The Effect of Cognitive Load on Lexical Activation and Competition

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Abstract of the Dissertation

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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. This dissertation includes a set of priming experiments that investigate the effect of cognitive load on multiple lexical activation and competition. The lexicality of the primes (i.e., Non-Word vs. Word) and the demands of two primary tasks (i.e., Rhyme vs. Association) were manipulated. In six experiments, I tested performance on the two primary tasks under conditions with no additional cognitive load, or with secondary tasks that either imposed phonological load or non-phonological load. The results under the No-Load condition demonstrated that each primary task tapped a different level of processing during speech perception. Specifically, with non-word primes, the Rhyme task reflects the bottom-up activation of sub-lexical representations, whereas with such non-word primes, the Association task reflects the initial access to lexical nodes, which in turn leads to the activation of semantic representations. With word primes, the Rhyme and Association tasks reflect the activation of lexical nodes as a result of bottom-up activation and lexical competition. The results under the Cognitive Load conditions suggest that the initial access of lexical items is relatively automatic, while lexical competition is more resource demanding. More specifically, lexical competition requires cognitive resources that are specific to phonological processing. Accomplishing unnatural tasks, such as using sub-lexical information in a rhyme task, also requires cognitive capacity. In this case, the required resources are not necessarily phonological. The overall result pattern across experiments and tasks provides insights into how different types of cognitive load constrain lexical activation and competition at different levels of processing. Future studies and theoretical models of spoken word recognition should consider both the flexibility and the processing limits of the speech system in order to have a comprehensive understanding of how speech is processed.

Keywords: spoken word recognition; phonological processing; semantic processing; cognitive load; cognitive resources

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NAM = Neighborhood Activation Model

ERP = event-related potential

ANOVA = analysis of variance

t = t statistic

F = F statistic

β = coefficient

SE = standard error

p = p value

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Chapter 1: Introduction

Understanding spoken language is one of the most fundamental cognitive skills human beings have. On one hand, 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. On the other hand, listeners map the acoustic waveform of the sounds produced by speakers to the phonological representations of lexical items, find the right item in long-term memory, activate its semantic representation, and understand a spoken word.

Decades of research have been devoted to the question of how spoken words are recognized with such remarkable efficiency. Models of spoken word recognition make different predictions about the dynamic properties of spoken word processing, but their assumptions are primarily based on empirical evidence coming from optimal listening conditions. Yet, most of our daily speech perception happens under some sort of cognitive load. For instance, we listen to the radio while driving a car, we watch TV shows while preparing food, and we audit lectures while taking notes. To have a more comprehensive understanding about language comprehension, it is important to investigate how the speech system functions under conditions that more complex and difficult. The purpose of this project is to compare spoken word recognition under optimal vs. cognitive load conditions.

Lexical Activation and Competition

In order to recognize a spoken word, listeners need to map the acoustic-phonetic information in the unfolding speech signal to the lexical representations stored in long-term memory. It is widely accepted that when an utterance is heard, multiple lexical candidates are activated in parallel if their phonological representations transiently match the incoming signal.

For instance, the Cohort model (Marslen-Wilson, 1987) assumes that hearing the first few speech segments of a word simultaneously activates a set of lexical candidates that begin with the same segments -- the cohort competitors. The Neighborhood Activation Model [NAM] (Luce & Pisoni, 1998) predicts that hearing a spoken word activates lexical candidates that differ by no more than one phoneme from the speech input, with an emphasis on the global similarity between a candidate's phonological representations and the speech signal. The TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994) models make an intermediate prediction and allow lexical candidates beginning at different points within the speech signal to be activated, with candidates that become activated early having a temporal advantage over those that are activated later.

Although models of spoken word recognition make different predictions about which items may be activated, they all assume that the bottom-up activation of a candidate depends primarily on the goodness-of-fit between the speech signal and the phonological representation of the candidate (when lexical frequency is held constant). The more similar the candidate representation is to the speech input, the stronger the bottom-up activation is. Once the lexical candidates are activated, the speech system needs to evaluate them and select a best candidate to be recognized.

All current models agree that a competition mechanism is necessary for this selection process. One type of competition depends on the degree of match or mismatch between the bottom-up signal and the phonological representations of lexical candidates. According to the Cohort model (Marslen-Wilson, 1987; Marslen-Wilson, Moss, & Van Halen, 1996), the activation of a candidate is reduced when the unfolding speech input is no longer consistent with its representations. 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. Studies on 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), 100ms after (Macizo, van Petten, & O’Rourke, 2012), and 500ms after the carrier words (Zhang & Samuel, 2015). This suggests an extended time window of activation even for less likely candidates (Dahan & Gaskell, 2007; Friedrish, Felder, Lahiri, & Eulitz, 2013; Marslen-Wilson & Welsh, 1978).

A second type of competition comes from co-activated lexical candidates. Models make different assumptions about when lexical competition arises and how it interacts with activation. The TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994) models assume 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. In contrast, models such as NAM (Luce, 1986; Luce & Pisoni, 1998) assert that competition takes place at a decision stage and does not influence the activation level of candidates directly. The activation level of a candidate is evaluated relative to that of all other candidates (weighted by the frequency of each candidate), and this candidate is selected for recognition when it passes a certain threshold. For this type of model, competition only provides evidence for the probability of a candidate being recognized, but does not affect the activation level of the candidate *per se*.

There have been a large number of empirical studies supporting the idea of multiple activation and competition using various tasks, such as 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). However, essentially all of these studies were conducted under optimal conditions, with listeners tested under unusually quiet conditions, focusing only on the critical task without being distracted by other stimuli or by other tasks. In contrast, our daily speech processing usually occurs while our attention is divided.

Despite decades of research on spoken word processing, relatively little attention has been given to word recognition under cognitive load conditions, conditions that are more like our conversations every day. The purpose of the current study is to investigate the effect of cognitive load on spoken word recognition, and more specifically, to examine how cognitive load influences multiple lexical activation and competition.

Effect of Cognitive Load

Previous studies have suggested that speech is sometimes processed in the same way under cognitive load as under optimal conditions. 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 tend to rely more on lexical cues under cognitive load conditions than when there is no cognitive load (Mattys, Brooks, & Cooke, 2009; Mattys, Carroll, Li, & Chan, 2010).

Moreover, previous studies have found that carrier words are able to prime words that are associated with words embedded in them under optimal conditions (Bowers, Davis, Mattys, Damian, & Hanley, 2009; Salverda, Dahan, & McQueen, 2003; van Alphen & van Berkum, 2010; Zhang & Samuel: Experiment 1, 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 (i.e., “nap”), whereas the isolated embedded words (i.e., “nap”) are still able to produce significant associative priming (Zhang & Samuel: Experiment 4, 2015). These results suggest that cognitive load constrains the speech system’s ability to consider multiple lexical candidates at the same time, although it still allows the candidate that perfectly matches the speech signal to become activated. This constraint poses a major potential challenge to the most widely accepted models discussed above, because the multiple activation and competition that they depend on may not occur when listening conditions become more difficult. Zhang and Samuel (2015) have proposed that the consideration of multiple lexical candidates during speech perception may require processing capacity. 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 the capacity to process multiple candidates as it does under optimal conditions.

A fundamental unresolved question is whether cognitive load impairs activation, competition, or both. Although models of spoken word recognition have proposed these two processes during speech perception, none of them explicitly addresses which of the processes might depend on cognitive resources. In Zhang and Samuel's (2015) study, significant associative priming was found for isolated embedded words under cognitive load. This indicates 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 largely constrained. It is possible that cognitive load prevents alternative candidates from being activated in the first place, but it is also possible that although the alternative candidates are activated under cognitive load, their ability to compete with the strongest candidate (normally, the correct item) is limited.

Studies of visual word recognition (Neely, 1991; Valdes, Catena, & Mari-Beffa, 2005) and auditory homophone and ambiguous word perception (Connine, Blasko, & Wang, 1994; Swinney, 1979) have suggested that mapping sensory information onto lexical representations occurs early in processing and may not require much attentional control. In contrast, distinguishing among lexical candidates and inhibiting inappropriate ones have been thought to take more time (Marslen-Wilson, 1987; Swinney, 1979) and to be relatively costly in terms of processing resources (Connine, Blasko, & Wang, 1994). Moreover, research on language deficits has also suggested that processes such as inhibition might be more likely to vary between individuals than activation (McMurry, Samelson, Lee, & Tomblin, 2010). Therefore, it may be that cognitive load has an impact on competition among multiple candidates, rather than on the initial activation of multiple candidates. It is possible that when processing resources are depleted, the activated candidates are more vulnerable to inconsistent input or to inhibition from other candidates that match the speech signal better.

One way to tease apart the processes of multiple activation and competition is to use non-words. According to most (but not all) models of spoken word recognition, words are represented as localist units in long-term memory (cf. Page, 2000). However, non-words do not have such representations in memory (Vitevitch & Luce, 1998). When a spoken word is heard, it activates the representations of similar sounding words in long-term memory and competes with these alternative memory representations. In contrast, when a non-word is heard, it can still activate lexical representations that are partially consistent with it in memory and produce bottom-up inhibition, but there is no way for the non-word to compete with words at the lexical level (Shtyrov, Kujala, Pulvermuller, 2009; Vitevitch & Luce, 1998). Therefore, if cognitive load affects lexical competition rather than activation, hearing a non-word should still be able to activate lexical candidates that are similar to it under cognitive load. The experiments in the current project took advantage of this distinction.

The Current Project

The purpose of the current project was to investigate lexical activation and competition under optimal vs. cognitive load conditions. According to current models, access of a lexical item should activate both the semantic representation and phonological representation of this item. The current project also aimed to examine whether cognitive load had a different effect on the processing of these two representations. To distinguish phonological processing and semantic processing, two primary tasks were used. Specifically, on each trial, participants listened to a prime, followed by an auditory target, and made either a rhyme decision or an associative decision on a visual probe that was presented at the same time as the target. The rhyme task was used to index phonological processing, and the association task was used to index semantic processing. The rationale here is that if the activation of the phonological representation of a target is enhanced by hearing a prime, there should be a priming effect for the rhyme decision; similarly, if the semantic representation of a target is supported by hearing a prime, there should be priming for the associative decision.

The current project also investigated whether lexical activation and/or competition required cognitive resources that are specific to speech processing. Therefore, two types of cognitive load tasks were imposed on the primary tasks. The participants needed to memorize either capital letters or unnamable non-alphabetical (i.e., Chinese) characters while performing the primary tasks, and to recognize them later. Since the participants had to rehearse 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. In contrast, the participants were unable to rehearse any of the non-alphabetical characters. Although it is possible that some participants would name some characters as certain symbols the characters looked like, this character recognition task should mostly impose a non-phonological load and require speech-irrelevant resources. The hypothesis was that if lexical activation and/or competition required resources that are specific to speech, the primary tasks should be impaired only by the letter recognition task. However, if general cognitive resources were needed, performance on the primary tasks should be impaired by both cognitive load tasks.

Two sets of experiments were conducted, with three experiments in each set. The first set of experiments (Experiments 1-3) used non-words as primes to examine the effect of cognitive load on processing when there was no lexical competition between the primes and the targets (Vitevitch & Luce, 1998). The second set of experiments (Experiments 4-6) used real words as primes to examine the effect of cognitive load on lexical competition. The rationale was that if cognitive load affected only lexical activation, the two sets of experiments should show similar impairment. If cognitive load only affected lexical competition, the primary tasks should only be impaired in the second set of experiments. If cognitive load affected both, then we should see impairment in both sets of experiments, but this effect should be more robust in the second set.

Experiments 1 and 4 were baseline experiments, in which only the primary tasks were tested and there was no additional load task. In Experiments 2 and 5, a letter recognition task was added to the primary tasks to impose a phonological load. In Experiments 3 and 6, a character recognition task was added to impose a non-phonological load. To make sure that the two cognitive load tasks had the same level of difficulty and had a similar influence on a primary task, a pilot study was conducted before the main experiments to compare participants' performance on these two load tasks while doing a lexical decision task.

In the next chapter, I describe the methodology and results of the pilot test. In Chapters 3 and 4, I describe the materials, methodology and results of the two sets of experiments, respectively. In Chapter 5, I summarize and compare the results across the six experiments. And finally, in the last chapter I discuss the implications of these findings and suggest future directions for research on this topic.

Chapter 2: Pilot Study

Participants

Twenty-two undergraduate students from Stony Brook University participated in the pilot 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 main 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 standard 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 word 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 an additional 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 recognize a consonant presented later. All letters were presented in upper case. On each trial, a fixation cross was presented at the center of a screen for 500 ms, followed by a four-consonant string at the same location for 2000 ms. The participants were asked to keep this string in mind during the trial. After the string disappeared, they 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 single upper case consonant was presented at the center of the screen. The participants were asked to decide whether this letter had been presented in the string they saw at the beginning of the trial; 50% of the time it had been. 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 recognize a character presented later. 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. The presentation method for the character recognition task was the same as the letter recognition task, except that a single character was presented initially, rather than four letters. As in the phonological load task, on half of the trials the correct response was “YES”.

Table 1. Stimulus Samples for Chinese Characters Used in the Pilot Test (with Number of Strokes in Parentheses; these numbers were not shown to the subjects). The Same Set of Chinese Characters was also used in Experiments 3 and 6.

Trials	**First Character**	**Second Character**
	丐 (4)	丐 (4)
	五 (4)	五 (4)
Same Trials	车 (4)	车 (4)
	牙 (4)	牙 (4)
	少 (4)	少 (4)
	开 (4)	干 (3)
	无 (4)	云 (4)
Different Trials	犬 (4)	太 (4)
	升 (4)	夭 (4)
	午 (4)	矢 (5)

Up to three participants were tested at the same time in a sound shielded booth. One third of the word pairs were presented in the no-load condition, in which they were tested only on the primary task. One third of the stimuli were presented with the letter recognition load task, and the rest were presented with the character 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

An Analysis of Variance (ANOVA) was conducted on reaction times and accuracies on the primary task under different conditions, as well as on the performance on the two cognitive load tasks. For the primary task, the accuracies were very similar under the three conditions (with the accuracies all being 92%), $F < 1$. There was a significant effect of condition on reaction times for the primary task, $F(2, 42) = 8.59$, $p = .001$. The participants responded faster in the no-load condition than with the letter recognition load (924 ms vs. 1033 ms, $p = .003$), and the character recognition load task (924 ms vs. 1011 ms, $p = .032$). The two load conditions did not differ from each other ($p = .998$). For the cognitive load tasks themselves, there was no significant difference between the letter recognition task and the character recognition task on accuracy (89% vs. 90%, $t(21) = -.04$, $p = .966$). The average reaction time on the letter recognition task was longer than that on the character recognition task (842 ms vs. 776 ms, $t(21) = 2.70$, $p = .013$).

The results of the pilot study demonstrated that the two cognitive load tasks had a similar level of difficulty, and more importantly, they had similar influence on the primary task. Therefore, they were used in the main experiments to impose cognitive load.

Chapter 3: Non-Word Primes (Experiments 1-3)

The first set of experiments used non-word primes to examine how close an auditory prime and its target needed to be in order for the prime to activate its target under No-Load (Experiment 1), Phonological Load (Experiment 2), and Non-Phonological Load conditions (Experiment 3). These experiments tested how non-words prime the phonological and semantic information of their targets, as a function of the goodness-of-fit between the primes and the targets. Specifically, each target word (e.g., **accent**) was preceded by three types of related non-word primes. One type of related prime was created by deleting the last one or two phonemes of the target (e.g., *accen_*). The second type was created by replacing the last or the last two phonemes of the target (e.g., *accend*). The final prime type was made by appending one phoneme to the target (e.g., *accenty*). In this way, the primes with a Deletion or a Replacement provided part of the phonological information of the targets, but there was no inconsistent phoneme in the primes with a Deletion. In contrast, the primes with an Addition contained all the phonemes of the targets, but also included extra signal.

Method

Participants

Each of the three experiments recruited 54 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

Half of the subjects were told to make a Rhyme judgment for their primary task, and half were given a semantic Association task (see below). For the primary tasks, 72 bi-syllabic words were chosen as critical targets, and each target was paired with three types of Related primes and an Unrelated prime. 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 consonant with another consonant or by replacing the last vowel with another vowel. For primes with an Addition, 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. Four lists were created, and each critical target was 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 non-word that rhymes with it and a word that is associated with it were selected as visual probes for the Rhyme decision task and the Associative decision task, respectively. Table 2 provides examples of the critical stimuli used in the two primary tasks.

Table 2. Stimulus Sample for Each Type of Prime Used in the Primary Tasks in Experiments 1, 2 & 3. Primes and Targets were Presented Auditorily, whereas Rhyming and Associated Probes were Presented Visually

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

Each list of stimuli also included 72 control pairs and 180 filler pairs. For the control trials, there were the same number of pairs in the Deletion, Replacement, Addition and Unrelated trials as for the critical stimuli. Each control target was paired with a visual non-word probe that does not rhyme with it for the Rhyme task, and with a visual word probe that is not associated with it for the Association task. Therefore, the control pairs resulted in "NO" responses in both primary tasks. For the filler pairs, the non-word primes were unrelated to the targets. Half of the filler pairs had visual probes that Rhyme or are Associated with the targets, leading to "YES" responses in the primary tasks, while the other half had unrelated visual probes, leading to "NO" responses. The design ensured that no prime or target was presented to a given subject more than once.

All the non-word primes and targets were recorded by a speaker of standard 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 associate word 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 (3.52) was significantly higher than that for the control targets (1.32), $t(9) = 24.07$, $p < .001$.

The two cognitive load tasks used the same materials as those in the pilot test. Consonants (except for R and L), written in capital letters, were used for the letter recognition load task. Chinese characters with a Uni-structure and with 3-5 strokes were used for the character recognition load task.

Design and Procedure

For each experiment, the participants were randomly divided into two groups and performed either the Rhyme task or the Association task. Up to three participants were tested at the same time in a sound shielded booth. Each experiment was a 4 Prime Type (Deletion vs. Replacement vs. Addition vs. Unrelated) * 2 Task (Rhyme vs. Association) factorial design, with Prime Type as a within-subject factor and Task as a between-subject factor.

In Experiment 1 (under No-Load), the participants were tested only on the primary tasks. They listened to non-word and word 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 non-word 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 (Association task) or non-word (Rhyme task) was presented at the location of the fixation cross. The participants needed to decide whether the visual probe rhymed (Rhyme group) or was associated (Association group) 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.

In Experiment 2 (under Phonological Load), a concurrent letter recognition task was added to the primary tasks. For each trial, a fixation cross was presented at the center of a screen for 500 ms, followed by a four-consonant string presented in capital letters at the same location for 2000 ms. The participants were asked to keep this string in mind during the trial. After the string disappeared, they heard a non-word prime followed by a target after a 300 ms ISI, and saw a visual probe presented at the onset time of the auditory target. The participants were asked to decide whether the visual probe rhymed (Rhyme group) or was associated (Association group) with the target by pressing the "YES" or "NO" button on the button board. They were asked to respond as quickly and as accurately as possible, and the reaction time was recorded from the onset of the target. After they had responded for the primary task, or if they had failed to respond within 3000ms, an upper case consonant was presented at the center of the screen. The participants needed to decide whether this letter was presented in the string they saw at the beginning of the trial, again 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 tested consonant was presented in the string, while for the other half it was not.

In Experiment 3 (under Non-Phonological Load), a concurrent character recognition task was added to the primary tasks. The procedure of Experiment 3 was similar to that of Experiment 2, except that a Chinese character was presented before and after the participants heard each non-word and word pair, and they needed to decide whether the second character was the same as the first one or not. For half of the trials, the participants saw the same character twice within a trial, while for the other half, they saw different characters.

Results

In Experiment 1, three participants in the Rhyme group and two participants in the Association group were removed from analyses because their error rates on the primary tasks exceeded 30%. In Experiments 2 and 3, three participants were removed from analyses for each primary task for each experiment, because they either had error rates over 30% on the primary tasks or they failed to respond on more than 30% of the trials on the cognitive load tasks. Across the rest of the participants, the average accuracies for the Rhyme task and Association task were 93% and 85% for Experiment 1, 94% and 89% for Experiment 2, and 94% and 90% for Experiment 3. For the letter recognition task (Experiment 2), the average accuracy was 71% for the Rhyme group, and 72% for the Association group. For the character recognition task (Experiment 3), the average accuracy was 70% for the Rhyme group, and 69% for the Association group. The accuracy rates for the two cognitive load tasks show that, as desired, the tasks were demanding (hence, far from ceiling performance) but possible to do (hence, well above chance).

Given the satisfactory performance on the cognitive load tasks and the high accuracy on the primary tasks, the primary focus here will be on reaction time analyses of the primary tasks. Data were analyzed in the same way for all three 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. Reaction times for the correct responses in the primary tasks 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). Each experiment was modeled as a 4 Prime Type (Deletion vs. Replacement vs. Addition vs. Unrelated) * 2 Task (Rhyme vs. Association) factorial design.

For each individual 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, 2013; Barr, Levy, Scheepers & Tily, 2013). The maximal random factor structure included by-subject and by-item intercepts, by-Subject and by-Item slopes for Prime Type and Task. However, the maximal model failed to converge for all three experiments. The maximal structure was then progressively simplified by excluding each random factor from the maximal structure. For all three experiments, the first model that converged included the by-subject and by-item intercepts only, and this model was used as the base model.

Fixed effects were then evaluated by testing the increase in model fit when each fixed factor was added to the base model. A likelihood ratio test was used to compare the fit between models (Baayen, Davidson, & Bates, 2008). The main effects of the fixed factors were assessed by adding Prime Type and Task individually to the base model, and the interaction between them was assessed by comparing a model including these two factors to a model including both them and their interaction term (Chang, 2010; Mattys, Barden, & Samuel, 2014; Zhang & Samuel, 2015). For each analysis, I report the model estimates (β), standard errors (*SE*), *t* values, and *p* values that were obtained from the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2013).

Experiment 1: No-Load

In the first experiment, participants performed only the primary tasks with no additional cognitive load. Figure 1 shows the priming effect (reaction time difference between each type of

Related trial and Unrelated trials) in each primary task under No-Load. Overall, the main effect of Prime Type was significant, χ^2 (3) = 35.63, $p < .001$. Participants responded faster in all types of Related trials (Deletion: 813 ms; Replacement: 811 ms; Addition: 795 ms) than in the Unrelated trials (847 ms) ($\beta = 28.89$, $SE = 8.16$, $t = 3.54$, $p < .001$; $\beta = 30.98$, $SE = 8.08$, $t = 3.83$, $p < .001$; $\beta = 47.82$, $SE = 8.13$, $t = 5.88$, $p < .001$). Moreover, the participants responded faster in the Addition trials than in the Deletion and Replacement trials ($\beta = 18.94$, $SE = 8.08$, $t = 2.34$, $p = .019$; $\beta = 16.84$, $SE = 8.13$, $t = 2.07$, $p = .038$). The main effect of Task was not significant, χ^2 (1) = .42, $p = .517$, with similar reaction times on the Rhyme task and on the Association task (808 ms vs. 825 ms, $\beta = 18.63$, $SE = 29.21$, $t = .64$, $p = .527$). The interaction between Prime Type and Task was not significant, χ^2 (3) = 3.00, $p = .391$. The reaction times were then analyzed individually for each primary task.

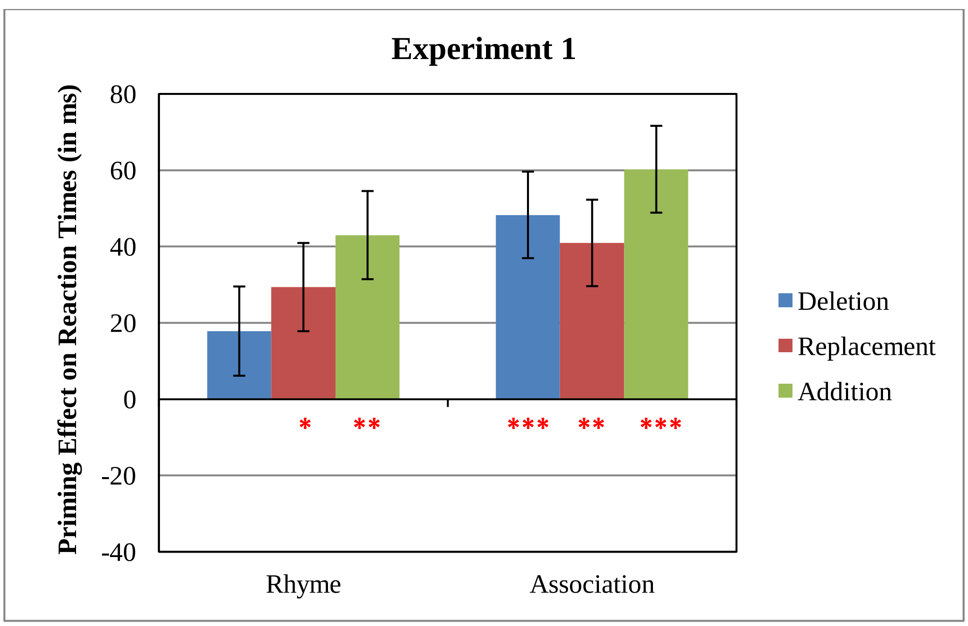


Figure 1. Priming effects on reaction times (reaction time difference between each type of Related trial and Unrelated trials) for each type of Related prime after hearing non-word primes in Experiment 1 (under No-Load).

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

The raw reaction times for each type of Related prime and the statistical results for priming effects are shown in Table 3. For the Rhyme task, the reaction times in the Replacement and Addition trials were significantly faster than those in the Unrelated trials. There was no significant difference between the Deletion trials and the Unrelated trials, and the difference between the Addition trials and the Deletion trials was marginally significant ($\beta = 21.19$, $SE = 11.29$, $t = 1.88$, $p = .061$). For the Association task, the participants responded significantly faster after all types of Related primes than after the Unrelated ones, and the response times in the Addition trials were marginally faster than those in the Replacement trials ($\beta = 19.93$, $SE = 11.51$, $t = 1.73$, $p = .083$).

Table 3. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Non-Word Primes in Experiment 1 (Under No-Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
Rhyme	Deletion	813	830	16.07	11.34	1.42	0.156	
	Replacement	801		23.55	11.33	2.08	0.038	*
	Addition	787		37.25	11.38	3.27	0.001	**
Association	Deletion	815	863	42.42	11.69	3.60	< .001	***
	Replacement	822		38.84	11.56	3.36	0.001	**
	Addition	803		58.77	11.55	5.09	< .001	***

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

Experiment 2: Phonological Load

Subjects in Experiment 2 had the same primary tasks as in Experiment 1, but in addition had to maintain four consonants in memory while doing the primary tasks. The letter recognition task was intended to draw on the listeners' phonological processing resources and thus impose a Phonological load. Figure 2 shows the priming pattern for each type of Related trial for each primary task under Phonological Load.

Under this load, the main effect of Prime Type was still significant, χ^2 (3) = 9.50, p = .023. The participants responded faster in the Deletion (941 ms) and Addition trials (930 ms) than in the Unrelated trials (959 ms) (β = 21.37, SE = 11.04, t = 1.94, p =.053; β = 33.35, SE = 11.07, t = 3.01, p = .003). The reaction times in the Replacement trials (948 ms) did not differ significantly from those in the Unrelated trials (β = 14.10, SE = 11.02, t = 1.28, p =.201), and were marginally slower than those in the Addition trials (β = 19.24, SE = 11.00, t = 1.75, p = .080). The main effect of Task was not significant, χ^2 (1) = 1.45, p = .227, even though the participants responded more slowly in the Rhyme task than in the Association task (971 ms vs. 919 ms, β = 40.98, SE = 41.98, t = 1.19, p = .239). Presumably this reflects the higher variance associated with a between-subject comparison (recall that Task was between-subject) than with the within-subject comparisons within each task. The interaction between Prime Type and Task was significant, χ^2 (3) = 9.27, p = .026. The reaction times were then analyzed for each primary task individually.

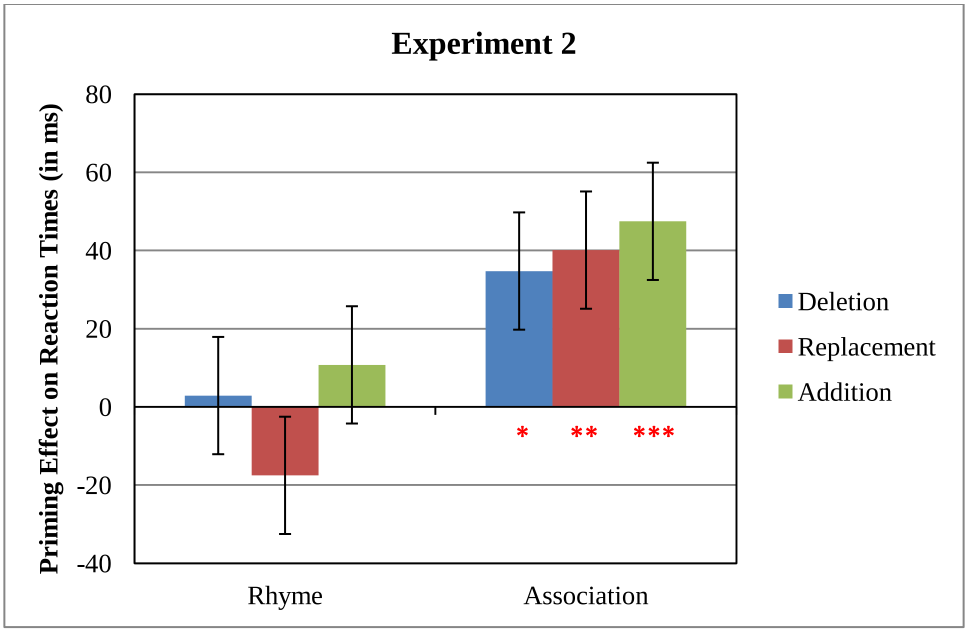


Figure 2. Priming effects on reaction times for each type of Related prime after hearing non-word primes in Experiment 2 (under Phonological Load).

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

The raw reaction times and the statistical results for the priming effects are shown in Table 4. For the Rhyme task, the reaction times were comparable between each type of Related trial and the Unrelated trials, but the participants responded slightly faster in the Addition trials than in the Replacement trials ($\beta = 28.82$, $SE = 15.39$, $t = 1.78$, $p = .060$). As is clear in Figure 2, the Phonological Load task essentially wiped out priming effects when listeners were required to make the phonological Rhyme judgment. In contrast, for the Association task, participants responded significantly faster after all types of Related primes than after the Unrelated primes, and different types of Related trials did not differ from each other, *ps* > .200.

Table 4. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Non-Word Primes in Experiment 2 (Under Phonological Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
	Deletion	967		6.17	15.35	0.40	0.688	
Rhyme	Replacement	987	970	-17.25	15.27	-1.13	0.259	
	Addition	959		11.57	15.43	0.75	0.453	
	Deletion	915		38.30	15.82	2.42	0.016	*
Association	Replacement	910	950	48.45	15.97	3.03	0.002	**
	Addition	902		56.80	15.82	3.59	<.001	***

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

Experiment 3: Non-Phonological Load

Subjects in Experiment 3 had the same primary tasks as in Experiments 1 and 2, but in addition had to maintain a Chinese character in memory while doing the primary tasks. The Chinese character recognition task was intended to require memory resources but not to specifically target phonological processing, and thus to primarily impose a Non-Phonological Load. Figure 3 shows the priming effects for each type of related trial for each primary task under Non-Phonological Load. Although a different type of cognitive load was imposed on the primary tasks in Experiment 3, the Non-Phonological Load task produced very similar results to the Phonological Load task in Experiment 2 – compare the priming patterns in Figures 2 and 3.

Under this type of load, the main effect of Prime Type was significant, χ^2 (3) = 9.11, p = .044. Only the Addition trials (930 ms) yielded significantly faster responses than the Unrelated trials (956 ms) (β = 30.56, *SE* = 11.01, *t* = 2.78, *p* = .006). The reaction times in the Deletion (951 ms) and Replacement trials (947 ms) did not differ from those in the Unrelated trials (β = 9.73, *SE* = 11.05, *t* = .88, *p* = .379; β = 12.54, *SE* = 11.09, *t* = 1.13, *p* = .258), and they were both marginally slower than those in the Addition trials (β = 20.84, *SE* = 10.94, *t* = 1.91, *p* = .057; β = 18.02, *SE* = 10.93, *t* = 1.65, *p* = .099). The main effect of Task was not significant, χ^2 (1) = .03, *p* = .861, with similar response times in the Rhyme and Association tasks (944 ms vs. 947 ms, β = 9.12, *SE* = 53.61, *t* = .17, *p* = .864). The interaction between Prime Type and Task was marginally significant, χ^2 (3) = 7.22, *p* = .065.

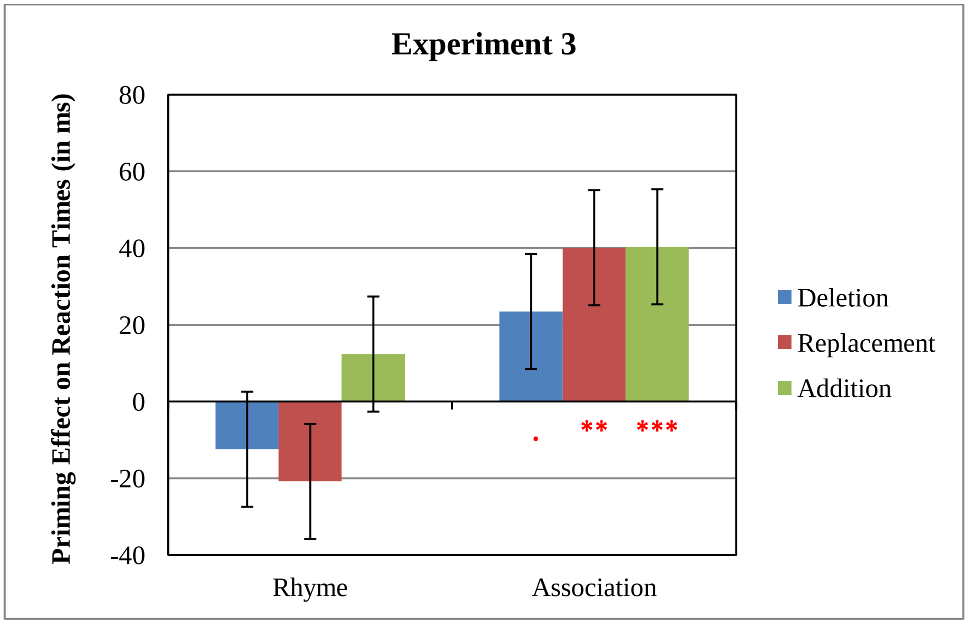


Figure 3. Priming effects on reaction times for each type of related prime after hearing non-word primes in Experiment 3 (under Non-Phonological Load).

Note: *** *p* < .001; ** *p* < .010; **.** *p* < .100

The raw reaction times and the statistical results for the priming effects are shown in Table 5. For the Rhyme task, there was no significant reaction time difference between any type of Related trial and the Unrelated trials, but the reaction times in the Addition trials were significantly faster than those in the Replacement trials (β = 32.04, *SE* = 15.28, t = 2.09, p = .036). For the Association task, the participants responded marginally faster on the Deletion trials than on the Unrelated trials, and responded significantly faster after the other two Related primes than after the Unrelated primes. The Related primes did not differ from each other, *p*s > .200.

Table 5. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Non-Word Primes in Experiment 3 (Under Non-Phonological Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
Rhyme	Deletion	951	939	-6.34	15.40	-0.41	0.681	
	Replacement	960		-16.47	15.48	-1.06	0.287	
	Addition	927		15.57	15.41	1.01	0.312	
Association	Deletion	950	973	26.25	15.82	1.66	0.097	.
	Replacement	933		42.83	15.82	2.71	0.007	**
	Addition	933		46.18	15.68	2.95	0.003	**

Note: *** $p < .001$; ** $p < .010$; **.** $p < .100$

Discussion

The first three experiments measured the priming effects of non-words that differed minimally from their target words, in three different ways: Deleting the word's ending, changing it, or appending an extra vowel or consonant. When there was no additional cognitive load

(Experiment 1), non-word primes with a Replacement and those with an Addition produced significant Rhyme priming, and all three types of Related primes produced robust Associative priming. This indicates that hearing non-word primes generally facilitated the phonological and semantic processing of similar target words. Moreover, there was an advantage for the Addition trials in both primary tasks over the other two types of primes, suggesting that the activation of a lexical candidate is enhanced by hearing all of its phonological information, even if there are additional inconsistent sounds. This is inconsistent with the prediction of the Cohort model that the activation of a lexical candidate will decrease when the speech signal becomes inconsistent with the candidate (Marslen-Wilson, 1987; Marslen-Wilson, Moss, & Van Halen, 1996).

Imposing a Phonological Load (Experiment 2) or a Non-Phonological Load (Experiment 3) on the primary tasks caused very similar changes. In both cases there was no Rhyme priming regardless of the type of prime, whereas Associative priming was still significant. Thus, the two types of cognitive load had similar effects on the activation of lexical candidates after hearing non-words. They both impaired phonological activation severely, but did not affect semantic activation as much. This equivalence is somewhat surprising and therefore interesting, as a priori one might expect that the letter recognition task that involves phonological encoding would have had a greater impact on the Rhyme task. Both the letter recognition task and the Rhyme task draw on phonological processing, and would therefore be expected to show greater mutual interference (e.g., Baddeley, 1992; Baddeley & Hitch, 1974) than a pairing of either a Non-Phonological Load (the Chinese character recognition task) or a primary task that is more semantic than phonological (the Association task).

Chapter 4: Word Primes (Experiments 4-6)

The second set of experiments used real words as primes to examine the effect of cognitive load on lexical competition, as a function of the similarity between the primes and their targets. Similar to the first set of experiments, the amount of phonological information shared between a prime and its target, and inconsistent information contained by a prime, were manipulated. The purpose was to investigate the effect of word primes that provided part of the phonological information of the targets without any extra signal (similar to the non-word Deletion trials), those that provided part of the phonological information but contained inconsistent signal (similar to the non-word Replacement trials) and those that contained all the phonological information of the targets but also included additional signal (similar to the non-word Addition trials). As in the first set of experiments, the test here compared priming of targets under the No-Load (Experiment 4), Phonological Load (Experiment 5), and Non-Phonological Load conditions (Experiment 6). Three types of related word primes, analogous to the three types of related non-word primes in the first set of experiments, were tested. For the first type, each prime was an initial Embedded word of its target (e.g., *nap*_ _ _ - **napkin**). For the second type, each prime was a Cohort member of its target (e.g., *access* - **accent**). For the last type, each prime was a Carrier word of its target (e.g., *napkin* - **nap**).

Method

Participants

Each of the three experiments recruited 54 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 none of them had participated in the previous experiments. They received research credit for their participation.

Materials

For the primary tasks, 18 Embedded-carrier word pairs, 18 Cohort word pairs, 18 Carrier-embedded word pairs and 18 Unrelated word pairs were selected as critical stimuli. 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 the first syllable. The Unrelated pairs included words that matched the three Related pairs in frequency and number of syllables. Similar to the previous experiments, a rhyming non-word and an associated word were selected for each critical target as the visual probes in order to test phonological and semantic processing, respectively. Table 6 provides examples of the critical stimuli used in the primary tasks.

Table 6. Stimulus Sample for Each Type of Prime Used in the Primary Tasks in Experiments 4, 5 & 6. Primes and Targets were Presented Auditorily, whereas Rhyming and Associated Probes were Presented Visually

Prime Type	**Word Prime**	**Target**	**Rhyming Probe**	**Associated Probe**
Embedded	*nap_ _ _*	**napkin**	VAPKIN	WIPE
Cohort	*access*	**accent**	BACCENT	LANGUAGE
Carrier	*fancy*	**fan**	HAN	AIR
Unrelated	*collar*	**essay**	TESSAY	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 non-word probe that does not rhyme with it (Rhyme group) and with a visual

word probe that is not associated with it (Association group), 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 a rhyming probe and 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 for the first three experiments, and were edited in the same way. All the visual probes were presented in capital letters. Again, ten undergraduate students who did not participate in the main experiments were asked rate the strength of association between each target and its potential semantic associate for the critical and control targets on a 4-point scale, with “1” indicating no association and “4” indicating a strong association. The rating for the critical targets (3.58) was significantly higher than that for the control targets (1.22), $t(9) = 24.39$, $p<.001$, and the ratings overall were quite similar to those for the stimuli in Experiments 1-3.

For the letter recognition task and the character recognition task, the materials were the same as those in Experiments 2 and 3.

Design and Procedure

Similar to the first set of experiments, Experiment 4 was a Baseline condition, in which only the primary tasks were tested with no additional load. In Experiment 5, the letter recognition task was added to impose a Phonological Load, and in Experiment 6, the character recognition task was added to impose a Non-Phonological Load. For each experiment, the participants were randomly divided into two groups and performed either the Rhyme task or the Association task. Therefore, each experiment was a 4 Prime Type (Embedded vs. Cohort vs. Carrier vs. Control) * 2 Task (Rhyme vs. Association) factorial design, with Prime Type as a within-subject factor and Task as a between-subject factor. The procedures of Experiments 4 to 6 were the same as those of Experiments 1 to 3, respectively, except that all the primes were real words in this set of experiments.

Results

In Experiment 4, data from three participants in the Rhyme group and two participants in the Association group were removed from analyses because their error rates on the primary tasks exceeded 30%. In Experiments 5 and 6, three participants were removed from analyses for each primary task for each experiment, because they either had error rates over 30% on the primary tasks or they failed to respond on more than 30% of the trials on the cognitive load tasks. Across the rest of the participants, the average accuracies for the Rhyme task and Association task were 96% and 90% for Experiment 4, 96% and 92% for Experiment 5, and 95% and 92% for Experiment 6. For the letter recognition task (Experiment 5), the average accuracy was 73% for the Rhyme group, and 72% for the Association group. For the character recognition task (Experiment 6), the average accuracy was 69% for the Rhyme group, and 70% for the Association group. These overall levels of performance on the primary and cognitive load tasks are quite similar to those in the first three experiments.

As in the previous experiments, the focus of the analysis here is on reaction times on the primary tasks. 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, and the data for incorrect trials in the primary task were removed from the analyses. The results of this set of experiments were analyzed in the same way as the first set using mixed effect modeling. For each individual experiment, the data were modeled as a 4 Prime Type (Embedded vs. Cohort vs. Carrier vs. Unrelated) * 2 Task (Rhyme vs. Association) factorial design. The random structure of the mixed model for each individual experiment was built in the same way as before. The first converging model included only the by-Subject and by-Item intercepts, and this model was used as the base model for all three experiments. The main effects and interactions were evaluated in the same way as before.

Experiment 4: No-Load

In Experiment 4, the participants performed only the primary tasks with no additional cognitive load, which is similar to Experiment 1. Figure 4 shows the priming effect for each type of related trial for each primary task under No-Load. Overall, the main effect of Prime Type was significant, χ^2 (3) = 16.21, *p* = .001. The participants responded significantly faster on the Embedded (815 ms) and Carrier trials (820 ms) than on the Unrelated trials (881 ms) (β = 66.17, *SE* = 18.65, *t* = 3.55, *p* = .001; β = 64.74, *SE* = 18.66, *t* = 3.47, *p* = .001), but there was no difference between the Cohort trials and the Unrelated trials (853 ms) (β = 28.97, *SE* = 18.67, *t* = 1.55, *p* = .125). Moreover, the reaction times on the Cohort trials were also slower than those on the Embedded (β = 37.20, *SE* = 18.60, *t* = 2.00, *p* = .050) and Carrier trials (β = 35.77, *SE* = 18.61, *t* = 1.92, *p* = .059). The main effect of Task was also significant, χ^2 (1) = 4.02, *p* = .045, with faster responses on the Rhyme task than on the Association task (808 ms vs. 877 ms: β = 68.78, *SE* = 34.25, *t* = 2.01, *p* = .050). The interaction between Prime Type and Task was significant, χ^2 (3) = 9.01, *p* = .029, reflecting the total absence of priming for the Cohort case on the Rhyme judgment. The reaction times were then analyzed individually for each primary task.

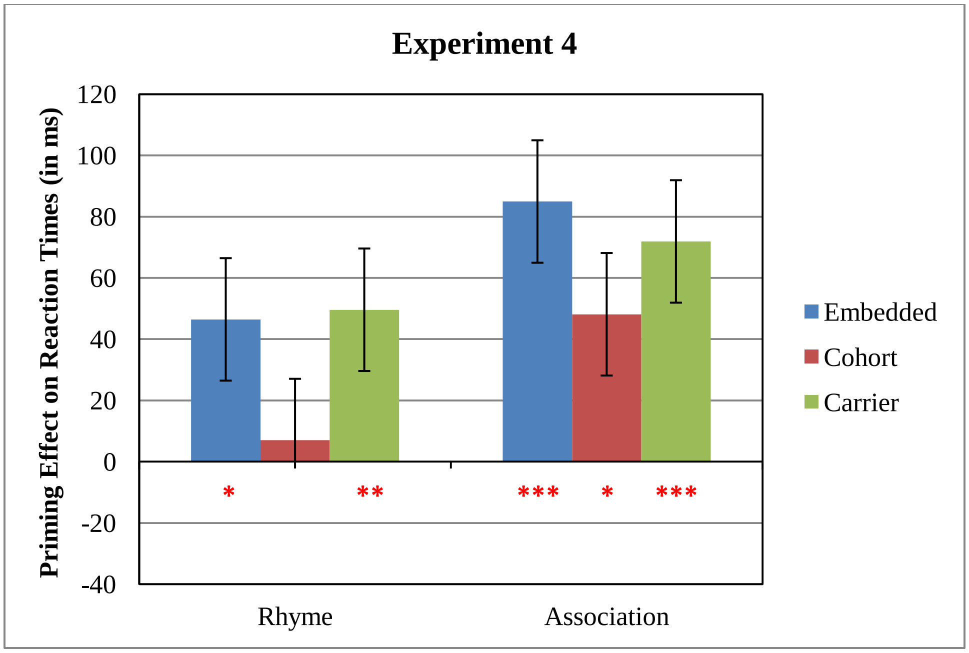


Figure 4. Priming effects on reaction times for each type of related prime after hearing word primes in Experiment 4 (under No-Load).

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

The raw reaction times and the statistical results for the priming effects are shown in Table 7. For the Rhyme task, the participants responded significantly faster on the Embedded and Carrier trials than on the Unrelated trials. In contrast, as noted, the Cohort trials did not differ significantly from the Unrelated trials. Moreover, the participants responded significantly slower on the Cohort trials than on the Embedded ($\beta = 40.20$, $SE = 20.04$, $t = 2.01$, $p = .048$) and Carrier trials ($\beta = 45.20$, $SE = 20.05$, $t = 2.25$, $p = .027$). For the Association task, faster responses were observed for all types of Related primes compared to the Unrelated primes, and the responses were marginally faster on the Embedded trials than on the Cohort trials ($\beta = 34.27$, $SE = 20.32$, $t = 1.69$, $p = .095$).

Table 7. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Word Primes in Experiment 4 (Under No-Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
Rhyme	Embedded	787	834	48.80	20.06	2.43	0.017	*
	Cohort	827		8.61	20.12	0.43	0.670	
	Carrier	784		53.78	20.07	2.68	0.009	**
Association	Embedded	843	928	86.54	20.50	4.22	<001	***
	Cohort	880		52.27	20.49	2.55	0.012	*
	Carrier	856		77.85	20.51	3.80	<001	***

*** $p < .001$; ** $p < .010$; * $p < .050$

Experiment 5: Phonological Load

In Experiment 5, participants had to perform a concurrent letter recognition task while doing the primary tasks, similar to Experiment 2. Figure 5 shows the priming effect for each type of related trial for each primary task under this Phonological Load condition. Overall, the main effect of Prime Type was not significant, χ^2 (3) = 5.86, p = .134. The generally weak priming effects here, compared to what was seen in the previous experiments, indicate that the Phonological Load had a stronger impact. Only the Embedded trials (934 ms) yielded significantly faster responses than the Unrelated trials (979 ms) (β = 49.24, *SE* = 21.99, t = 2.24, p = .029). There was no difference between the other Related trials (Cohort: 972 ms; Carrier word: 960 ms) and the Unrelated trials (β = 11.76, *SE* = 22.03, t = .53, p = .595; β = 25.00, *SE* = 22.00, t = 1.14, p = .260). The reaction times on the Embedded trials were marginally faster than those on the Cohort trials (β = 37.47, *SE* = 21.93, *t* = 1.71, *p* = .092). The main effect of Task was not significant, χ^2 (1) = .72, *p* = .396, although the participants responded somewhat faster on the Rhyme task than on the Association task (941 ms vs. 982 ms: β = 39.06, *SE* = 46.80, *t* = .84, *p* = .408). The interaction between Prime Type and Task was not significant either, χ^2 (3) = 3.01, *p* = .390. The reaction times were then analyzed for each primary task individually.

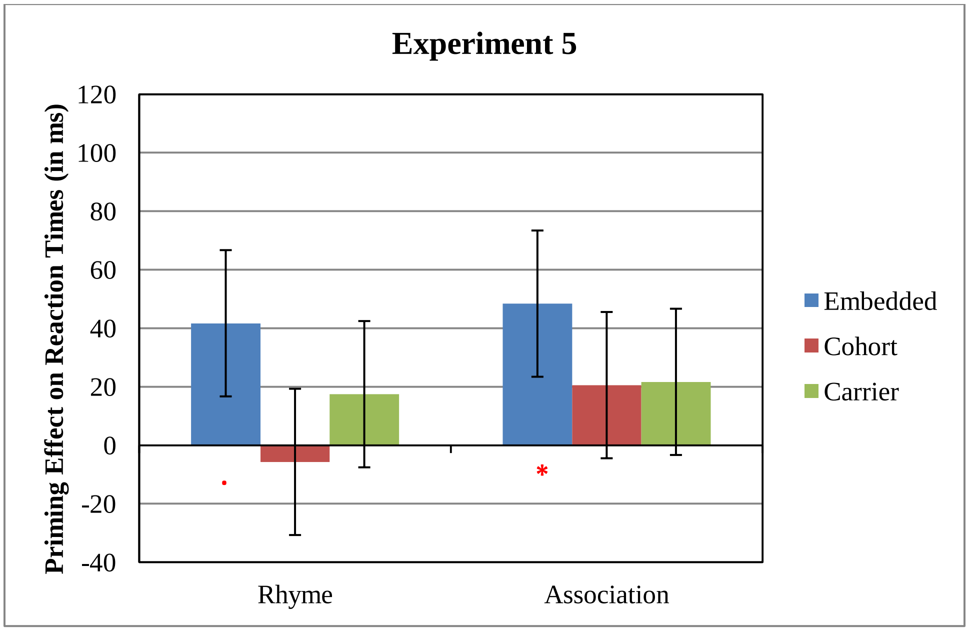


Figure 5. Priming effects on reaction times for each type of related prime after hearing word primes in Experiment 5 (under Phonological Load).

Note: * *p* < .050; **.** *p* < . 100

The raw reaction times for each type of prime and the statistical results for the priming effects are shown in Table 8. For the Rhyme task, only the Embedded primes produced faster responses compared to the Unrelated primes; the response times on the Embedded trials were also significantly faster than those on the Cohort trials (β = 50.15, *SE* = 24.51, *t* = 2.05, *p* = .043). Similarly, for the Association task, there was a significant difference in reaction times between the Embedded trials and the Unrelated trials, while the other types of primes did not differ significantly from each other, *p*s > .200. Clearly, imposing a Phonological Load created substantial interference with the priming provided by words, both on the Rhyme task and on the Association task.

Table 8. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Word Primes in Experiment 5 (Under Phonological Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
	Embedded	913		44.01	24.57	1.79	0.076	.
Rhyme	Cohort	960	954	-6.14	24.62	-0.25	0.804	
	Carrier	937		20.78	24.54	0.85	0.399	
	Embedded	956		54.98	24.74	2.22	0.028	*
Association	Cohort	984	1004	30.42	24.84	1.22	0.224	
	Carrier	983		29.62	24.80	1.20	0.235	

Note: * $p < .050$; **.** $p < .100$

Experiment 6: Non-Phonological Load

In Experiment 6, participants had to perform a concurrent character recognition task while doing the primary tasks, similar to Experiment 3. Figure 6 shows the priming effect for each type of related trial for each primary task under this Non-Phonological Load condition.

Overall, the main effect of Prime Type was significant, χ^2 (3) = 11.65, p = .009. The participants responded significantly faster on the Embedded (943 ms) and Carrier (946 ms) trials than on the Unrelated trials (1003 ms) (β = 67.90, *SE* = 21.97, *t* = 3.09, *p* = .003; β = 62.79, *SE* = 21.99, *t* = 2.86, *p* = .006). There was no significant difference between the Cohort trials (974 ms) and the Unrelated trials (β = 34.69, *SE* = 22.01, *t* = 1.58, *p* = .120), and there was no difference among the three types of Related trials, *p*s < .14. The main effect of Task was also not significant, χ^2 (1) = .01, *p* = .923, with similar response times on the Rhyme task and on the Association task (967 ms vs. 966 ms: β = 4.92, *SE* = 50.61, *t* = .10, *p* = .923). The interaction between Prime Type and Task was not significant either, χ^2 (3) = 2.72, *p* = .518. The reaction times were then analyzed for each primary task individually.

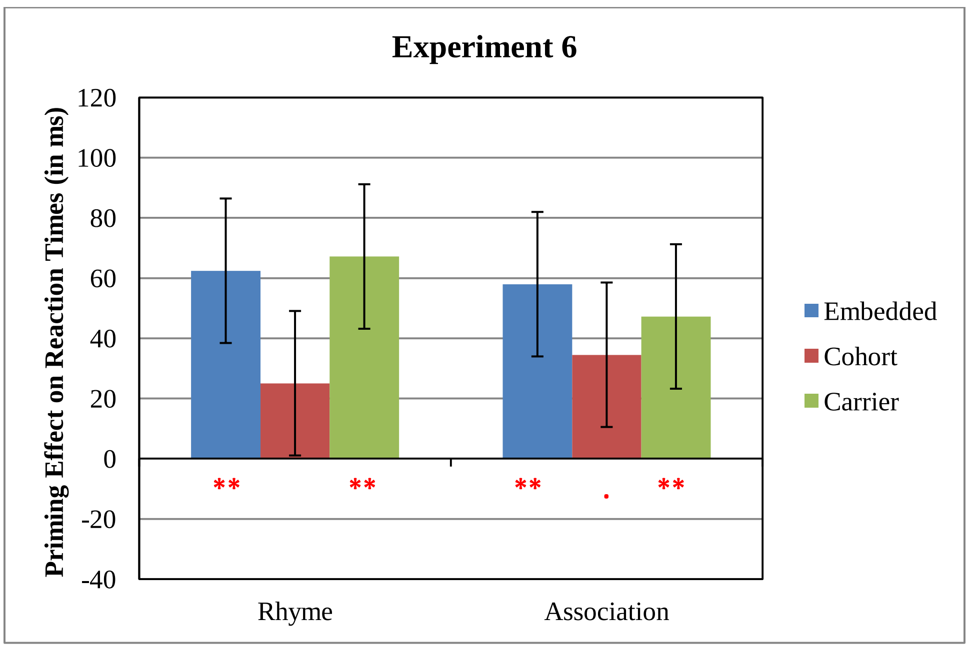


Figure 6. Priming effects on reaction times for each type of related prime after hearing word primes in Experiment 6 (under Non-Phonological Load).

Note: ** *p* < .010; **.** *p* < .100

The raw reaction times and the statistical results for the priming effects are shown in Table 9. For the Rhyme task, the participants responded significantly faster on the Embedded and Carrier trials than on the Unrelated trials, with no significant difference between the Cohort trials and the Unrelated trials. Moreover, the participants responded marginally slower on the Cohort trials than on the other two types of Related trials (β = 45.80, *SE* = 24.32, *t* = 1.88, *p* = .063; β = 42.72, *SE* = 24.35, *t* = 1.76, *p* = .082). For the Association task, all three types of Related primes produced faster reaction times than the Unrelated primes, but the effect for the Cohort primes was only marginal. The Related primes did not differ significantly from each other, *p*s < .400.

Table 9. Raw Reaction Times for Each Type of Related Prime and the Statistical Results for Priming Effects after Hearing Word Primes in Experiment 6 (Under Non-Phonological Load)

Primary Task	**Prime Type**	**Related Trials**	**Unrelated Trials**	***β***	***SE***	***t***	***p***	
Rhyme	Embedded	943	1005	69.69	24.35	2.86	0.005	**
	Cohort	980		23.89	24.45	0.98	0.331	
	Carrier	938		66.61	24.38	2.73	0.007	**
Association	Embedded	943	1001	66.11	24.61	2.69	0.008	**
	Cohort	967		45.72	24.65	1.86	0.066	.
	Carrier	954		58.83	24.65	2.39	0.019	*

Note: ** *p* < .010; * *p* < .050; **.** *p* < . 100

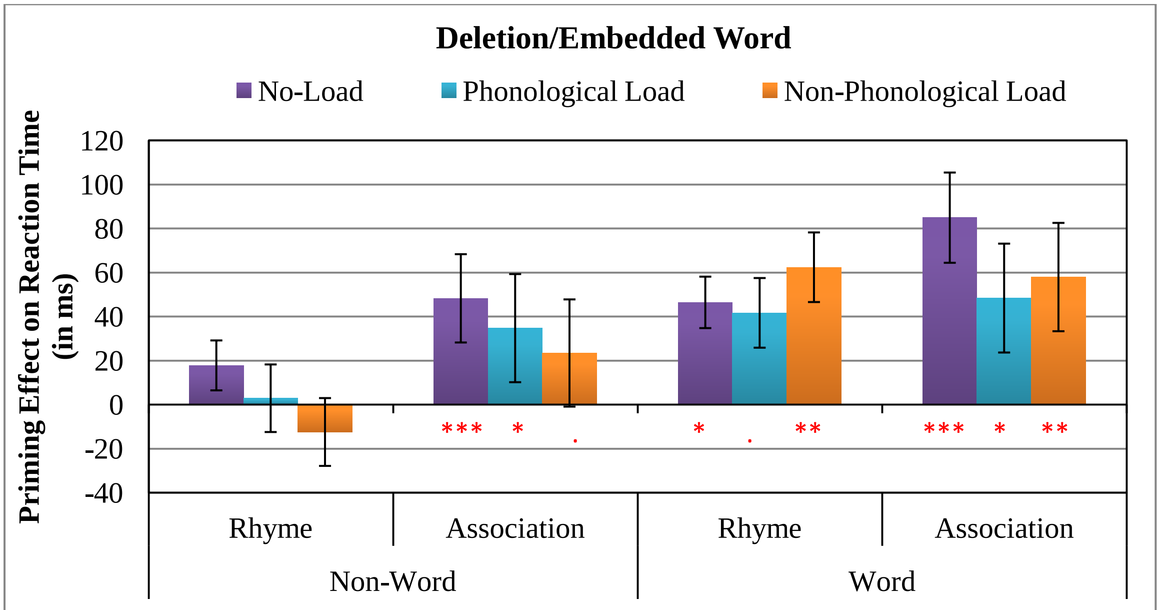
Discussion

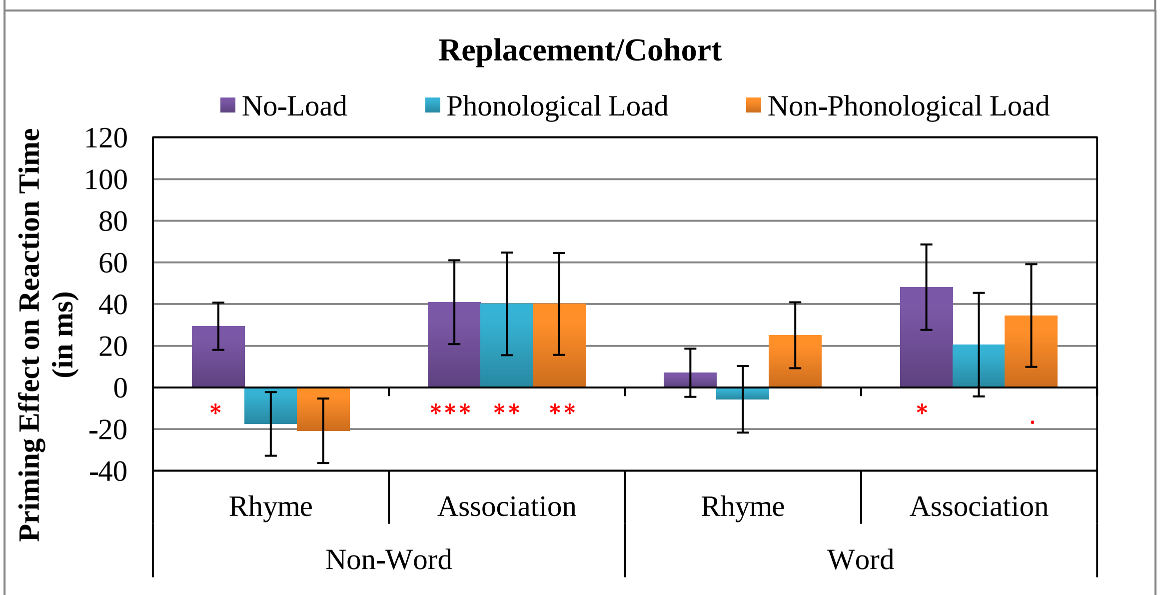
The second set of experiments showed a very different pattern of results than the first set. In Experiment 4, when there was no cognitive load, word primes that either were Carrier words or Embedded words of the targets produced significant Rhyme priming for their targets, and all types of word primes produced robust Associative priming. These results indicate that words were being activated both phonologically and semantically while hearing their Embedded words or Carrier words, despite lexical competition. However, the Cohort primes failed to produce any sign of Rhyme priming, and they produced the weakest associative priming among all types of primes.

Phonological Load and Non-Phonological Load also differed in their impact on the activation of real word primes. In Experiment 5, when a Phonological Load was imposed, only the Embedded primes produced Rhyme priming and Associative priming, suggesting that the phonological and semantic activation of the Cohort and Carrier primes was largely eliminated. However, in Experiment 6, when a Non-Phonological Load was imposed, the result pattern was similar to that of Experiment 4. There was still significant Rhyme priming and Associative priming for the Embedded and Carrier primes. There was no Rhyme priming and only weak Associative priming for the Cohort primes. These results suggest a much weaker impact of Non-Phonological Load than Phonological Load. Recall that with the non-word primes in the first set of experiments, the two types of cognitive load produced relatively similar effects on performance, unlike what was found here with real word primes.

Chapter 5: Summary of the Results

Figure 7 summarizes the result patterns across the six experiments. Recall that the prime-target relations were similar between the two sets of stimuli (i.e., between the non-word and word primes). The major difference among the three types of primes within each set was how closely each type of prime matched the target, and the major difference between the two sets was whether the primes could compete with the targets at the lexical level. Specifically, in both the non-word Deletion (e.g., *accen_* - **accent**) and the Embedded word (e.g., *nap_ _ _* - **napkin**) cases, the targets received only partial bottom-up support from the primes. In both the non-word Addition (e.g., *accenty* - **accent**) and the Carrier word (e.g., *fancy* - **fan**) cases, the targets received full bottom-up support from the primes, but there was also extra signal. In the non-word Replacement (e.g., *accend* - **accent**) and the Cohort word (e.g., access - **accent**) cases, the targets received only partial bottom-up support from the primes, and they also received extra signal.


Deletion/Embedded Word
No-Load
Phonological Load
Non-Phonological Load
Priming Effect on Reaction Time (in ms)
120
100
80
60
40
20
0
-20
-40
*** * .
* . **
*** * **
Rhyme
Association
Rhyme
Association
Non-Word
Word


Replacement/Cohort
No-Load
Phonological Load
Non-Phonological Load
Priming Effect on Reaction Time (in ms)
120
100
80
60
40
20
0
-20
-40
*
*** ** **
* .
Rhyme
Association
Rhyme
Association
Non-Word
Word

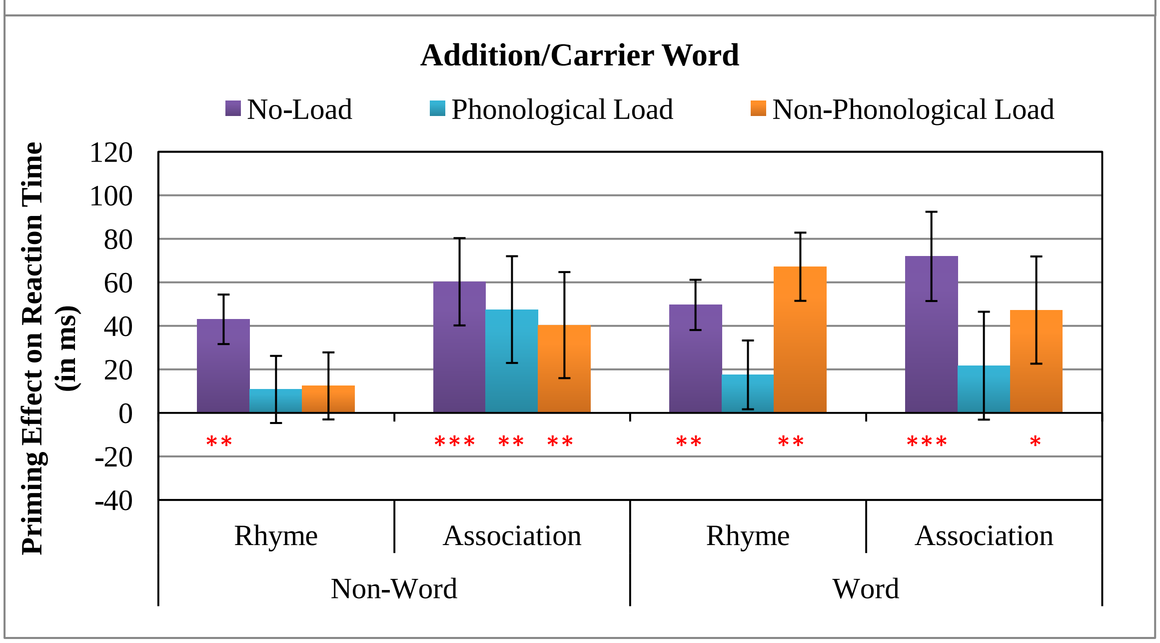

Addition/Carrier Word
No-Load
Phonological Load
Non-Phonological Load
Priming Effect on Reaction Time (in ms)
120
100
80
60
40
20
0
-20
-40
**
*** ** **
** **
*** *
Rhyme
Association
Rhyme
Association
Non-Word
Word

Figure 7. A summary of priming effects across the six experiments. The “Deletion”, “Replacement” and “Addition” cases refer to different types of non-word primes tested in Experiments 1-3, and the “Embedded Word”, “Cohort Word” and “Carrier Word” cases refer to different types of word primes tested in Experiments 4-6.

Note: *** $p < .001$; ** $p < .010$; * $p < .050$; . $p < .100$

No-Load

As shown in Figure 7, when there was no cognitive load (Experiment 1), the Addition trials produced the strongest priming among all types of non-word primes in both primary tasks, suggesting the importance of hearing all of the phonological information for activating the targets when the primes were non-word. The Replacement trials and Deletion trials produced similarly weaker effects, indicating that hearing inconsistent information in the non-word primes did not reduce target activation. Moreover, there was a clear disadvantage for the Deletion case in the Rhyme task but not in the Association task as the Rhyme priming was not significant at all. Thus, with non-word primes, not hearing all of the phonological information was particularly detrimental to phonological activation.

The results were quite different for the word primes (Experiment 4). The Carrier words and Embedded words produced robust and comparable priming effects in both primary tasks, which is different from the clear discrepancy shown between their non- word counterparts (i.e., the Addition and Deletion cases). Moreover, the Cohort primes always produced the weakest effects among all types of word primes in both primary tasks. Most strikingly, this disadvantage was much more salient in the Rhyme task than in the Association task as the Rhyme priming totally disappeared. This pattern was not observed for the Replacement case, the word counterpart of the Cohort word primes.

In summary, the results under the No-Load conditions showed that 1) when the primes were non-words, not hearing all the phonological information in the speech signal reduced the activation of the targets, whereas hearing inconsistent information did not matter very much; and 2) when the primes were real words, only receiving part of the phonological information, together with inconsistent information, had a strong negative effect. Importantly, both types of impairment were particularly salient in a task that involved phonological encoding (i.e., the Rhyme task). Moreover, the lack of Rhyme priming in the Deletion case and the Cohort case did not predict a loss of their Associative priming. This is surprising because in most models of word recognition phonological processing is used to achieve lexical access and thus should be necessary for semantic processing (Cutler & Clifton, 1999; Rodriguez-Fornells, Schmitt, Kutas, & Münte, 2002). Further discussion on this issue will be provided below.

Cognitive Load

After testing the two primary tasks under the No-Load condition, performance on the same primary tasks was further investigated when the participants were asked to perform either a letter recognition task or a character recognition task while doing the primary tasks. Different cognitive load effects were found for different types of primes and for different primary tasks.

With non-word primes (Experiments 2 & 3), the two types of cognitive load produced very similar effects on both primary tasks. Specifically, there was still significant Associative priming for all types of primes, but no Rhyme priming was found for any of them regardless of the load type. In contrast, with word primes (Experiments 5 & 6), the Phonological Load consistently produced more impairment than the Non-Phonological Load on both primary tasks.

Specifically, under Phonological Load, only the Embedded case showed measurable Rhyme and Associative priming, with priming effects suppressed for the Cohort and Carrier cases on both the Rhyme and Association tasks. Under Non-Phonological Load, there was Rhyme priming and Associative priming for all types of word primes, except for the Cohort case in the Rhyme task, which did not show any priming in the Baseline experiment in the first place. Clearly, the phonological load task had a much stronger impact than the non-phonological load task when the primes were real words.

To have a better understanding of the general patterns of the cognitive load effect, I then collapsed reaction times across the three types of Related trials and compared the average reaction times of the Related trials with those of the Unrelated trials. I modeled the results as a 3 Load (No-Load vs. Phonological Load vs. Non-Phonological Load) *2 Relatedness (Related vs. Unrelated) * 2 Prime Status (Non-Word vs. Word) * 2 Task (Rhyme vs. Association) factorial design. Figure 8 shows the collapsed results.

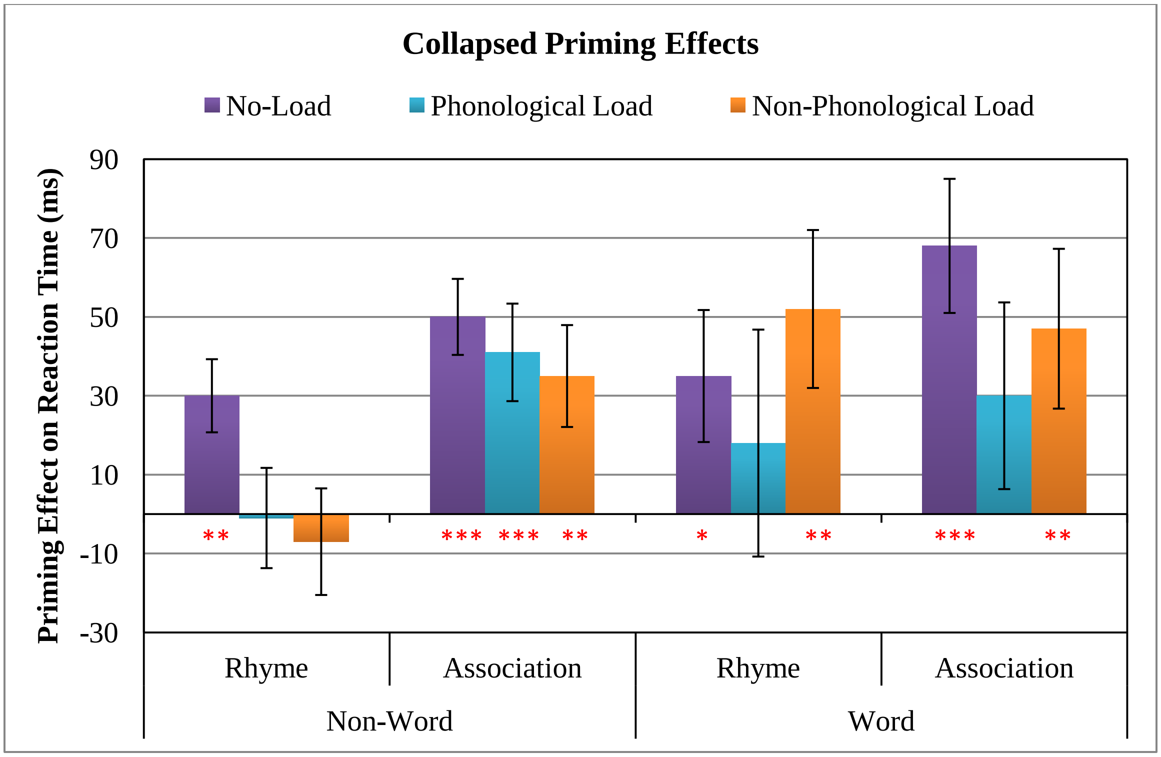


Figure 8. Collapsed priming effects across the six experiments.

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

Table 10 shows the statistical results for the collapsed priming effects. For the non-word primes, when there was no cognitive load (Experiment 1), both the Rhyme priming and Associative priming were significant, and the effect sizes were comparable ($\beta = 21.19$, $SE = 13.23$, $t = 1.60$, $p = .109$). When a cognitive load task was imposed (Experiments 2 & 3), regardless of the nature of the load task, only the Associative priming was significant. For the word primes, there was also robust Rhyme and Associative priming under No-Load (Experiment 4), but the latter effect was much stronger ($\beta = 35.09$, $SE = 12.97$, $t = 2.71$, $p = .007$). Neither primary task produced measurable priming under Phonological Load (Experiment 5). In contrast, both priming effects were significant under Non-Phonological Load (Experiment 6), and the effect sizes were comparable ($\beta = 20.01$, $SE = 27.64$, $t = .72$, $p = .470$).

Table 10. Statistical Results for the Collapsed Priming Effects

Primes	Primary Tasks	*β*	*SE*	*t*	*p*	
Non-Word Primes	**No-Load (Exp 1)**					
	Rhyme Task	25.34	9.27	2.73	0.006	**
	Association Task	48.27	9.64	5.01	<.001	***
	Phonological Load (Exp 2)					
	Rhyme Task	-1.03	12.71	-0.08	0.936	
	Association Task	46.55	12.36	3.77	< .001	***
	Non-Phonological Load (Exp 3)					
	Rhyme Task	-7.1	13.52	-0.53	0.601	
	Association Task	38.49	12.92	2.98	0.003	**
Word Primes	**No-Load (Exp 4)**					
	Rhyme Task	37.18	16.74	2.22	0.029	*
	Association Task	67.85	17.11	4.22	<.001	***
	Phonological Load (Exp 5)					
	Rhyme Task	22.50	28.77	0.78	0.436	
	Association Task	38.79	24.67	1.57	0.117	
	Non-Phonological Load (Exp 6)					
	Rhyme Task	53.56	20.03	2.68	0.009	**
	Association Task	56.90	20.26	2.81	0.006	**

Note: *** $p < .001$; ** $p < .010$; * $p < .050$

Looking at Table 10, perhaps the most informative cases are those where priming failed. There were four such cases, three involving the Rhyme task, and one involving the Association task. Two of these four cases show that Rhyme priming was abolished for non-word or word primes when the speech system was busy with a concurrent task that also involved phonological encoding (i.e., the letter recognition task). This is consistent with theories of working memory (Baddeley, 1992; Baddeley & Hitch, 1974) that predict that tasks that both engage phonological processing will cause mutual interference. Somewhat surprisingly, the character recognition task, which does not involve phonological encoding as much, also impaired the phonological processing of the targets, but this effect was only found for the non-word primes.

Moreover, the absence of Rhyme priming by non-words under both types of cognitive load did not prevent Associative priming; there were consistent priming effects on the Association task, in the absence of such priming effects on the Rhyme task. There was a similar pattern for word primes in the No-Load condition, where the lack of Rhyme priming for the Deletion and Cohort cases was coupled with significant priming for the Association task. Collectively, these results suggest that although phonological and semantic processing are closely related (Marslen-Wilson, 1987; McClelland & Elman, 1986; Norris, 1994), they proceed relatively independently, with semantic processing not requiring fully successful phonological encoding as a prerequisite. These issues are considered in more detail in the General Discussion.

Chapter 6: General Discussion

The present project aims to compare spoken word recognition under optimal conditions, which are relatively simple and similar to the lab situations that current models of spoken word recognition have based their assumptions on (e.g., NAM: Luce & Pisoni, 1998; Cohort: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994), to spoken word recognition under cognitive load conditions, which are more complicated and difficult. This project addresses this broad issue by answering three sub-questions:

1) How do different types of cognitive load affect activation and competition?
2) How do different types of cognitive load affect the processing of phonological and semantic information?
3) How similar does the speech input need to be to a lexical candidate in order for the candidate to be accessed?

To answer these questions, the prime lexicality (i.e., Non-Word vs. Word) was manipulated to dissociate activation and competition, and two primary tasks (i.e., Rhyme vs. Association) were created to distinguish the processing of different representations. Similarity between a prime and its target was varied by changing how many phonemes they shared and didn’t share (i.e., Non-Word Deletion/Embedded Word vs. Non-Word Replacement/Cohort Word vs. Non-Word Addition/Carrier Word). Because recent work has shown that lexical activation of an embedded word may be blocked if the listening conditions are difficult (Zhang & Samuel, 2015), priming was measured under conditions with no additional cognitive load, or with a secondary task that either imposed a phonological load (i.e., the letter recognition task) or a non-phonological load (i.e., the character recognition task).

In the Baseline experiments (Experiments 1 & 4), there was a clear advantage for the Addition case after hearing the non-word primes, and a clear disadvantage for the Cohort case after hearing the word primes. Surprisingly, the Rhyme priming of the Cohort case totally disappeared while its Associative priming was still significant. In the Cognitive Load experiments (Experiments 2, 3, 5 & 6), the two types of cognitive load had similar effects on non-word primes, with both of them blocking Rhyme priming but not Associative priming. For the word primes, however, the Phonological Load had a much stronger effect than the Non-Phonological Load. The data patterns across primes and tasks provide a more comprehensive picture of how utterances are understood under optimal as well as under more difficult listening conditions.

No-Load

When there was no cognitive load, the results in the Association task with word primes replicated what has been found in previous empirical studies. There is a great deal of evidence for the activation of word candidates while hearing words that share the first few phonemes (e.g., Zwitserlood,1989; Allopenna, Magnuson, & Tanenhaus, 1998), and for the activation of carrier words while hearing embedded words (e.g., Salverda, Dahan, Tanenhaus, Crosswhite, Masharov, & McDonough, 2007) and vice versa (e.g., Shillcock, 1990), when the tasks involve semantic processing (e.g., associative priming: Shillcock, 1990; sentence comprehension: Allopenna, Magnuson, & Tanenhaus, 1998; Van Alphen & Van Berkum, 2010; picture naming: Bowers et al., 2009).

The results for real word primes, on the Rhyme task, were also consistent with the predictions made by models of spoken word recognition (e.g., Cohort: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994). These models predict that the activation of the targets in the Embedded and Carrier word cases should be similar. Carrier words provide all of the phonological information for their targets, which should lead to stronger bottom-up activation than Embedded word primes, but they are also stronger competitors than Embedded words are for Carrier targets. Previous studies have shown that longer words produce stronger activation than shorter words (Bowers et al., 2009; Pitt & Samuel, 2006). Hence, Carrier word primes should be more effective in suppressing their targets than Embedded word primes. For the Cohort words, priming should be weak because Cohort words only match part of the phonological representations of their targets, which should lead to weaker bottom-up activation than that for Carrier word primes. In addition, Cohort primes should produce strong competition for their targets, which should suppress their targets' activation level more effectively than Embedded word primes. The results for the Rhyme task with word primes showed exactly this pattern: Strong and similar priming for Carrier words and Embedded words, and extremely weak priming for Cohort word primes.

However, none of the models explicitly predicts the striking difference between the two primary tasks for word primes: Rhyme priming for Cohorts totally disappeared while Associative priming remained robust. Furthermore, the results of the non-word primes were not completely consistent with the assumptions of the models either. Specifically, the non-word primes produced weaker priming than the word primes, and this difference was especially salient for the Rhyme task. A priori, one would predict the opposite because the targets for non-word primes should not receive lexical competition from the primes. Moreover, conditions designed to be parallel across the lexicality manipulation did not produce parallel results. The non-word Replacement case, which was the counterpart of the Cohort word case, was not the weakest of the non-word primes; the Cohort words were consistently the weakest. The non-word Deletion case produced weaker priming than the non-word Addition case, whereas as just discussed, their real-word counterparts (Embedded words and Carrier words, respectively) produced strong and comparable priming.

Previous studies have suggested that stimuli and tasks with different demands may reflect processing at different levels. For instance, Slowiaczek, Nusbaum, & Pisoni (1987) found significant priming between words that shared one to three phonemes at the beginning using perceptual identification, whereas Slowiaczek and Pisoni (1986) failed to replicate this facilitation in a lexical decision task. Luce and Pisoni (1998), and Vitevitch and Luce (1998) also found a similar dissociation between participants who performed either perceptual identifications or lexical decisions while listening to non-words that varied in their neighborhood density. There was an advantage for the high density non-words in the identification task, while there was a disadvantage for them in the lexical decision task. In all of these cases, the authors suggested that different levels of processing were being tapped by different tasks. Lexical decisions require the discriminations of non-words from words and thus presumably involve processing at the lexical level; perceptual identification does not require lexical access and thus might involve processing at the sub-lexical level.

This idea of both sub-lexical and lexical processing during spoken word recognition is found in most current models (Cohort: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994). When speech comes in, it first makes contact with sub-lexical representations, where components of speech are stored. Whether the sub-lexical representations are acoustic-phonetic features or phonemes has been a matter of debate in the field (Slowiaczek, McQueen, Soltano, & Lynch, 2000; Norris, McQueen, & Cutler, 2000). In most models, processing at the sub-lexical level provides the entry code for accessing lexical representations (Slowiaczek et al., 2000), where semantic information and abstract phonological information of words are stored. Therefore, the discrepancy between the results in the Rhyme and Association tasks, and between the effects of the non-word and word primes, might be because they tap different levels of processing. However, note that finding priming effects on the association (semantic) task, in the absence of such effects on the rhyme (phonological) task, is inconsistent with the latter providing the entry code for the former.

Non-Word Primes

In the Rhyme task with non-word primes, hearing all the phonological information in the primes facilitated the Rhyme decisions, and hearing only part of the phonological information hurt, while hearing inconsistent information did not matter. Since non-words are non-lexical items and the rhyme task only involves phonological encoding, lexical access is not a necessity for the task. Therefore, the non-word Rhyme task should tap bottom-up activation of sub-lexical representations by acoustic-phonetic information from the speech signal, and the use of these representations to make decisions. The Rhyme decisions should be facilitated when the phonological information needed for task has already been activated by the speech signal. Therefore, hearing primes with an Addition (e.g., *accenty*) would have an advantage over hearing Deleted primes (e.g., *accen_*) because latter does not activate all of the phonological information needed for the decision, while the former does.

Although there was extra sound in the Addition case (e.g., the /i/ sound in *accenty*), the results of Experiment 1 suggest that the extra sound might not interfere or compete with the sub-lexical representations that have been activated. Presumably the added sound does activate the sub-lexical representation corresponding to itself, raising the question: Why is there no cost associated with this mismatch? Although the TRACE model (McClelland & Elman, 1986) has suggested that lateral inhibition does takes place at the sub-lexical level as well as at the lexical level, the inhibition that is proposed in TRACE is among the co-activated phonemes that receive support from the same set of features or from ambiguous sounds in the speech, rather than between an activated representation and one that is activated later.

Note that this does not mean that there is no lexical access at all in this task. Actually, hearing non-word primes might still lead to the access of similar sounding words at the lexical level, but the lexical access might not be used in the Rhyme task. In contrast, the Association task for non-word primes does require lexical interaction, because the decisions are made upon the activation of semantic representations at the lexical level. Since a non-word (e.g., *accen_*, *accend*, or *accenty*) does not have a corresponding node at the lexical level (Vitevitch & Luce, 1998), the target (e.g., **accent**) would be the strongest candidate (if not the only one), and would not receive any/strong competition from other lexical candidates. Therefore, non-word Associative priming should be driven by the bottom-up activation of lexical nodes, which in turn leads to the activation of their semantic representations, with little lexical competition being involved.

Without an additional cognitive load task, similar results were found for the Rhyme and Association tasks with non-word primes, except that the disadvantage for the Deletion case was much smaller in the Association task. This indicates that hearing only a few segments at the beginning of a speech token is enough to provide the entry code to the lexical level and activate lexical nodes that share those segments. This is consistent with what the Cohort model has suggested (Marslen-Wilson, 1987). However, the similar results between the Replacement and Deletion cases in the Association task suggest that the bottom-up activation of a lexical node is primarily determined by how much overlap there is between the speech signal and the lexical candidate. Hearing inconsistent signal might lead to the access of other possible candidates, but it does not reduce the activation level of the candidates that have been accessed by the preceding signal. This is different from what the Cohort model would predict (Marslen-Wilson, 1987; Marslen-Wilson, Moss, & Van Halen, 1996).

Word Primes

The results for the word primes were different from those of their non-word counterparts. In particular, there were similar effects for the Carrier and Embedded cases, while there was a clear disadvantage for the Cohort case on both primary tasks. According to several models (Cohort: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994), hearing a real word activates the candidates that share phonological representations with it, and there is lexical competition among those activated nodes. The activation level of a given lexical node at a certain moment depends on its own activation and the competition from other activated nodes. In turn, its activation will dynamically affect the activation level of the semantic and phonological representations associated with it.

Therefore, with word primes, both the Rhyme and Association tasks reflect the activation of a lexical node as a result of the dynamic interaction between bottom-up activation and lexical competition. The Association task taps the activation of semantic representations of the lexical nodes, whereas the Rhyme task taps the phonological activation of the lexical nodes. However, it is uncertain whether phonological activation indexes the activation of abstract phonological representations at the lexical level, or the activation of sub-lexical representations resulting from top-down lexical feedback (McClelland & Elman, 1986; Vitevitch & Luce, 1998).

The significant disadvantage for the Cohort case, but not for its non-word counterpart, suggests that hearing inconsistent information is detrimental to lexical activation when there is lexical competition. Although different models of spoken word recognition have different assumptions about the nature of lexical competition (e.g., NAM: Luce & Pisoni, 1998; Cohort: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994), it seems that lexical competition among lexical nodes has a particularly strong effect on phonological representations compared to semantic representations. The inconsistent phonological information between the activated candidates is the core of the competition. Therefore, when a primary task requires precise phonological mapping, such as the Rhyme task, the Cohort case showed more impairment due to lexical competition than when the task does not, as in the Association task.

This dissociation is consistent with previous studies of Embedded word activation when hearing Carrier words. Significant priming has usually been found when the task was Associative priming (Isel & Bacri, 1999; Luce & Cluff, 1998; Shillcock, 1990; Vroomen & de Gelder, 1997), while no effect, or sometimes even inhibition, has usually been found when the task was identity priming (Marslen-Wilson, Tyler Waksler, & Older, 1994; Norris, Cutler, McQueen & Butterfield, 2006). Norris and his colleagues (2006) have argued that identity priming taps the activation of word forms, while associative priming taps the activation of word concepts. It seems that even when the form of a lexical node has been inhibited due to lexical competition, its semantic representation can still remain activated for some time.

In summary, the results in the No-Load experiments provide a comprehensive picture of the structure of the speech processing system, and how speech is processed at different levels. The manipulation of the primary task and the lexicality of the primes allow us to separate the processing of the sub-lexical and lexical levels, and to examine separately how phonological and semantic representations are primed. The use of non-word versus word primes also isolates bottom-up activation from lexical competition. These dissociations provide the opportunity to attribute cognitive load effects to specific levels of processing and to the processing of specific representations.

Cognitive Load

Non-Word Primes

Both the phonological and non-phonological load tasks impaired Rhyme priming but not Associative priming for the non-word primes. The intact Associative priming suggests that the initial access of lexical nodes, which leads to the activation of their semantic representations, might be relatively automatic and resource-independent. This is consistent with the assumption of the Cohort model (Marslen-Wilson, 1987) that there is an early activation of lexical candidates (i.e., after hearing only the first few segments). It is also consistent with visual word recognition results using masked priming, where semantic priming is found for visual stimuli that are masked after being displayed for a short amount of time, with participants being unaware of the prime at all (e.g., Forster, 1970). This does not mean that lexical access does not require any resources, or cannot be disrupted at all. For instance, lexical access can be disrupted if the distracters are presented during a very specific time window (Samuel, 2014).

The disappearance of the Rhyme priming in both cognitive load conditions suggests that, unlike the relatively automatic access of lexical items, bottom-up activation of sub-lexical representations and mapping the sub-lexical information to the visual probes required cognitive resources. Since participants had to keep rehearsing letters in the letter recognition task whereas they were unable to name characters in the character recognition task, the former task would use cognitive resources that are primarily speech-related whereas the latter task would not. Therefore, the lack of Rhyme priming with non-word primes under load suggests that the required cognitive resources are not specifically phonological. Moreover, it seems counterintuitive at first glance that no Rhyme priming was observed under either type of cognitive load but that the Associative priming was almost intact. One would assume that the activation of sub-lexical information is a prerequisite of lexical access. A possible explanation is that whereas lexical access, which relies on the activation of sub-lexical representations, is relatively automatic, using sub-lexical information to accomplish cognitive tasks such as making rhyme decisions might be more resource demanding. Making explicit decisions based on acoustic-phonetic features and phonemes is rarely called for in our real-life use of language. As such, this type of unnatural task might require special attention.

Thus, the effects of different cognitive load tasks on the priming patterns for the non-word primes allow us to distinguish between the processes of using sub-lexical representations to make phonological judgments at the sub-lexical level and using sub-lexical representations to access word nodes and thus the semantic representations at the lexical level. The results suggest that the former process requires general cognitive resources that are not specific to speech processing, while the latter is relatively automatic and requires few cognitive resources.

Word Primes

For the word primes, in contrast, the phonological load task produced a much stronger impairment on both primary tasks than the non-phonological load. Specifically, there was no Rhyme priming or Associative priming under Phonological Load (except for the Embedded word case). In contrast, the Non-Phonological Load did not have a strong effect on either task. These results suggest that lexical competition, which is different from the two processes involved in non-word processing that have been mentioned above, is resource demanding, and more specifically, it requires cognitive resources that are speech-related. This is consistent with previous studies, which have suggested that distinguishing among lexical candidates and inhibiting inappropriate ones might take more time and more attentional control than mapping sensory information onto lexical representations (Connine, Blasko, & Wang, 1994; Marslen-Wilson, 1987; Swinney, 1979). Moreover, the particular requirement of phonological resources for lexical competition provides further evidence for the claim that lexical competition has a strong effect on phonological representations. When a concurrent task uses cognitive resources that are less phonological, it does not hurt lexical competition very much. Priming probably survived in the embedded case under phonological load because embedded words are weaker competitors than cohort and carrier words because they are shorter, and hence may suppress the targets less effectively (Pitt & Samuel, 2006).

In summary, the cognitive load experiments indicate that initial lexical access is a fast-acting and relatively automatic process. It does not require much cognitive capacity. Somewhat paradoxically, the bottom-up activation of sub-lexical representations and the use of this information is a relatively unnatural task, and therefore is more resource demanding. It is vulnerable to the depletion of various cognitive resources that are not necessarily phonological. Lexical competition, unlike both initial lexical access and bottom-up processing of sub-lexical information, requires cognitive resources that are specific to phonological processing. Therefore, imposing a phonological load has a stronger impact than a non-phonological load on this kind of phonologically-induced competition.

Conclusion

The current project demonstrates that hearing both non-words and words will activate sub-lexical representations, and lead to lexical access, which in turn leads to the activation of both semantic and phonological representations. But, the level of processing depends on the demands of the primary task and the nature of the stimuli. Moreover, not all the stages of processing during speech perception are as fast and effortless as researchers have assumed. The results under the cognitive load conditions suggest that the initial access of lexical items is relatively automatic, whereas lexical competition is more resource demanding. Importantly, lexical competition requires cognitive resources that are specific to phonological processing. Accomplishing unnatural tasks, such as using sub-lexical information in a rhyme task, also requires cognitive capacity. In this case, the required resources are not necessarily phonological. The overall result pattern across experiments and tasks provides insights into how different types of cognitive load constrain lexical activation and competition at different levels of processing. Future studies and theoretical models of spoken word recognition should consider both the flexibility and the processing limits of the speech system in order to have a comprehensive understanding of how speech is processed.

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Appendix A: Critical Stimuli for Experiments 1 to 3

Non-Word Prime			Target	Rhyming Probe	Associated Probe
Deletion	Replacement	Addition			
/'æk,sɛn/	*/'æk,sɛnd/*	*/'æk,sɛntɪ/*	**accent**	BACCENT	LANGUAGE
/'æŋg/	*/'æŋgiː/*	*/ˈæŋgərm/*	**anger**	LANGER	MAD
/'ɑrg/	*/'ɑrg/*	*/ˈɑrgjuːb/*	**argue**	TARGUE	FIGHT
/'ɑnəs/	*/'ɑnəsk/*	*/ˈɑnəstəl/*	**honest**	WANNEST	TRUTH
/ˈstætʃ/	*/ˈstætʃəl/*	*/ˈstætʃərp/*	**stature**	TATURE	HEIGHT
/ˈdiːsən/	*/ˈdiːsənk/*	*/ˈdiːsəntəl/*	**decent**	HEESENT	GOOD
/ˈiːg/	*/ˈiːgɔn/*	*/ˈiːgərd/*	**eager**	LEEGUR	WILLING
/ˈegzə/	*/ˈegzəp/*	*/ˈegzətəl/*	**exit**	BLEXIT	ENTER
/ˈliːʒ/	*/ˈliːʒəl/*	*/ˈliːʒənt/*	**lesion**	WEEZHUN	CUT
/ˈerən/	*/ˈerənk/*	*/ˈerəndɑ/*	**errand**	LERRAND	TASK
/ˈædˌvər/	*/ˈædˌvərp/*	*/ˈædˌvərbər/*	**adverb**	GADVERB	NOUN
/ˈhɑstɪ/	*/ˈhɑstɪsʃ/*	*/ˈhɑstɪdʒər/*	**hostage**	JOSTAGE	TERRORIST
/ˈhev/	*/ˈhevəl/*	*/ˈheviːk/*	**heavy**	DEVVY	LIGHT
/rɪˈfre/	*/rɪˈfres/*	*/rɪˈfreʃəl/*	**refresh**	LEEFRESH	ENERGY
/ˈhjuːmə/	*/ˈhjuːmət/*	*/ˈhjuːmədiː/*	**humid**	PYOOMID	HOT
/ˈlev/	*/ˈlevoʊ/*	*/ˈlevərp/*	**lever**	KEVVER	PULL
/ˈmɑd/	*/ˈmɑdiː/*	*/ˈmɑdəlp/*	**model**	GODDLE	BEAUTIFUL
/dɪˈfen/	*/dɪˈfent/*	*/dɪˈfendiː/*	**defend**	BEFEND	PROTECT
/ˈmoʊtɪ/	*/ˈmoʊtɪf/*	*/ˈmoʊtɪvəl/*	**motive**	HOATIVE	REASON
/'es/	*/'esiː/*	*/eˈseɪt/*	**essay**	TESSAY	WRITE

/ˈpælə/	*/ˈpæləsʃ/*	*/ˈpæləsiː/*	**palace**	TALLICE	CASTLE
/ˈplæstɪ/	*/ˈplæstɪg/*	*/ˈplæstɪkəl/*	**plastic**	BLASTIC	BAG
/ˈpoʊlən/	*/ˈpoʊlənt/*	*/ˈpoʊləndəl/*	**poland**	TOWLAND	COUNTRY
/ˈriːˌsɔr/	*/ˈriːˌsɔrsʃ/*	*/ˈriːˌsɔrsəl/*	**resource**	HESOURCE	LIBRARY
/ˈsɑlə/	*/ˈsɑlət/*	*/ˈsɑlədiː/*	**solid**	CAHLID	HARD
/ˈsekən/	*/ˈsekənt/*	*/ˈsekəndiː/*	**second**	PECKIND	FIRST
/ˈterə/	*/ˈterəsʃ/*	*/ˈterəsəl/*	**terrace**	MERRISS	BALCONY
/ˈvɪkt/	*/ˈvɪktəl/*	*/ˈvɪktərd/*	**victor**	BICTOR	WINNER
/ˈwɑlə/	*/ˈwɑlək/*	*/ˈwɑlətəl/*	**wallet**	ZOLLIT	PURSE
/ˈbælə/	*/ˈbæləp/*	*/ˈbælətər/*	**ballot**	GRALLIT	VOTE
/ˈhæp/	*/ˈhæpər/*	*/ˈhæpəng/*	**happen**	BAPPEN	OCCUR
/ˈem(p)t/	*/ˈem(p)tər/*	*/ˈem(p)tiːg/*	**empty**	KEMPTY	FULL
/ˈpərˌfjuː/	*/ˈpərˌfjuːn/*	*/ˈpərˌfjuːmiː/*	**perfume**	MERFUME	SMELL
/ˈpræktə/	*/ˈpræktəsʃ/*	*/ˈpræktəsəl/*	**practice**	ACTIS	PERFECT
/ˈθənd/	*/ˈθəndəl/*	*/ˈθəndərm/*	**thunder**	MUNDER	RAIN
/ˈsərk/	*/ˈsərkiː/*	*/ˈsərkəlm/*	**circle**	MIRCLE	SQUARE
/ˈælb/	*/ˈælbər/*	*/ˈælbəmt/*	**album**	MALBUM	RECORD
/ˈeɪnʃən/	*/ˈeɪnʃənd/*	*/ˈeɪnʃəntəl/*	**ancient**	TAINSHENT	OLD
/ˈɔθ/	*/ˈɔθiː/*	*/ˈɔθərt/*	**author**	LAWTHER	WRITER
/ˈbɑt/	*/ˈbɑtɑ/*	*/ˈbɑtəlk/*	**bottle**	NOTTLE	BEER
/ˈendʒ/	*/ˈendʒər/*	*/ˈendʒənt/*	**engine**	KENJIN	MOTOR
/ˈfeɪmə/	*/ˈfeɪməsʃ/*	*/ˈfeɪməsər/*	**famous**	LAYMISS	STAR
/ˈfrækʃ/	*/ˈfrækʃəl/*	*/ˈfrækʃənt/*	**fraction**	BRACTION	NUMBER

/ˈdʒend/	/ˈdʒendiː/	/ˈdʒendərm/	**gender**	HENDER	SEX
/ˈlæð/	/ˈlæðiː/	/ˈlæðərk/	**lather**	NATHER	SOAP
/ˈtɑrd/	/ˈtɑrdən/	/ˈtɑrdiːk/	**tardy**	KARDY	LATE
/ˈərb/	/ˈərbər/	/ˈərbənt/	**urban**	MURBIN	CITY
/ˈrɪð/	/ˈrɪðər/	/ˈrɪðəmt/	**rhythm**	NYTHM	BEAT
/ˈsɪmp/	/ˈsɪmpɑ/	/ˈsɪmpəlt/	**simple**	IMPLE	EASY
/ˈkəntræs/	/ˈkəntræsk/	/ˈkəntræstiː/	**contrast**	MONTRAST	DIFFER
/ˈkɔrˌtek/	/ˈkɔrˌtekz/	/ˈkɔrˌteksər/	**cortex**	MORTEX	BRAIN
/ˈpəz/	/ˈpəziː/	/ˈpəzəlp/	**puzzle**	TUZZLE	JIGSAW
/ˈmemb/	/ˈmembəl/	/ˈmembərk/	**member**	DEMBER	CLUB
/ˈhɑrvəs/	/ˈhɑrvəsp/	/ˈhɑrvəstɪn/	**harvest**	MARVEST	CROPS
/ˈhəndrə/	/ˈhəndrət/	/ˈhəndrədəl/	**hundred**	LUNDRED	NUMBER
/ˈdʒuːnj/	/ˈdʒuːnjəl/	/ˈdʒuːnjərm/	**junior**	YOONYER	YOUNG
/ˈkɪtʃ/	/ˈkɪtʃər/	/ˈkɪtʃənk/	**kitchen**	MITCHEN	COOK
/ˈlɪs/	/ˈlɪsəl/	/ˈlɪsənt/	**listen**	WISSEN	HEAR
/ˈlɑdʒɪ/	/ˈlɑdʒɪg/	/ˈlɑdʒɪkər/	**logic**	TAHJICK	COMPUTER
/ˈmɑrdʒ/	/ˈmɑrdʒər/	/ˈmɑrdʒənt	**margin**	NARGIN	DIVORCE
/ˈmædʒɪ/	/ˈmædʒɪt/	/ˈmædʒɪkən/	**magic**	ADJICK	TRICK
/ˈmeʒ/	/ˈmeʒəl/	/ˈmeʒərt/	**measure**	GREZHURE	CUP
/ˈmərd/	/ˈmərdiː/	/ˈmərdərp/	**murder**	PURDER	KILL
/ˈneɪtʃ/	/ˈneɪtʃiː/	/ˈneɪtʃərt/	**nature**	RAYCHURE	TREE
/ˈrædɪ/	/ˈrædɪs/	/ˈrædɪʃəl/	**radish**	TADDISH	VEGETABLE
/ˈgɑsə/	/ˈgɑsət/	/ˈgɑsəpən/	**gossip**	WOSSIP	TALK

/ˈbɪz/	*/ˈbɪzəl/*	*/ˈbɪziːp/*	**busy**	MIZY	BORED
/ˈkalɪ/	*/ˈkalɪsʃ/*	*/ˈkalɪdʒər/*	**college**	MOLLEGE	SCHOOL
/ˈnef/	*/ˈnefər/*	*/ˈnefjuːm/*	**nephew**	WEFFEW	NIECE
/ˈkwɪv/	*/ˈkwɪvən/*	*/ˈkwɪvərk/*	**quiver**	WIVVER	SHAKE
/tekˈniː/	*/tekˈniː/*	*/tekˈniːkən/*	**technique**	BECKNEEK	STYLE
/ˈvɪvə/	*/ˈvɪvəp/*	*/ˈvɪvədəl/*	**vivid**	MIVVID	CLEAR

Appendix B: Critical Stimuli for Experiments 4 to 6

Prime Type	Word Prime	Target	Rhyming Probe	Associated Probe
Embedded	*sock*	**socket**	WOCKET	LIGHT
	pad	**paddle**	NADDLE	BOAT
	deck	**decade**	MECKADE	YEAR
	east	**Easter**	REASTER	SUNDAY
	buck	**bucket**	NUCKET	WATER
	cab	**cabin**	MABBIN	LOG
	mark	**market**	TARKET	STORE
	tick	**ticket**	JICKET	CONCERT
	mess	**message**	HESSAGE	NOTE
	stew	**stupid**	YOOPID	DUMB
	bowl	**boulder**	POULDER	ROCK
	brow	**brownie**	KROWNY	CAKE
	tie	**tidy**	RYDEE	NEAT
	pie	**pirate**	NYRITE	SHIP
	spy	**spider**	PIDER	WEB
	pick	**picnic**	FICNIC	FOOD
	guard	**garden**	RARDEN	FLOWER
	bay	**baby**	TAYBY	CHILD
Cohort	*happy*	**happen**	BAPPEN	OCCUR
	victim	**victor**	BICTOR	WINNER
	modern	**model**	GODDLE	BEAUTIFUL

	heaven	**heavy**	DEVVY	LIGHT
	advent	**adverb**	GADVERB	NOUN
	recent	**resource**	HESOURCE	LIBRARY
	level	**lever**	KEVVER	PULL
	eagle	**eager**	LEEGUR	WILLING
	argon	**argue**	TARGUE	FIGHT
	fracture	**fraction**	BRACTION	NUMBER
	metal	**measure**	GREHZHURE	CUP
	gentle	**gender**	HENDER	SEX
	autumn	**author**	LAWTHER	WRITER
	kitten	**kitchen**	MITCHEN	COOK
	ladder	**lather**	NATHER	SOAP
	ribbon	**rhythm**	NYTHM	BEAT
	nation	**nature**	RAYCHURE	TREE
	little	**listen**	WISSEN	HEAR
Carrier	*badger*	**badge**	NADGE	POLICE
	charter	**chart**	SHART	GRAPH
	topic	**top**	ZOP	BOTTOM
	sausage	**sauce**	HAUCE	TOMATO
	campus	**camp**	ZAMP	FIRE
	blanket	**blank**	SLANK	EMPTY
	bullet	**bull**	VULL	COW
	summer	**sum**	PUM	ADD

	agent	**age**	NAGE	OLD
	fancy	**fan**	HAN	AIR
	furnace	**fur**	LUR	COAT
	napkin	**nap**	VAP	SLEEP
	crucial	**crew**	PREW	SHIP
	dental	**den**	CEN	CAVE
	pumpkin	**pump**	TUMP	GAS
	needle	**knee**	KEE	LEG
	Friday	**fry**	BRY	COOK
	paper	**pay**	TAY	MONEY
Unrelated	*aim*	**honest**	WANNEST	TRUTH
	loaf	**decent**	HEESENT	GOOD
	maze	**lesion**	WEEZHUN	CUT
	full	**errand**	LERRAND	TASK
	paste	**refresh**	LEEFRESH	ENERGY
	once	**humid**	POOMID	HOT
	galley	**defend**	BEFEND	PROTECT
	April	**motive**	HOATIVE	REASON
	collar	**essay**	TESSAY	WRITE
	temple	**Poland**	TOWLAND	COUNTRY
	ankle	**second**	PECOND	FIRST
	wallet	**terrace**	MERRISS	BALCONY
	window	**hut**	FUTT	STRAW

	cradle	**beard**	HEERD	MUSTACHE
	curly	**hoot**	WOOT	OWL
	dozen	**pluck**	BLUCK	PICK
	hungry	**twist**	WIST	TURN
	Jewish	**west**	MEST	EAST