prevent listeners from maintaining their lexical representations at a level that would have been sufficient to generate significant semantic priming. The different results across Experiments 4 and 6 indicate that lexical competition processes rely on resources that are more specifically phonological.

Experiment 7: Phonological vs Non-Phonological Load, Within-Subject

A central goal of the current study is to determine whether the initial lexical activation phase is more automatic than subsequent lexical competition. The six core experiments were built on the idea that a Word prime creates more lexical competition than a Non-Word prime does, and therefore that Load effects should be larger for Word prime conditions if lexical competition is less automatic than lexical activation. As we just noted, the pattern of priming in the six core experiments is consistent with this prediction: Priming by Non-Words was not significantly affected by the Load manipulation (with average priming effects of 50 msec, 34 msec, and 41 msec for the No Load, Non-Phonological Load, and Phonological Load conditions). In contrast, priming by Words changed significantly as a function of load, with average effects of 68 msec, 46 msec, and 30 msec in the corresponding conditions. The priming effect in the Phonological Load condition was significantly smaller than in the No-Load condition.

This pattern supports the idea that initial lexical activation is largely automatic, initiated by the early segments of the utterance being heard, whereas competition between these activated candidates is more resource dependent. The critical resource appears to be phonological processing, as this type of load task significantly reduced priming (to the point of non-significance). However, as we noted in the Introduction, our experimental design decisions were heavily constrained by the available set of words in English for the various types of Word primes, and a consequence of these design decisions was that between-experiment comparisons were underpowered. Thus, although the pattern of priming for Word primes as a function of Load type was as expected, there was not sufficient statistical power to show that the significant 46 msec priming effect under Non-Phonological Load was significantly larger than the non-significant 30 msec priming effect under Phonological Load.

Experiment 7 provides a direct test of whether these two conditions are in fact different from each other. In order to provide a within-subject (and thus much more sensitive) test, we had a new group of participants take part in what was essentially a replication of Experiments 4 (Non-Phonological Load) and 6 (Phonological Load). Given the word constraints, this meant giving up the restriction on stimulus repetition: Participants received the same set of stimuli, once with the Non-Phonological Load task, and once with the Phonological Load task. To mitigate the expected repetition effects, we separated the two sessions by at least a week, and counterbalanced the order of the two Load conditions across participants. Our central question is whether the Phonological Load significantly reduces priming effects, compared to the Non-Phonological Load. If so, we may conclude that lexical competition requires processing resources (i.e., it is not as automatic as initial lexical access), and those resources are primarily phonological.

Methods

Participants

Forty native English speakers who did not know Chinese participated in the study. They received research credit for their participation.

Materials

The materials used in this study were the same as those in Experiments 2, 4, and 6.

Procedure

The procedure was as in Experiments 4 and 6. The primary task was the same semantic association task. However, now each participant took part in two sessions that were 7-14 days apart. In one session, the participants were tested in the Non-Phonological Load condition, and in the other they were tested in the Phonological Load condition. The order of the two load conditions was counterbalanced across participants.

Results

Overall Priming

The data screening process was the same as in the previous experiments. The average accuracies for the primary task and for the two cognitive load tasks are shown in Table 4.

Reaction times for each type of prime are shown in Table 8. Overall, the accuracy and response times are similar to those in Experiments 4 and 6 (see Table 4).

Table 8

Raw reaction times for each type of prime in the association task under Non-Phonological vs. Phonological Load.

Prime Type	**Under Non-Phonological Load**			**Under Phonological Load**		
	M	***SE***	**95% CI**	***M***	***SE***	**95% CI**
Embedded	889	17	[856, 922]	946	25	[897, 995]
Cohort	936	20	[896, 976]	982	23	[936, 1028]
Carrier	927	17	[894, 960]	961	27	[907, 1015]
Unrelated	987	20	[949, 1025]	1015	26	[964, 1066]

Figure 5 shows the overall priming effects for the association task under the two types of cognitive load, with reaction times collapsed across all three types of related trials. Data were modeled as a 2 Relatedness (Related vs. Unrelated) * 2 Load (Non-Phonological vs. Phonological) factorial design, with both factors as within-subject factors. The main effect of Relatedness was significant, $\chi^2(1) = 7.95$, $p = .005$, with faster responses on Related trials (M = 940ms, SE = 22, 95% CI = [898, 982]) than on Unrelated trials (M = 1001ms, SE = 23, 95% CI = [956, 1046]), $\beta = 66.22$, SE = 23.15, $t = 2.86$, $p = .005$. The main effect of Load was also significant, $\chi^2(1) = 50.41$, $p < .001$, with faster responses under the Non-Phonological load condition (M = 935ms, SE = 18, 95% CI = [899, 971]) than under the Phonological Load condition (*M* = 976ms, *SE* = 25, 95% CI = [926, 1026]), *β* = 43.17, *SE* = 6.07, *t* = 7.11, *p* < .001. Critically, there was a significant interaction between Relatedness and Load, $\chi^2(3) = 10.68$, *p* = .014. In particular, while the semantic priming was significant under both load conditions (Non-Phonological Load: *β* = 78.34, *SE*= 24.44, *t* = 3.21, *p* = .002; Phonological Load: *β* = 55.44, *SE* = 24.04, *t* = 2.26, *p* = .030), the interaction indicates that priming was more robust under Non-Phonological Load. This significant difference confirms the pattern we saw in the core experiments, and demonstrates that the lexical competition process is particularly dependent on phonological processing resources.

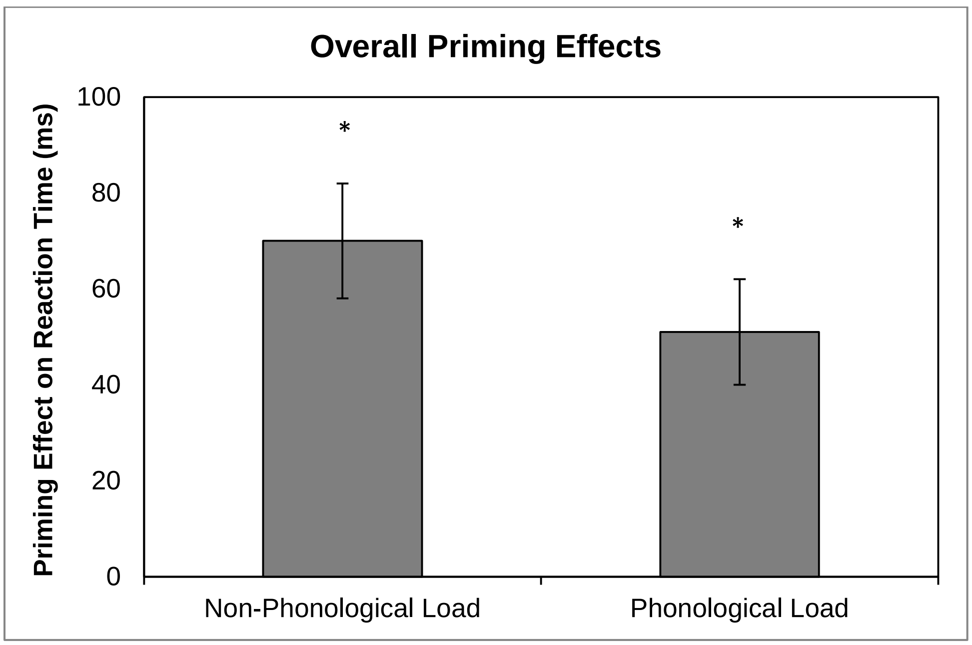

Figure 5. Overall priming effects for the association task under Non-Phonological vs. Phonological Load. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

Overall Priming Effect by Session

Recall that in order to conduct a sensitive within-subject test we had to relax our constraint on item repetition. We separated this repetition by at least a week, and counterbalanced order of the Load conditions, to minimize repetition effects. Nonetheless, as Figure 6 shows, our concern about item repetition was well-founded. Figure 6 shows the overall semantic priming effect under each type of cognitive load for each session. In the first session, there was a significant effect of Relatedness, $\chi^2(1) = 7.31$, $p = .007$, with faster responses on Related trials (*M* = 914ms, *SE* = 22, 95% CI = [871, 957]) than on Unrelated trials (*M* = 975ms, *SE* = 23, 95% CI = [930, 1020]), $\beta = 61.53$, *SE* = 22.40, $t = 2.75$, $p = .007$. The main effect of Load was not significant, $\chi^2(1) = 0.32$, p = .573. The critical interaction was significant, $\chi^2(3) = 60.07$, $p < .001$, due to a stronger priming effect under the Non-Phonological load condition ($\beta = 80.54$, *SE*= 26.31, $t = 3.061$, $p = .003$) than under the Phonological Load condition ($\beta = 42.88$, *SE* = 23.57, $t = 1.82$, $p = .073$).

The difference between the two cognitive load conditions was virtually eliminated in the second session. The main effects of Relatedness ($\chi^2(1) = 6.64$, $p = .010$) and Load ($\chi^2(1) = 7.97$, $p = .004$) were significant, but the interaction was not ($\chi^2(3) = 4.10$, $p = .250$). Simple effect analyses revealed that the priming effect was similar under Non-Phonological Load ($\beta = 73.28$, *SE*= 26.95, $t = 2.72$, $p = .008$) and under Phonological Load ($\beta = 66.22$, *SE* = 27.65, $t = 2.39$, $p = .021$).

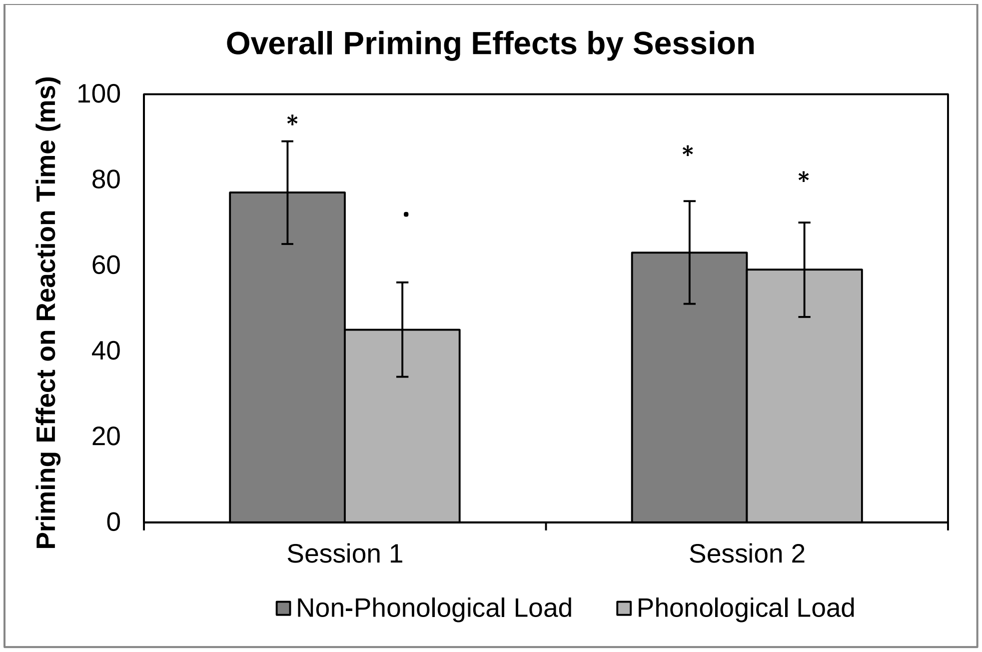

Figure 6. Overall priming effects for the association task under Non-Phonological vs. Phonological Load for each session separately. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant, and ˙ indicates a marginal effect.

General Discussion

The present project aimed to investigate whether different sub-processes of speech recognition -- initial lexical access and later lexical competition -- differ in their reliance on cognitive resources. Despite decades of research on spoken word recognition, no current model has explicitly addressed this question. Moreover, essentially all of the empirical evidence that current models base their assumptions on has been collected under optimal lab situations. In this study, we tested speech recognition under optimal conditions and under different types of cognitive load.

The core of the current study included three pairs of experiments, with cognitive load (i.e., No-Load vs. Non-Phonological Load vs. Phonological Load) manipulated across the three pairs.

Two types of cognitive load tasks (i.e., the character recognition task vs. the letter recognition task) were imposed to primarily deplete either general (non-phonological) or phonological cognitive resources. Across the two experiments within each pair, the lexicality of the primes was manipulated, with non-word primes designed to index lexical access and word primes designed to affect both lexical access and lexical competition. As we outlined in the Introduction, lexical competition here refers to the ability of alternative candidates that do not match the speech signal perfectly (i.e., the target) to compete with the perfect-matching candidate (i.e., the prime when it is a real word). Our primary task – semantic association – was chosen to provide information about initial lexical access and subsequent lexical competition. With non-word primes, it indexes the initial access of similar-sounding lexical candidates (which leads to the activation of their semantic representations), without direct lexical competition from the non-word primes. With word primes, it indexes the activation of semantic representations of targets as a result of both bottom-up activation and lexical competition.

Figure 7 provides a comparison of the overall priming effects across different load conditions. The priming effect with non-word primes was not impacted much by either the Non-Phonological Load (a loss of only 16 msec in priming) or by the Phonological Load (a loss of only 9 msec of priming). This result strongly suggests that the initial access of lexical items is relatively automatic and resource-independent. The largely intact priming effect under both types of cognitive load also demonstrates that participants were encoding the primes. If subjects had chosen to completely ignore the primes, then we should not have seen any priming, or any differences in prime effectiveness across different types of related trials (see Appendix C for these differences). The conclusion that initial lexical access is relatively automatic is consistent with the assumption of the Cohort model (Marslen-Wilson & Welsh, 1978; Marslen-Wilson,

1987) that there is early and obligatory bottom-up activation of lexical candidates (i.e., after hearing only the first few segments). Support for this conclusion also comes from studies using ERP techniques, which have found that lexical representations in long-term memory are activated automatically even if words are not specifically attended to (Pulvermüller & Shtyrov, 2006; Shtyrov, Kujala, & Pulvermüller, 2010; Shtyrov & Pulvermüller, 2007). There are also studies of visual word recognition showing that words are activated to meaning even when the participants are not consciously aware of the presence of the primes (Fuentes, Carmona, Agis, & Catena, 1994; MacLeod, 1991, 1992; Marcel, 1983;Valdés, Catena, & Marí-Beffa, 2005). However, this does not mean that lexical access does not require any resources, or cannot be disrupted at all. For instance, recent research has shown that lexical access can be disrupted if a distracter task is presented during a very specific time window (Samuel, 2016).

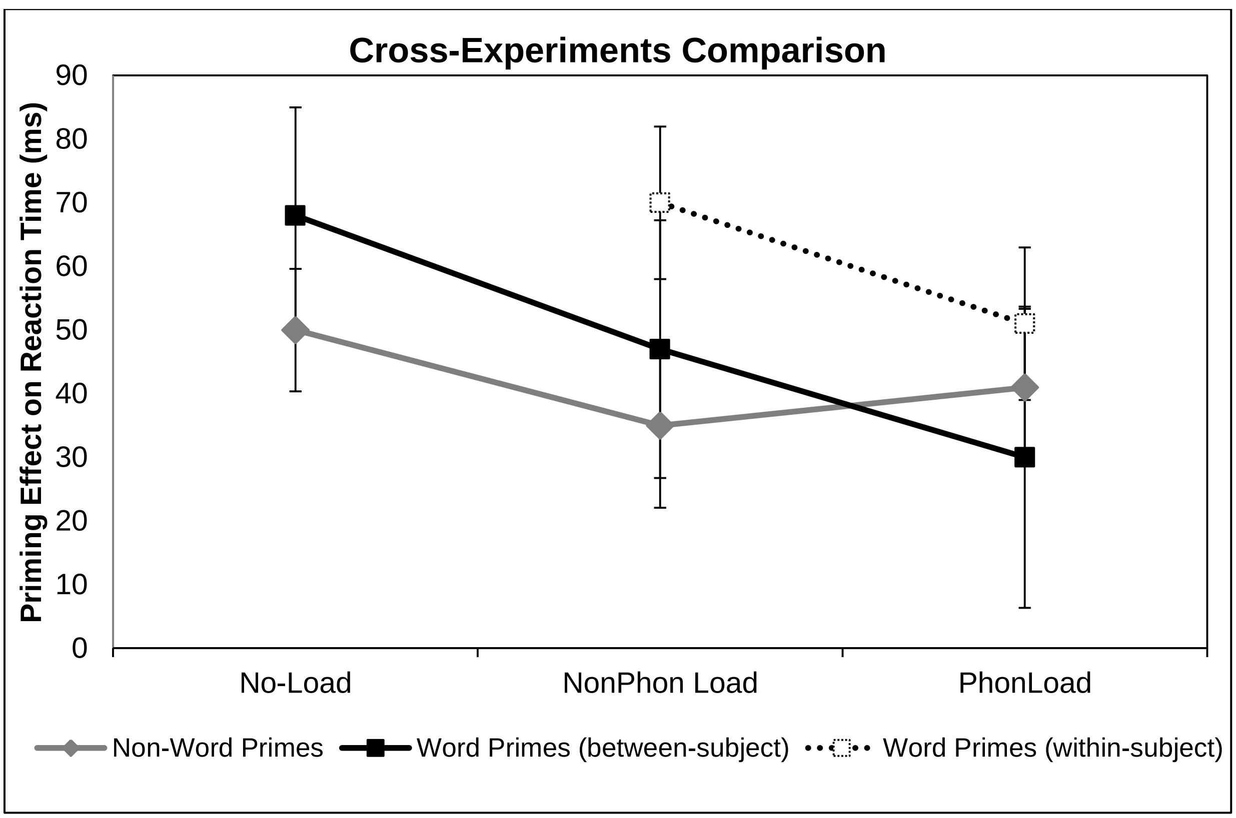

Figure 7. A comparison of the overall priming effects among no-load, non-phonological load, and phonological load conditions across seven experiments. The error bars represent the standard errors.

The word primes showed a quite different pattern. The priming effect was somewhat reduced under Non-Phonological Load (22 msec less priming), and was reduced to non-significance under Phonological Load (a significant loss of 38 msec of priming). The within-subject test in Experiment 7 confirmed that priming was significantly weaker under Phonological Load than under Non-Phonological Load. Because participants had to rehearse letters in the Phonological Load condition but not in the Non-Phonological load condition, the former load task depletes cognitive resources that are primarily speech-related whereas the latter one does not. The observed patterns demonstrate that lexical competition is resource demanding, unlike the relatively automatic access of lexical items. More specifically, the lexical competition process requires cognitive resources that are speech-related. When there is no cognitive load, alternative candidates (including the target) are able to stay activated at the time of testing despite lexical competition from the prime, as suggested by most models of spoken word recognition (McClelland & Elman, 1986; Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987; Norris, 1994). When a secondary task primarily depletes cognitive resources that are less phonological (e.g., keeping an unnamable character in memory), the alternative candidates are still able to compete with the prime and their residual activation is strong enough to be measured at the time of testing. However, when phonologically-related cognitive resources are recruited by a secondary task (e.g., keeping letters in mind), the ability of the alternative candidates to compete with the perfect-matching candidate is largely eliminated. The activation of alternative candidates cannot be maintained when competing with the prime itself when there are not enough phonological resources available.

When conditions are optimal, lexical processing seems to follow the scheme that most models describe: The initial acoustic input from a word activates a set of lexical candidates and subsequent processes winnow this set down, generally leading to the correct lexical representation being most strongly activated. This two-step process was first spelled out in the Cohort model (Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987), and subsequent models have taken this as their starting point. However, perceiving speech in the real world rarely occurs under the kind of optimal conditions typically used in the laboratory, and our results indicate that although the initial activation process is relatively robust, the subsequent selection process is significantly affected by the difficulty of the listening situation.

If we combine our results with those of Connine, Blasko, and Wang (1994), and those of Zhang and Samuel (2015), the picture that emerges is one in which difficult conditions lead to a kind of "tunnel vision" (which is itself a phenomenon that tends to occur when humans operate under a heavy load). We will briefly summarize the relevant findings from those two studies, to show how the evidence converges on this view. The Zhang and Samuel study shares many features with the current study, making the connection straightforward. The focus of that study was the activation of embedded words (e.g., "nap" within "napkin"). Under optimal conditions, embedded words primed words related to them (e.g., the "nap" in "napkin" produced priming of "sleep"). However, under difficult conditions, the priming disappeared, even though under the same conditions the isolated word "nap" still primed "sleep". Thus, the results indicate that the sustained activation of multiple candidates (including embedded ones) occurs when conditions are good, but not when they are not.

The Connine et al. (1994) study is a bit more complicated, but it provides information that converges with the findings of the current study in an interesting way. The authors first demonstrated a form of multiple activation. They constructed stimuli with ambiguous initial phonemes, such as [cg]old, an item designed to be ambiguous in terms of the voicing of the initial /k/ or /g/. In three experiments they showed that this stimulus activates both “cold” and “gold”, with the evidence being significant priming of both “hot” and “silver”. Their final experiment is most relevant to the current study. The authors took each ambiguous item and put it at the end of a sentence that strongly favored one interpretation, e.g., “He looked for the ___”. A participant in this case should interpret the ambiguous item as “gold”, not “cold”. Immediately after the presentation of the critical word, a visual stimulus was presented for a semantic judgment – was the visual word semantically related to the sentence? The trials of interest are those in which the word was not related to the sentence, but was related to the “other” meaning of the ambiguous word. In this example, the probe would be “hot”, and a participant should answer No because the sentence was about looking for gold. The delay in rejecting this item, relative to a baseline, provides an index of whether multiple candidates were in play, despite the context. The quite intriguing result is that participants who had been independently classified as high memory span showed a very large interference effect, whereas low memory span individuals produced a much smaller interference effect. The interpretation is that those with high capacity had both “cold” and “gold” active, making it difficult to reject “hot”; the low capacity participants apparently only had the contextually likely candidate “gold” active, and thus suffered less interference in rejecting “hot” as being related. If the probe was delayed for 850ms, the high span participants showed almost no interference, indicating that they had resolved the competition.

If we take the memory capacity manipulation to be analogous to a load manipulation – a load manipulation essentially reduces high capacity individuals to low capacity – we have three studies that show the same pattern: When conditions are difficult, it becomes difficult or impossible to maintain the set of competitors. In other words, the competition process collapses immediately in favor of the single strongest candidate. The results from the current study show that multiple candidates do get activated, but as in Connine et al. (1994) and Zhang and Samuel (2015), when conditions are difficult then only the single strongest candidate is maintained. In particular, our results indicate that phonological resources are needed to keep multiple candidates active. When these are taken away, the competition process cannot operate. As we said above, under load, a form of tunnel vision operates, with a loss of the ability to consider a broader set of stimuli. Presumably, consideration of the broader set normally reduces the chance of missing the actual stimulus, making such a miss more likely when multiple candidates cannot be maintained.

The idea that lexical competition is not as automatic as initial lexical access is not incorporated in the Cohort model (Marslen-Wilson & Welsh, 1978; Marslen-Wilson, 1987), TRACE (McClelland & Elman, 1986), Shortlist (Norris, 1994), or the neighborhood activation model (Luce & Pisoni, 1998): These models make no distinctions in terms of the automaticity of sub-processes during speech recognition (although Mirman, McClelland, Holt & Magnuson (2008) suggest that attentional modulation can be implemented in TRACE). Moreover, the particular requirement of *phonological* resources indicates that maintaining candidates for lexical competition primarily relies on phonological processing.

The difference between the two cognitive load conditions cannot be attributed to the character recognition task being easier. The results of the Preliminary Study showed that the two load tasks had comparable accuracies and had a similar impact on the reaction times of the primary task. In the main experiments, the character recognition task actually produced lower accuracy than the phonological load task (see Table 4, *p*s < .001), but this was not because participants selectively chose to focus more on the primary tasks under non-phonological load: The accuracy on the primary task was comparable across the two cognitive load conditions (see Table 4, *p*s > .100), and the reaction times on the unrelated trials were also comparable across the two load conditions (see Tables 6 and 7, *p*s > .100). Given that the character recognition task was not easier than the letter recognition task, the difference in the priming effects across the two load conditions must be attributed to the nature of the secondary task. The essentially flat function for priming by nonword primes shown in Figure 7, versus the load-dependent priming found for word primes, is consistent with the idea that the nonword primes are mostly affecting load-independent lexical access, while word primes are also engaging load-dependent lexical competition. Because the word and nonword priming conditions were tested in a between-subject design, we cannot rule out some strategic basis for the difference, even though the observed pattern is just what the manipulation was designed to test. Potential strategic effects might be tested in future work by using a mixed design that would minimize any opportunity for participants to adopt different strategies for word versus nonword primes.

In summary, our results demonstrate that both non-words and words activate sub-lexical representations and lead to lexical access, which in turn leads to the activation of semantic representations. But, the detailed pattern of processing depends on the demands of the primary task and the nature of the stimuli. Moreover, not all of the stages of processing during speech recognition are as fast and effortless as researchers have assumed (e.g., Assmann & Summerfield, 2004; Cutting & Pisoni, 1978; Marslen-Wilson, 1987). The results under the cognitive load conditions suggest that the initial access of lexical items is relatively automatic, whereas maintaining lexical competitors is more resource demanding. Importantly, these resources are specific to phonological processing. Imposing a phonological load has a stronger impact than a non-phonological load on this kind of competition. Collectively, the pattern of results across experiments and tasks provides insights into how different types of cognitive load constrain lexical activation and competition.

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Appendix A: Critical Stimuli for Experiments 1, 3 and 5 (Non-Word Primes)

Non-Word Prime			Target	Associated Probe
Deletion	Replacement	Addition		
/'æksɛn/	*/'æksɛnd/*	*/'æksɛntɪ/*	**accent**	LANGUAGE
/'æŋg/	*/'æŋgiː/*	*/ˈæŋgərm/*	**anger**	MAD
/ˈɑrg/	*/ˈɑrg/*	*/ˈɑrgjuːb/*	**argue**	FIGHT
/ˈɑnəs/	*/ˈɑnəsk/*	*/ˈɑnəstəl/*	**honest**	TRUTH
/ˈstætʃ/	*/ˈstætʃəl/*	*/ˈstætʃərp/*	**stature**	HEIGHT
/ˈdiːsən/	*/ˈdiːsənk/*	*/ˈdiːsəntəl/*	**decent**	GOOD
/ˈiːg/	*/ˈiːgɔn/*	*/ˈiːgərd/*	**eager**	WILLING
/ˈegzə/	*/ˈegzəp/*	*/ˈegzətəl/*	**exit**	ENTER
/ˈliːʒ/	*/ˈliːʒəl/*	*/ˈliːʒənt/*	**lesion**	CUT
/ˈerən/	*/ˈerənk/*	*/ˈerəndɑ/*	**errand**	TASK
/ˈædvər/	*/ˈædvərp/*	*/ˈædvərbər/*	**adverb**	NOUN
/ˈhɑstɪ/	*/ˈhɑstɪS/*	*/ˈhɑstɪdʒər/*	**hostage**	TERRORIST
/ˈhev/	*/ˈhevəl/*	*/ˈheviːk/*	**heavy**	LIGHT
/rɪˈfre/	*/rɪˈfres/*	*/rɪˈfreʃəl/*	**refresh**	ENERGY
/ˈhjuːmə/	*/ˈhjuːmət/*	*/ˈhjuːmədiː/*	**humid**	HOT
/ˈlev/	*/ˈlevoʊ/*	*/ˈlevərp/*	**lever**	PULL
/ˈmɑd/	*/ˈmɑdiː/*	*/ˈmɑdəlp/*	**model**	BEAUTIFUL
/dɪˈfen/	*/dɪˈfent/*	*/dɪˈfendiː/*	**defend**	PROTECT
/ˈmoʊtɪ/	*/ˈmoʊtɪf/*	*/ˈmoʊtɪvəl/*	**motive**	REASON
/'es/	*/'esiː/*	*/'eseɪt/*	**essay**	WRITE

/ˈpælə/	/ˈpæləS/	/ˈpæləsiː/	**palace**	CASTLE
/ˈplæstɪ/	/ˈplæstɪg/	/ˈplæstɪkəl/	**plastic**	BAG
/ˈpoʊlən/	/ˈpoʊlənt/	/ˈpoʊləndəl/	**poland**	COUNTRY
/ˈriːsɔr/	/ˈriːsɔrS/	/ˈriːsɔrsəl/	**resource**	LIBRARY
/ˈsɑlə/	/ˈsɑlət/	/ˈsɑlədiː/	**solid**	HARD
/ˈsekən/	/ˈsekənt/	/ˈsekəndiː/	**second**	FIRST
/ˈterə/	/ˈterəS/	/ˈterəsəl/	**terrace**	BALCONY
/ˈvɪkt/	/ˈvɪktəl/	/ˈvɪktərd/	**victor**	WINNER
/ˈwɑlə/	/ˈwɑlək/	/ˈwɑlətəl/	**wallet**	PURSE
/ˈbælə/	/ˈbæləp/	/ˈbælətər/	**ballot**	VOTE
/ˈhæp/	/ˈhæpər/	/ˈhæpəng/	**happen**	OCCUR
/ˈem(p)t/	/ˈem(p)tər/	/ˈem(p)tiːg/	**empty**	FULL
/ˈpərfjuː/	/ˈpərfjuːn/	/ˈpərfjuːmiː/	**perfume**	SMELL
/ˈpræktə/	/ˈpræktəS/	/ˈpræktəsəl/	**practice**	PERFECT
/ˈθənd/	/ˈθəndəl/	/ˈθəndərm/	**thunder**	RAIN
/ˈsərk/	/ˈsərkiː/	/ˈsərkəlm/	**circle**	SQUARE
/ˈælb/	/ˈælbər/	/ˈælbəmt/	**album**	RECORD
/ˈeɪnʃən/	/ˈeɪnʃənd/	/ˈeɪnʃəntəl/	**ancient**	OLD
/ˈɔθ/	/ˈɔθiː/	/ˈɔθərt/	**author**	WRITER
/ˈbɑt/	/ˈbɑtɑ/	/ˈbɑtəlk/	**bottle**	BEER
/ˈendʒ/	/ˈendʒər/	/ˈendʒənt/	**engine**	MOTOR
/ˈfeɪmə/	/ˈfeɪməS/	/ˈfeɪməsər/	**famous**	STAR
/ˈfrækʃ/	/ˈfrækʃəl/	/ˈfrækʃənt/	**fraction**	NUMBER

/ˈdʒend/	*/ˈdʒendiː/*	*/ˈdʒendərm/*	**gender**	SEX
/ˈlæð/	*/ˈlæðiː/*	*/ˈlæðərk/*	**lather**	SOAP
/ˈtɑrd/	*/ˈtɑrdən/*	*/ˈtɑrdiːk/*	**tardy**	LATE
/ˈərb/	*/ˈərbər/*	*/ˈərbənt/*	**urban**	CITY
/ˈrɪð/	*/ˈrɪðər/*	*/ˈrɪðəmt/*	**rhythm**	BEAT
/ˈsɪmp/	*/ˈsɪmpɑ/*	*/ˈsɪmpəlt/*	**simple**	EASY
/ˈkəntræs/	*/ˈkəntræsk/*	*/ˈkəntræstiː/*	**contrast**	DIFFER
/ˈkɔrtek/	*/ˈkɔrtekz/*	*/ˈkɔrteksər/*	**cortex**	BRAIN
/ˈpəz/	*/ˈpəziː/*	*/ˈpəzəlp/*	**puzzle**	JIGSAW
/ˈmemb/	*/ˈmembəl/*	*/ˈmembərk/*	**member**	CLUB
/ˈhɑrvəs/	*/ˈhɑrvəsp/*	*/ˈhɑrvəstɪn/*	**harvest**	CROPS
/ˈhəndrə/	*/ˈhəndrət/*	*/ˈhəndrədəl/*	**hundred**	NUMBER
/ˈdʒuːnj/	*/ˈdʒuːnjəl/*	*/ˈdʒuːnjərm/*	**junior**	YOUNG
/ˈkɪtʃ/	*/ˈkɪtʃər/*	*/ˈkɪtʃənk/*	**kitchen**	COOK
/ˈlɪs/	*/ˈlɪsəl/*	*/ˈlɪsənt/*	**listen**	HEAR
/ˈlɑdʒɪ/	*/ˈlɑdʒɪg/*	*/ˈlɑdʒɪkər/*	**logic**	COMPUTER
/ˈmɑrdʒ/	*/ˈmɑrdʒər/*	*/ˈmɑrdʒənt*	**margin**	DIVORCE
/ˈmædʒɪ/	*/ˈmædʒɪt/*	*/ˈmædʒɪkən/*	**magic**	TRICK
/ˈmeʒ/	*/ˈmeʒəl/*	*/ˈmeʒərt/*	**measure**	CUP
/ˈmərd/	*/ˈmərdiː/*	*/ˈmərdərp/*	**murder**	KILL
/ˈneɪtʃ/	*/ˈneɪtʃiː/*	*/ˈneɪtʃərt/*	**nature**	TREE
/ˈrædɪ/	*/ˈrædɪs/*	*/ˈrædɪʃəl/*	**radish**	VEGETABLE
/ˈgɑsə/	*/ˈgɑsət/*	*/ˈgɑsəpən/*	**gossip**	TALK

/ˈbɪz/	*/ˈbɪzəl/*	*/ˈbɪziːp/*	**busy**	BORED
/ˈkalɪ/	*/ˈkalɪS/*	*/ˈkalɪdʒər/*	**college**	SCHOOL
/ˈnef/	*/ˈnefər/*	*/ˈnefjuːm/*	**nephew**	NIECE
/ˈkwɪv/	*/ˈkwɪvən/*	*/ˈkwɪvərk/*	**quiver**	SHAKE
/tekˈniː/	*/tekˈniː/*	*/tekˈniːkən/*	**technique**	STYLE
/ˈvɪvə/	*/ˈvɪvəp/*	*/ˈvɪvədəl/*	**vivid**	CLEAR

Appendix B: Critical Stimuli for Experiments 2, 4, and 6 (Word Primes)

Prime Type	Word Prime	Target	Associated Probe
Embedded	*sock*	**socket**	LIGHT
	pad	**paddle**	BOAT
	deck	**decade**	YEAR
	east	**Easter**	SUNDAY
	buck	**bucket**	WATER
	cab	**cabin**	LOG
	mark	**market**	STORE
	tick	**ticket**	CONCERT
	mess	**message**	NOTE
	stew	**stupid**	DUMB
	bowl	**boulder**	ROCK
	brow	**brownie**	CAKE
	tie	**tidy**	NEAT
	pie	**pirate**	SHIP
	spy	**spider**	WEB
	pick	**picnic**	FOOD
	guard	**garden**	FLOWER
	bay	**baby**	CHILD
Cohort	*happy*	**happen**	OCCUR
	victim	**victor**	WINNER
	modern	**model**	BEAUTIFUL

	heaven	**heavy**	LIGHT
	advent	**adverb**	NOUN
	recent	**resource**	LIBRARY
	level	**lever**	PULL
	eagle	**eager**	WILLING
	argon	**argue**	FIGHT
	fracture	**fraction**	NUMBER
	metal	**measure**	CUP
	gentle	**gender**	SEX
	autumn	**author**	WRITER
	kitten	**kitchen**	COOK
	ladder	**lather**	SOAP
	ribbon	**rhythm**	BEAT
	nation	**nature**	TREE
	little	**listen**	HEAR
Carrier	*badger*	**badge**	POLICE
	charter	**chart**	GRAPH
	topic	**top**	BOTTOM
	sausage	**sauce**	TOMATO
	campus	**camp**	FIRE
	blanket	**blank**	EMPTY
	bullet	**bull**	COW
	summer	**sum**	ADD

	agent	**age**	OLD
	fancy	**fan**	AIR
	furnace	**fur**	COAT
	napkin	**nap**	SLEEP
	crucial	**crew**	SHIP
	dental	**den**	CAVE
	pumpkin	**pump**	GAS
	needle	**knee**	LEG
	Friday	**fry**	COOK
	paper	**pay**	MONEY
Unrelated	*aim*	**honest**	TRUTH
	loaf	**decent**	GOOD
	maze	**lesion**	CUT
	full	**errand**	TASK
	paste	**refresh**	ENERGY
	once	**humid**	HOT
	galley	**defend**	PROTECT
	April	**motive**	REASON
	collar	**essay**	WRITE
	temple	**Poland**	COUNTRY
	ankle	**second**	FIRST
	wallet	**terrace**	BALCONY
	window	**hut**	STRAW

	cradle	**beard**	MUSTACHE
	curly	**hoot**	OWL
	dozen	**pluck**	PICK
	hungry	**twist**	TURN
	Jewish	**west**	EAST

Appendix C: Priming Effects as a Function of Prime Type

Appendix C presents the reaction time analyses of the priming effects for each type of Related prime across different load conditions. For the six core experiments, the data were modeled as a 4 Prime Type (Deletion vs. Replacement vs. Addition vs. Unrelated) single factorial design for the Non-Word primes (Experiments 1, 3, and 5), or as a 4 Prime Type (Embedded vs. Cohort vs. Carrier vs. Unrelated) factorial design for the Word primes (Experiments 2, 4, and 6). Mixed linear modeling was conducted, and the base model of each analysis included only the by-Subject and by-Item intercepts. Facilitation in the responses on any of the three types of Related primes relative to the Unrelated prime indexes semantic priming.

Semantic Priming for Non-Word Primes

Figure A1 shows the semantic priming effects for the Non-Word primes across different cognitive load conditions. Under No-Load (Experiment 1), all types of Related primes produced robust semantic priming (Deletion: $\beta = 42.42$, $SE = 11.69$, $t = 3.60$, $p < .001$; Replacement: $\beta = 38.84$, $SE = 11.56$, $t = 3.36$, $p = .001$; Addition: $\beta = 58.77$, $SE = 11.55$, $t = 5.09$, $p < .001$). Under Non-Phonological Load (Experiment 3), there was marginally significant priming for the Deletion case ($\beta = 26.25$, $SE = 15.82$, $t = 1.66$, $p = .097$), and significant priming for the other two Related primes (Replacement: $\beta = 42.83$, $SE = 15.82$, $t = 2.71$, $p = .007$; Addition: $\beta = 46.18$, $SE = 15.68$, $t = 2.95$, $p = .003$). Under Phonological Load (Experiment 5), there was robust semantic priming for all types of Related primes (Deletion: $\beta = 38.30$, $SE = 15.82$, $t = 2.42$, $p = .016$; Replacement: $\beta = 48.45$, $SE = 15.97$, $t = 3.03$, $p = .002$; Addition: $\beta = 56.80$, $SE = 15.82$, $t = 3.59$, $p < .001$), similar to the pattern under No-Load. Thus, semantic priming for the Non-Word primes was significant for all types of Related primes under No-Load, and these effects remained robust under both types of cognitive load (except for a marginally significant effect for the Deletion case under Non-Phonological Load). In addition, for each individual type of Related prime, the priming effect was not different across experiments, *t*s < 1. The consistency of these priming effects suggests that initial lexical access (the assumed consequence of a nonword prime) is largely unaffected by either Non-Phonological Load, or Phonological Load.

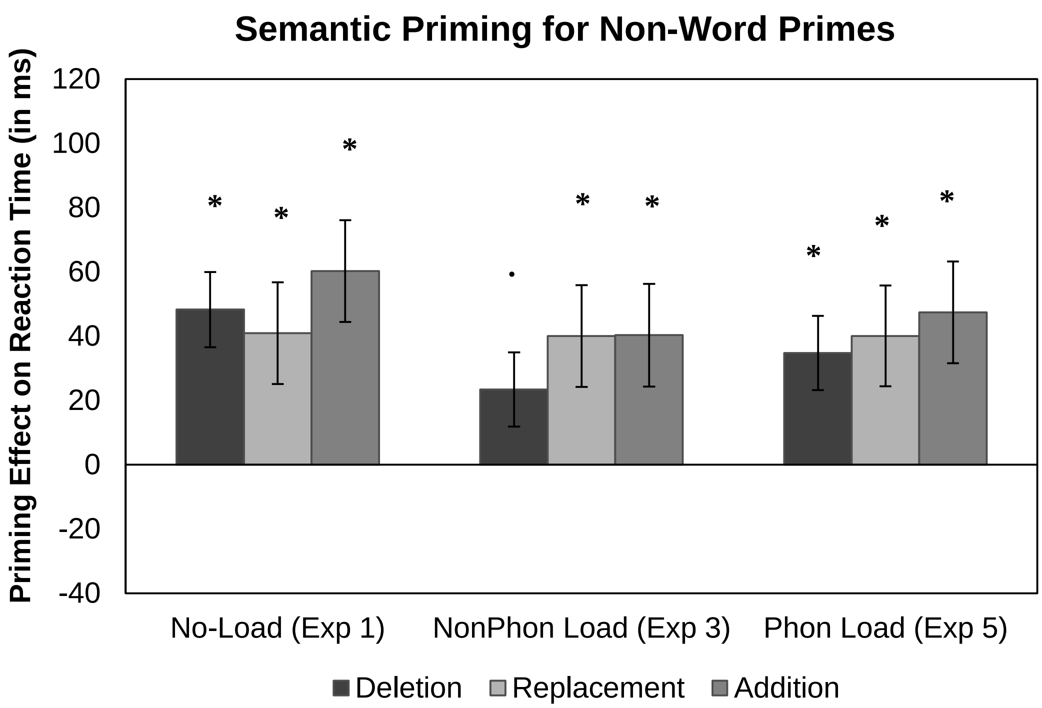

Figure A1. Semantic priming effects on reaction times for each type of Related prime after hearing the Non-Word primes in Experiments 1, 3 and 5. The dark grey bars represent the Deletion case, the light grey bars represent the Replacement case, and the medium grey bars represent the Addition case. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

. indicates that the effect was marginally significant.

Semantic Priming for Word Primes

Figure A2 shows the semantic priming effects for the Word primes across different cognitive load conditions. All three types of Related trials produced robust semantic priming under No-Load (Experiment 2) (Embedded: β = 86.54, *SE* = 20.50, *t* = 4.22, *p* <001; Cohort: β = 52.27, *SE* = 20.49, *t* = 2.55, *p* = .012; Carrier: β = 77.85, *SE* = 20.51, *t* = 3.80, *p* <001). The Non-Phonological Load condition (Experiment 4) showed similar patterns as the No-Load condition, except that the priming effect for the Cohort word prime was marginally significant (Embedded: β = 66.11, *SE* = 24.61 *t* = 2.69, *p* = .008; Cohort: β = 45.72, *SE* = 24.65, *t* = 1.86, *p* = .066; Carrier: β = 58.83, *SE* = 24.65, *t* = 2.39, *p* = .019). In contrast, under Phonological Load (Experiment 6), only the Embedded word prime produced robust priming (Embedded: β = 54.98, *SE* = 24.74, *t* = 2.22, *p* = .028; Cohort: β = 30.42, *SE* = 24.84, *t* = 1.22, *p* = .224; Carrier: β = 29.62, *SE* = 24.80, *t* = 1.20, *p* = .235). Cross-experiments comparison indicates that there was no difference among the three load conditions for the Embedded word primes, *p*s > .20. However, there was a marginally significant difference between the No-Load and Phonological Load conditions for the Cohort word primes (β = 28.98, *SE* = 18.89, *t* = 1.61, *p* = .101), and a significant difference between these two load conditions for the Carrier word primes (β = 50.19, *SE* = 18.17, *t* = 2.68, *p* = .005), suggesting the Carrier word primes suffered the strongest impact. Semantic priming survived only for the Embedded word case under Phonological Load. One possible reason is that Embedded word primes are shorter words, and hence are less effective in competing with the targets, compared to the other two types of Related primes. This assumption is also consistent with the prediction of the TRACE model that longer words would have stronger competition than shorter words (McClelland & Elman, 1986). It is also possible that phonological load still impaired the priming effect of the Embedded word priming. The non-significant difference across experiments here may be due to a lack of statistical power in the between-subject experimental designs.

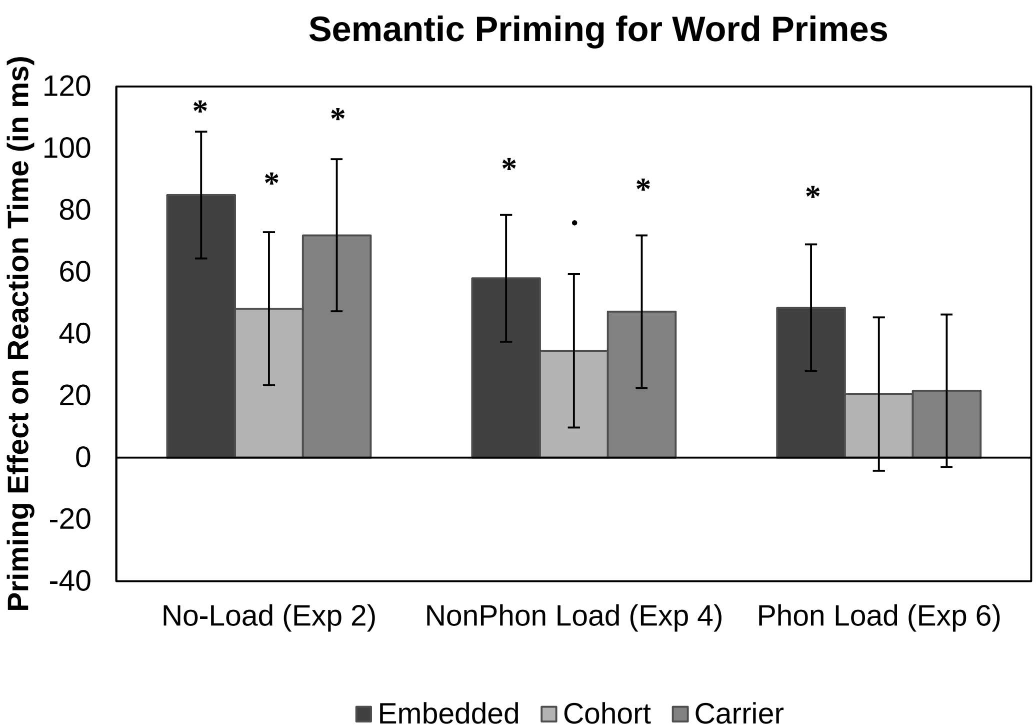

Figure A2. Semantic priming effects on reaction times for each type of Related prime after hearing the word primes in Experiments 2, 4 and 6. The dark grey bars represent Embedded words, the light grey bars represent the Cohort words, and the medium grey bars represent the Carrier words. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

. indicates that the effect was marginally significant.

Priming Effect as a Function of Prime Type in the Within-Subject Experiment

Figure A3 shows the semantic priming effect for each type of Related prime under the two types of cognitive load. Data were modeled as a 4 Prime Type (Embedded vs. Cohort vs. Carrier vs. Unrelated) * 2 Load (Non-Phonological vs. Phonological) factorial design, with both factors as within-subject factors. The main effect of Prime Type was significant, $\chi2(3) = 9.35$, $p = .025$. There was a significant semantic priming effect for both the embedded ($\beta = 79.58$, $SE = 28.48$, $p = .007$) and carrier ($\beta = 72.09$, $SE = 28.48$, $t = 2.53$, $p = .014$) word primes. The priming effect for the cohort word primes was marginally significant, $\beta = 47.96$, $SE = 28.50$, $t = 1.68$, $p = .097$. The main effect of Load was also significant, $\chi2(1) = 50.41$, $p<.001$, with a longer reaction time under the Phonological load condition (935ms) than under the Non-Phonological Load condition (976ms), $\beta = 43.19$, $SE = 6.07$, $t = 7.12$, $p < .001$.

More importantly, there was a significant interaction between Prime Type and Load, $\chi2(7) = 70.22$, $p<.001$, suggesting that the two types of cognitive load had different impacts on the semantic priming effects. Simple effect analyses showed that the interaction was due to a stronger effect of Prime Type under Non-Phonological Load ($\chi2(3) = 12.51$, $p = .006$) than under Phonological Load ($\chi2(3) = 6.53$, $p = .088$). In particular, under the Non-Phonological Load condition, the priming effect was significant for all types of related primes (Embedded: $\beta = 104.98$, $SE = 29.72$, $t = 3.53$, $p = .001$; Cohort: $\beta = 58.61$, $SE = 29.76$, $t = 1.97$, $p = .053$; Carrier: β = 71.28, SE = 29.71, t = 2.40, p = .019). But under the Phonological Load condition, the priming effect was significant only for the embedded word primes ($\beta = 71.83$, $SE = 29.51$, $t = 2.43$, $p = .018$), but this effect was significantly weaker compared to the Non-Phonological Load condition, β = 44.35, SE = 17.51, t = 2.53, p = .011. The priming effect was not significant for the cohort word primes ($\beta = 36.54$, $SE = 29.53$, $t = 1.24$, $p = .220$), and was only marginally significant for the carrier word primes ($\beta = 54.93$, $SE = 29.53$, $t = 1.24$, $p = .067$).Comparisons for each individual type of Related word primes between the two load conditions showed that there was a significant load effect for the Embedded word primes, (β = 44.42, SE = 17.32, t = 2.57, p = .010), but not for the other types of Related primes (ps > .20).Overall, the pattern of effects shown in Figure A3 is quite similar to the pattern for the corresponding cases in Figure A2, and provides further evidence that the Embedded word primes are also vulnerable to phonological load.

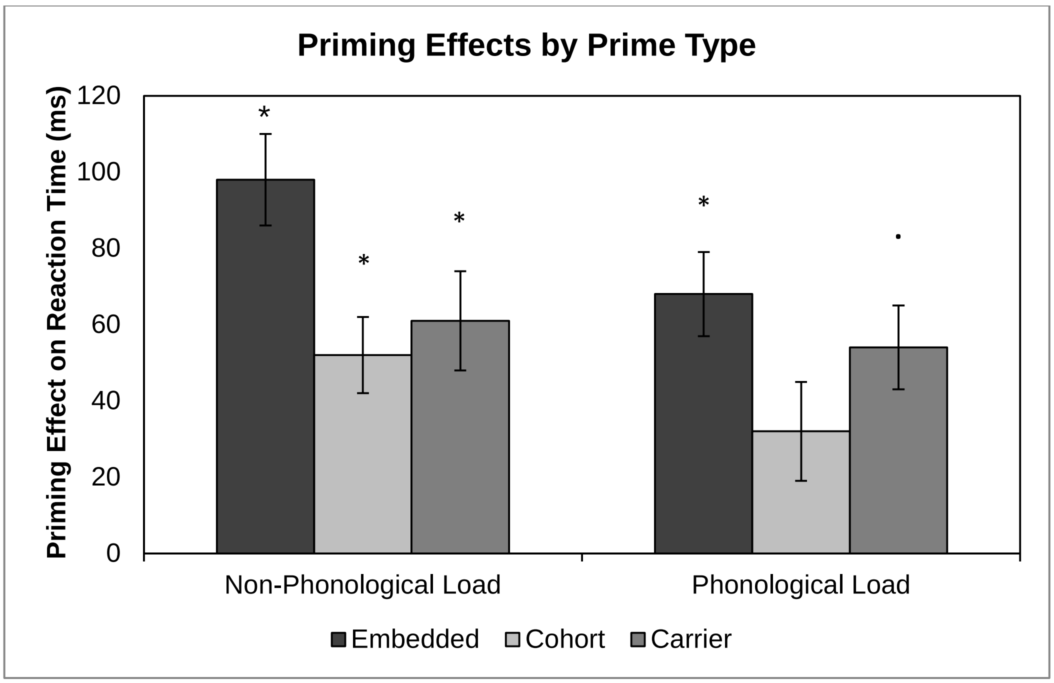

Figure A3. Semantic priming effects on reaction times for each type of related prime under Non-Phonological vs. Phonological Load. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

. indicates that the effect was marginally significant.

Priming Effects by Session

In the first session, the main effect of Prime Type was marginally significant ($\chi 2(3) = 7.53$, $p = .057$) and the main effect of Load was not significant ($\chi 2(1) = 0.32$, $p = .574$). The interaction between these two factors was significant, $\chi 2(7) = 17.09$, $p = .017$ (see Figure A4). Specifically, under the Non-Phonological Load condition, the priming effect was significant for all three types of related primes, with the strongest being the embedded word primes ($\beta = 100.07$, $SE = 32.32$, $t = 3.10$, $p = .003$), followed by the cohort case ($\beta = 74.91$, $SE = 32.37$, $t = 2.32$, $p = .024$) and then by the carrier word case ($\beta = 66.74$, $SE = 32.29$, $t = 2.07$, $p = .042$). Patterns are different under the Phonological Load condition though. With a phonological load, only the embedded word primes produced significant priming ($\beta = 59.72$, $SE = 29.98$, $t = 2.06$, $p = .043$). Again this priming effect was significantly weaker than that under the Non-Phonological Load condition, $\beta = 59.52$, SE = 24.44, t = 2.44, p = .015. The other two cases did not produce significant priming (Cohort: $\beta = 34.30$, $SE = 29.00$, $t = 1.18$, $p = .241$; Carrier: $\beta = 34.61$, $SE = 28.99$, $t = 1.19$, $p = .237$). This is exactly what was found in Experiment 6. Cross-load comparisons for each individual type of Related word primes showed that there was a significant difference between the two types of cognitive load for the Embedded word primes ($\beta = 50.97$, $SE = 23.51$, $t = 2.17$, $p = .030$), and a marginally significant cognitive load difference for the Cohort ($\beta = 38.10$, $SE = 23.57$, $t = 1.61$, $p = .107$) and Carrier word primes ($\beta = 38.54$, $SE = 23.18$, $t = 1.66$, $p = .097$). This further confirmed that the Embedded word primes are vulnerable to phonological load, although they still produced robust semantic priming under the phonological load condition.

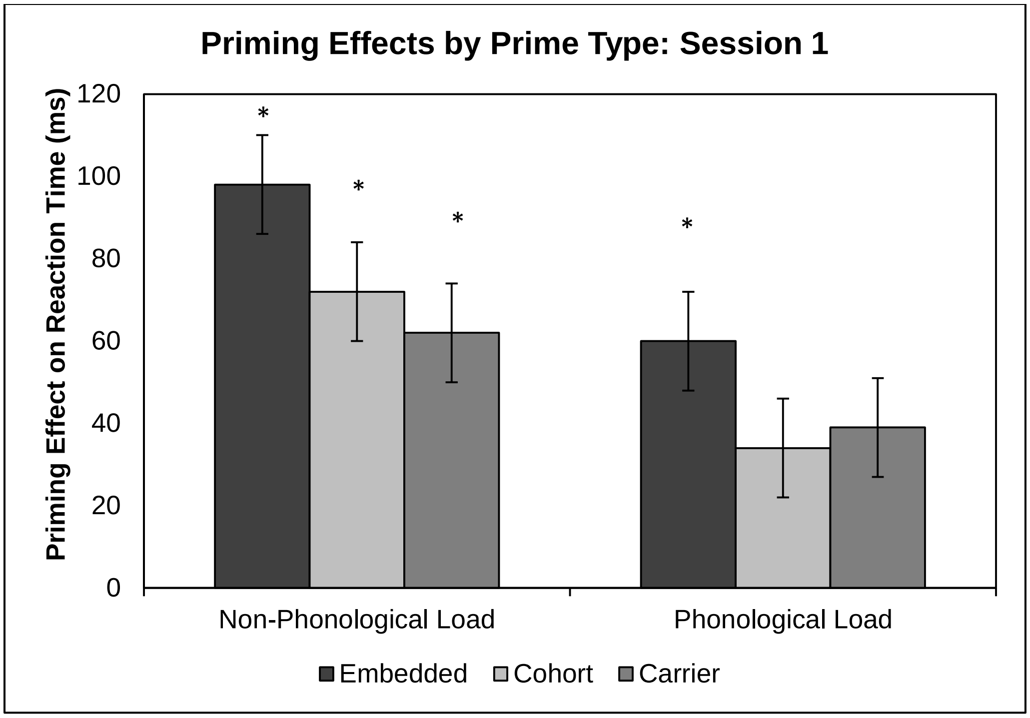

Figure A4. Semantic priming effects on reaction times for each type of related prime under Non-Phonological vs. Phonological Load in the first session. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.

In the second session, the main effects of Prime Type and Load were both significant ($\chi2(3) = 9.54$, $p = .023$; $\chi2(1) = 7.972$, $p = .005$). Again, there was a robust interaction between these two factors (see Figure A5), which was due to a stronger main effect of Prime Type under the Non-Phonological Load condition ($\chi2(3) = 11.57$, $p = .009$) than under the Phonological Load condition ($\chi2(3) = 6.72$, $p = .081$). In particular, under the Non-Phonological condition, the priming effect was significant for the embedded ($\beta = 106.79$, $SE = 32.28$, $t = 3.31$, $p = .002$) and the carrier word primes ($\beta = 71.52$, $SE = 32.29$, $t = 2.22$, $p = .030$), but not for the Cohort ones ($\beta = 40.70$, $SE = 32.36$, $t = 1.26$, $p = .213$). A pattern was found in the Phonological Load condition in the second session, with the embedded (β = 84.04, *SE* = 36.81, *t* = 2.28, *p* = .026) and the carrier (β = 77.08, *SE* = 26.82, *t* = 2.09, *p* = .040) word primes producing robust priming, but the cohort case failing to do so (β = 37.44, *SE* = 36.87, *t* = 1.02, *p* = .314). The comparisons between different cognitive load or each type of Related word primes did not reveal any significant differences. Overall, while there are clearly some similarities to the patterns found in the first session and in the corresponding cases from the core experiments, the item repetition inherent in session 2 makes it somewhat different than those cases.

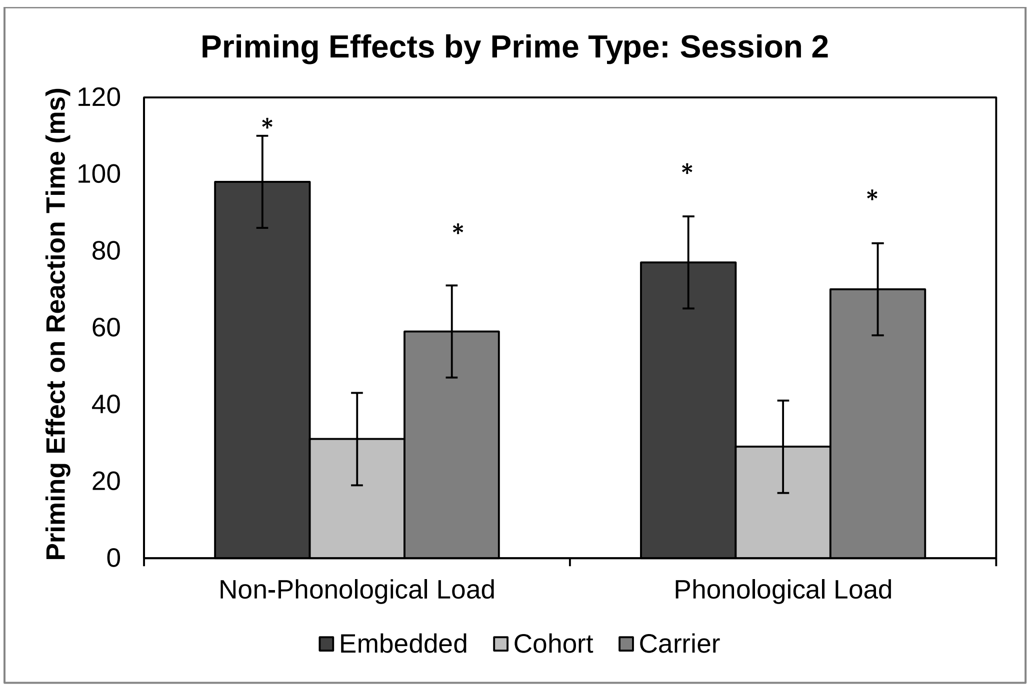

Figure A5. Semantic priming effects on reaction times for each type of related prime under Non-Phonological vs. Phonological Load in the second session. The error bars represent the standard errors.

Note: * indicates that the effect was statistically significant.