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Semantic and subword priming during binocular suppression

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In general, stimuli that are familiar and recognizable have an advantage of predominance during binocular rivalry. Recent research has demonstrated that familiar and recognizable stimuli such as upright faces and words in a native language could break interocular suppression faster than their matched controls. In this study, a visible word prime was presented binocularly then replaced by a high-contrast dynamic noise pattern presented to one eye and either a semantically related or unrelated word was introduced to the other eye. We measured how long it took for target words to break from suppression. To investigate word-parts priming, a second experiment also included word pairs that had overlapping subword fragments. Results from both experiments consistently show that semantically related words and words that shared subword fragments were faster to gain dominance compared to unrelated words, suggesting that words, even when interocularly suppressed and invisible, can benefit from semantic and subword priming.

1. Introduction

Semantic priming is the improvement in speed or accuracy to respond to a stimulus, such as a word or a picture, when it has been preceded by a semantically related picture or word (e.g., *ketchup* primes *mustard*) in comparison to when it is preceded by a stimulus that is not semantically related (*bee* does not prime *crowd*). Semantic priming effects have been demonstrated in a variety of tasks including lexical-decision tasks, naming, and semantic categorization (McNamara, 2005). Often tasks investigating semantic priming are constructed such that the observers are not aware of the presence of prime stimuli. The prime word is masked or presented too briefly to prevent conscious or explicit recognition. Many behavioral and imaging studies have demonstrated that masked prime words speed the recognition of following words that are semantically related to the prime, and these masked words activate cerebral networks for word processing. For example, Diaz and McCarthy (2007) found that masked words, but not masked non-words, activated left hemisphere language areas. Recent studies have reliably demonstrated that specific information about a number or word's identity can be extracted and encoded unconsciously, and this priming effect occurred for prime stimuli that were never presented as target stimuli (Dehaene et al., 2001, 1998; Naccache & Dehaene, 2001). These studies provide evidence that semantic information can be processed and represented unconsciously.

Furthermore, Abrams and Greenwald (2000) provided evidence that subword fragments of earlier viewed targets could function as effective evaluative primes in a classification experiment using the masking paradigm. This happened for nonword combinations (e.g., *hulip* formed from *humor* and *tulip* functioned as a positive prime) as well as for words that were formed from combinations of earlier target words (e.g., the word *smile* functioned as a negative masked prime after having to classify its predecessors, *smut* and *bile*). Primes that were not classified or viewed earlier in the experiment did not produce a

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priming effect. They concluded that significant unconscious priming was obtained, but only for primes composed of recombined parts of earlier viewed targets. It may be the case that unconscious whole-word analysis takes place, but the effect could be very limited and short-lived, while subword analysis priming is more robust in this case. In the current study, we examined both semantic and subword priming possibilities with a new paradigm.

In addition to masking approaches, a newer way to investigate the unconscious processing of information is the interocular suppression or continuous flash suppression (CFS) paradigm (Tsuchiya & Koch, 2005). As in binocular rivalry, this technique uses dichoptic stimulation (two different stimuli are presented to each eye concomitantly). In interocular suppression, images or words are prevented from reaching awareness by simultaneously presenting strong dynamic noise to the opposite eye, which results in longer suppression times than with standard binocular rivalry paradigms (Tsuchiya, Koch, Gilroy, & Blake, 2006). Recent studies utilizing this paradigm have demonstrated that interocularly suppressed information is able to attract or repel observers' spatial attention depending on their gender and sexual orientation (Jiang, Costello, Fang, Huang, & He, 2006). Emotional faces under interocular suppression can be represented in the brain (Jiang & He, 2006; Jiang et al., 2009) and are detected more quickly than neutral faces (Yang, Zald, & Blake, 2007). More importantly, familiar and recognizable stimuli also possess a significant advantage in breaking suppression (Jiang, Costello, & He, 2007). Specifically, the stimuli that emerged from suppression the fastest were those stimuli that were most meaningful to the participants. For example, upright faces emerged from suppression faster than inverted faces. Similarly, Hebrew and Chinese words broke suppression faster differentially for participants native to Hebrew and Chinese, respectively. Invisible Hebrew words were processed faster than Chinese characters for native Hebrew speakers, and the opposite was true for native Chinese speakers, thus indicating that unconscious stimuli are processed at a higher, meaningful level (Jiang et al., 2007; Yang et al., 2007).

As discussed above, the suppression-breaking paradigm takes advantage of binocular rivalry (and interocular suppression), and provides a unique opportunity to reveal automatic visual information processing in the absence of awareness as compared to other paradigms (Kim & Blake, 2005). The current study used this method to investigate the supraliminal priming of target words under interocular suppression. Previous studies have used binocular rivalry to investigate whether semantic information in particular is able to affect the predominance of binocular rivalry, and found that semantic context had an influence on which word was seen while observers dichoptically viewed a pair of words that differed in meaning. After monocular priming with one word, observers tended to report seeing the second word that was related to the prime under conditions of rivalry. These results suggest that semantic information can influence predominance during binocular rivalry (Rommetveit, Toch, & Svendsen,1968a, 1968b). However, Blake argued that binocular rivalry may not have truly taken place in these experiments because the target words were flashed for only 400 ms. Subsequently, he used binocular rivalry to assess whether word meaning could influence the dominance of one eye during rivalry (Blake, 1988). In this experiment, observers viewed two different streams of letters, and the semantic content of the letter streams was varied to determine whether meaningful text could dominate nonsense text. Two different measures were used to assess whether meaning could influence what is seen during rivalry. Blake reported no linguistic or semantic influence on rivalry dominance. He concluded that rivalry events occur prior to the stage where semantic information could be extracted. However, since binocular rivalry has been more and more suggested to be a process involving multistage competition (Blake & Logothetis, 2002; Freeman, 2005; Nguyen, Freeman, & Alais, 2003; Tong, Nakayama, Vaughan, & Kanwisher, 1998), it remains possible that the prime word could still influence the processing of the target word under the suppression phase of rivalry.

The present experiments expand the scope of earlier studies and used interocular suppression to investigate both semantic and word-parts priming effects, using longer rivalry durations and separate prime words. Here, participants viewed a prime word for 2 s (e.g., *sock*). Following presentation of the prime word presented to each eye, one eye was presented with a high-contrast suppression noise and the other eye with the second word either semantically or word-parts related (e.g., *shoe* or *shock*) or unrelated (e.g., *tape*) to the first word (Fig. 1a). The pairs of prime and target words were all counter-balanced so that all prime and target words were presented twice (in different blocks), one in the related pair (related here meaning semantically related and word-parts related) and the other in the unrelated pair (see Methods for more detail and Appendix A and B for a full list of words used in the current study). This ensured that there was no difference between the related and unrelated conditions in regard to prime and target words used in the experiments. Response times to report the perception of any portion of the second (target) word were recorded and compared for related and unrelated word pairs to evaluate whether a suppressed target word would come out of suppression faster if primed with a related word (either semantically related or word-parts related). If so, this implies that semantic and/or word-parts activation from the prime word, seen for 2 s with both eyes, is able to influence an invisible target word to come out of suppression faster. Briefly, there are some significant differences of this approach as compared to traditional backward masking and binocular rivalry paradigms. (1) Previous studies usually assess the priming effect of a visible target word when the prime word is masked (McNamara, 2005) or binocularly suppressed (Zimba & Blake, 1983), while in the current study the prime word is presented visibly (for 2 s) and the target word is suppressed and probed. (2) The target stimuli are competing against the same noise pattern but are not competing against each other. This ensures that the suppressed times of the target stimuli can be interpreted more precisely. (3) An irrelevant detection task was adopted, which is potentially sensitive to both semantic and subword priming. In each trial, as soon as the observer detected the stimulus or any part of it, the trial stopped. This ensures that the key factor influencing the dependent variable (suppression duration) was operating while the stimulus remained invisible, and can maximally reduce the influence of a non-exclusive rivalry stage.

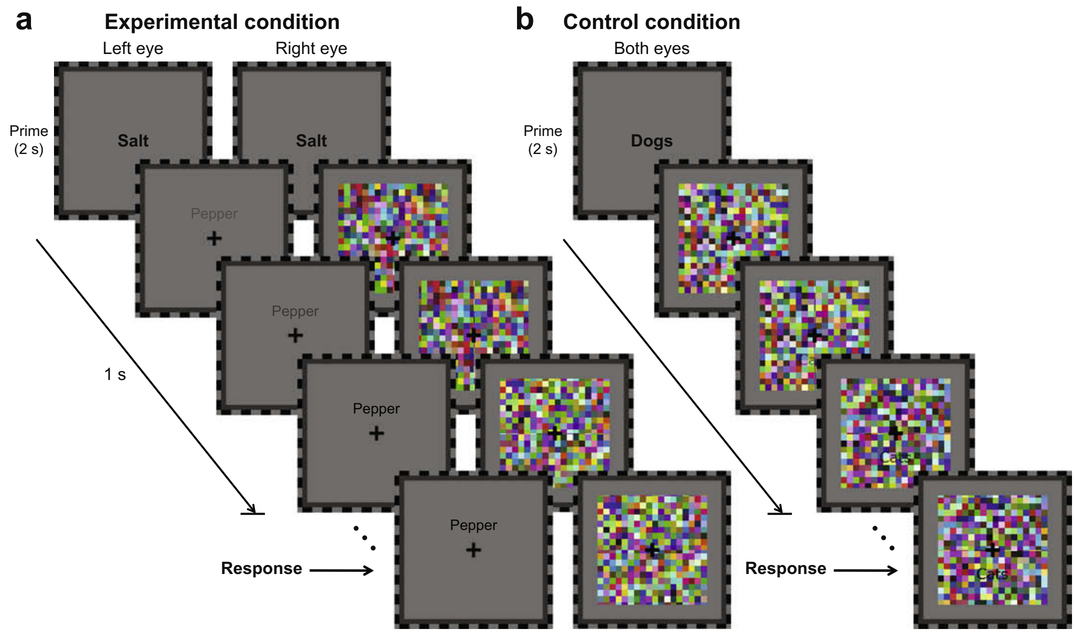

Fig. 1. Schematic representation of the experimental paradigms. In the experimental condition (a), the prime word was presented for 2 s to both eyes. The target word (related or unrelated to the prime) was then gradually introduced to one eye and competed with a dynamic noise pattern presented to the other eye. The contrast of the target word was linearly ramped up from 0% to 100% over 1 s, and then remained constant until the observer made a response to indicate where relative to fixation (above or below) the target word appeared. In the control condition (b), the prime word was seen by both eyes for 2 s, and then the target word was blended into the noise background with contrast gradually increased (at a slower rate than in the experimental condition). Participants viewed the words binocularly and responded to the appearance of the target word as soon as they detected it either above or below fixation.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Nine observers (three male) with normal or corrected-to-normal vision, naïve to the purpose of the experiment, took part in Experiment 1. The ninth observer took part in the first block of trials only due to eye strain. All the observers were proficient and native English speakers. All participants gave written informed consent in accordance with the Gustavus Adolphus College human-subjects review committee.

2.1.2. Stimuli and procedure

Stimuli were generated with MATLAB and presented on a 19-in NEC MultiSync monitor (1280 × 1024 at 85 Hz) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The images presented to the two eyes were displayed side by side on the monitor and fused using a mirror stereoscope mounted on a chin rest. A frame (10.7° × 10.7°) and fixation mark were used to aid in convergence of the two images. The frame extended beyond the outer border of the stimulus and the fixation mark (a central cross, 0.8° × 0.8°) was located in the middle of each frame. The viewing distance was held constant for each participant at 40 cm.

Fig. 1a provides an overview of the general paradigm for the experimental condition. The frames and fixation marks were always first presented to each eye to stabilize fixation and merge the two images. Observers viewed images through a mirror stereoscope mounted on a chinrest. After fixation and merging of the two images was obtained, participants pushed the space bar to initiate the first experimental trial. Each participant first ran through five to ten practice trials to familiarize themselves with the experimental paradigm (none of the prime and target words in the experimental condition were used here). At the beginning of each trial, a word appeared to each eye and remained on screen for a duration of 2 s (to the observer, this appeared as one centrally located word). A dynamic noise pattern (with small color squares moving back and forth along the horizontal and vertical directions) was then presented to one of the observer's eyes at full contrast and then the second word was presented to the other eye either above or below fixation (randomly) within the region corresponding to the noise. The contrast of the second word was ramped up gradually from 0% to 100% within a period of 1 s starting from the beginning of the trial and then remained constant until the observer made a button press (up or down arrow key) to indicate where the word was located.

Each block of trials consisted of 40 word pairs. These word pairs were either semantically related (20 pair) or unrelated (20 pair). These word pairs were taken from the commonly used word pairs in previous studies (Borowsky & Besner, 1993).

The first word was presented in the middle of the box in place of the fixation mark and on average subtended 3.6°–7.4° of visual angle, depending on the length of the particular word (four letters to nine letters). The word height subtended 0.72° on average. (See Appendix A for a full list of words for each block of trials.) After the first word was presented for 2 s, observers then perceived the noise patch and were unaware which side contained the second word. The second word was presented in a random position either above or below fixation. The distance between the center of the word and fixation was 1.7° and the second word ranged from 2.4° to 4.4°, depending on the length of the word (four letters to eight letters). The second word height subtended approximately 0.57°. To measure the time it took for the second word to overcome the suppression noise and become dominant, observers were instructed to press the up or down arrow key on a standard keyboard to indicate where relative to fixation the second word appeared. They were told to respond as soon as they detected the presence of the word or part of the word, and that they did not need to read or know what the actual word was.

Each participant viewed a total of 80 trials over two blocks, 40 with related word pairs and 40 with unrelated word pairs. The pairs of prime and target words were also counter-balanced so that all prime and target words were presented twice (in different blocks), one in the related pair and the other in the unrelated pair (see Appendix A). This ensured that there was no difference between the related and unrelated conditions in terms of prime and target words. The stimuli were presented in a randomized sequence, and the target word's location relative to fixation was also randomized. Response times (RTs) were calculated based on correct trials only (correct up or down arrow key press), but very few trials were excluded because accuracy was above 99% for each participant. To reject data outliers, we also excluded trials in which the RT was longer than 10 s (this is more than three standard deviations from the sample mean). This was because if the second word was not able to be detected within 10 s, the observed RT could reflect unknown factors. However, overall less than 1% of the trials were excluded from our analysis based on this criterion.

2.2. Results and discussion

We compared how long it took for semantically related words vs. unrelated words to break out of interocular suppression. Results from all participants indicated a significant effect of word relatedness on suppression time. Words primed with a related word took less time than an unrelated word to gain dominance against the identical suppression noise (1.68 s vs. 1.93 s, $t(7) = 3.02$, $p < .02$; see Fig. 2, left panel). Data from the 9th participant was not included in the analyses because she participated in the first block only, but her block 1 data were consistent with the overall findings. This result implies that related words are processed faster than unrelated words as a result of semantic priming. However, a small subset of the word pairs used in this experiment have subword components in common (e.g., *rock* and *roll*). The advantage for related vs. unrelated word pairs could have been due to either semantic or subword priming (Abrams & Greenwald, 2000). Hence, we conducted a second experiment (Experiment 2) to specifically test this issue, in which three conditions (semantically related word pairs without any subword components, in common subword component word pairs without any semantic relation, and unrelated control pairs) were tested (see Appendix B). If the priming effect observed in Experiment 1 is simply due to a priming effect from subword components only, an advantage for the subword pairs but not the semantic pairs (compared with the unrelated control pairs) would be expected. On the other hand, if both the subword and semantic pairs have an advantage in breaking suppression, it would suggest that there is indeed a semantic priming effect under binocular suppression.

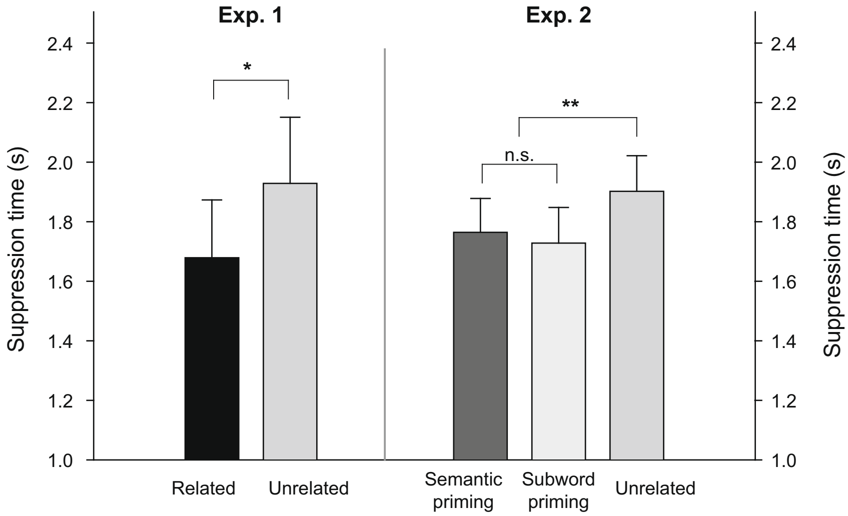

Fig. 2. Suppression time results from Experiment 1 and Experiment 2. The left side of the figure shows the average suppression times of semantically related and unrelated words in Experiment 1, and the right side shows the average suppression times of semantically primed words, subword primed words, as well as unrelated words in Experiment 2. Results from the two experiments showed significant semantic and subword priming effects under binocular suppression. *, $p < .05$; **, $p < .01$; n.s., no significance.

3. Experiment 2

3.1. Methods

3.1.1. Participants

Another eight observers (four male) with normal or corrected-to-normal vision, naïve to the purpose of the experiment, took part in Experiment 2. All the observers were proficient and native English speakers. All participants gave written informed consent in accordance with the Gustavus Adolphus College human-subjects review committee.

3.1.2. Stimuli and procedure

Stimuli generation and presentation followed the same parameters and timing as in Experiment 1. In this experiment, each block of trials consisted of 48 word pairs. These word pairs were semantically related, word-parts related, or unrelated. The semantically related word pairs did not share any subword components, and the word-parts pairs were never semantically related. The unrelated word pairs were neither semantically related nor word-parts related (see Appendix B for a full list of words for each block of trials). Each participant viewed a total of 96 trials over two blocks: 32 were semantically related word pairs, 32 were word-parts related word pairs, and 32 were unrelated word pairs. All the other aspects were the same as in Experiment 1.

3.2. Results and discussion

We compared how long it took for related words (semantic and word-parts) vs. unrelated words to break out of interocular suppression. A one-way repeated measures ANOVA revealed a significant effect ($F(2,14) = 22.7$, $p < .001$; see Fig. 2, right panel) with the suppression times of both of semantically related words (1.76 s) and word-parts related words (1.73 s) significantly shorter compared with that of unrelated control words (1.90 s, $p < .01$ with Bonferroni correction for multiple comparisons). Moreover, the suppression times of the semantically related words and the word-parts related words did not significantly differ from each other ($p > .1$). The results suggest that words primed with a related word (both semantic and word-parts) took less time than an unrelated word to gain dominance against the identical suppression noise, and that the subword priming effect was as effective as, if not stronger than, the semantic priming effect, consistent with previous findings using a backward masking paradigm (Abrams & Greenwald, 2000).

4. Control experiment

Although we have controlled the presence of the prime and target words in both related and unrelated conditions (Experiment 1 and Experiment 2), there is still the possibility that the results for the experimental (rivalry) condition could simply be due to different recognition speeds of the second word or different detection criteria depending on the prime and target words. To test this possibility, we ran two control experiments in which the same word pairs were used, but the second word was blended into the dynamic noise pattern and the contrast was again ramped up gradually. Observers viewed the stimuli binocularly (non-rivalry) rather than dichoptically. The observers' task was exactly the same as the experimental condition, and their perceptual experience in this control condition also mimicked the rivalry situation where the target words overcame the suppression and gradually came into view out of the noise.

4.1. Methods

4.1.1. Participants

Another eight observers (two male) with normal or corrected-to-normal vision, naïve to the purpose of the experiment, took part in this experiment. All observers were proficient and native English speakers. All participants gave written informed consent in accordance with the Gustavus Adolphus College human-subjects review committee.

4.1.2. Stimuli and procedure

Fig. 1b displays the control paradigm. For the control study, observers viewed the words binocularly (non-rivalry) rather than dichoptically. Their task and the parameters were essentially the same as for the experimental condition (Experiment 1 and Experiment 2) described above. Their perceptual experience in this condition was set so that it was similar to the rivalry condition in that the second word was blended into the noise pattern and gradually came into view out of the noise. We again measured the time it took for observers to detect the presence of the second word either above or below fixation after viewing the first word for 2 s. The same 40 word pairs were used in each block of trials for a total of 80 trials over two blocks (as in Experiment 1). In an earlier version of the control condition, we found that observers could detect the second word fairly fast when the ramping time was set at 10 s, so the time course of the contrast ramping was modified in order to keep the detection time in a similar range as the suppression time in the experimental condition. Therefore, we further slowed down the ramping-up speed with a 20 s time course to reach full contrast to examine if the priming effect we observed in the experimental condition was due to a longer suppression or uncertainty duration.

4.2. Results and discussion

Results from the control condition showed that there was no significant difference in detection time between related and unrelated word pairs in the non-rivalry control conditions (0.90 s vs. 0.89 s, $t(7) < 0.1$, $p > 0.9$; see Fig. 3, left panel). Further slowing down the ramping-up speed increased the overall detection times, but still didn't differentiate between related and unrelated word pairs (2.71 s vs. 2.71 s, $t(7) < 0.03$, $p > 0.9$; see Fig. 3, right panel). These results indicate that the shorter suppression time for related words is specific to interocular competition, and is not due to a general advantage in detection.

5. General discussion

We found that when suppressed and invisible, words either semantically related to or containing overlapping subword components with a prime word came out of suppression significantly faster than unrelated words. In other words, both semantic priming and subword priming can take place under binocular suppression. A control experiment further showed that this effect is not due to any specific properties of the words themselves (e.g., word recognizability or response criterion). As discussed in our earlier study comparing upright and inverted faces and words in one's native language in suppression (Jiang et al., 2007), the current results also suggest that some information from the suppressed related word is able to interact with the neural networks activated by the prime word and overcome suppression faster than the suppressed unrelated word**.**

In a previous study, Zimba and Blake (1983) found that prime words were able to produce a RT advantage on a lexical-decision task, but only when these words were presented during the dominance phase of binocular rivalry. In contrast, the effect was not found during the suppression phase, which seems to be inconsistent with the findings from the current study. However, there are a few critical differences in the experimental designs between the two studies. In Zimba & Blake's study, the prime words were briefly flashed (<200 ms) during the suppression phase and the target words to be categorized were visible to participants, while in our experiments the visible prime words were presented binocularly for 2 s to participants and the target words were initially suppressed through interocular suppression. This major difference of experimental design could account for the different results in terms of the priming effect between the two studies, but it is consistent with the view that the unconscious activation of primes is short-lived (Greenwald, Draine, & Abrams, 1996). Moreover, in the previous study RTs were measured in a task which required discrimination of a word vs. non-word, and the non-word was constructed by replacing one or two letters of the word to create a meaningless string (e.g., *near* vs. *kear*). On the one hand, this would have forced observers to pay more attention to the overall orthography of the word instead of word-parts. On the other hand, for those word pairs that contained overlapping word-parts between the prime and target words, this manipulation would have also induced substantial but similar subword priming effects for both the target words and non-words (Abrams & Greenwald, 2000). This could be the reason why a subword priming effect was not revealed. In the current study, we included three test conditions (semantic priming, subword priming, and unrelated word pairs) and asked the participants to push the button as soon as they detected the presence of a word either above or below fixation. This task was intended to probe automatic processing, and thus could be sensitive to both semantic and subword priming effects.

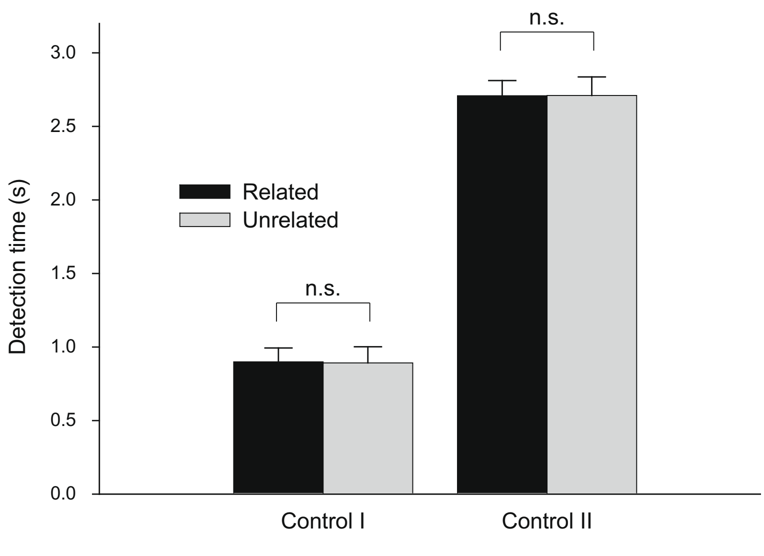

Fig. 3. Detection times for the non-rivalry control conditions (Experiment 3). In the experiment, the target word was presented binocularly and was blended into the noise background. There was no significant difference in detection times between the semantically related and unrelated word pairs for the two conditions. Left: shorter ramping time (a time course of 10 s to reach full contrast); Right: longer ramping time (a time course of 20 s to reach full contrast).

Indeed, based on their compelling subword priming results, Abrams & Greenwald proposed that masked primes are analyzed mainly at the level of word-parts in contrast to whole-word meaning (Abrams & Greenwald, 2000). However, they did consider that there could also be a limited degree of whole-word analysis in which the unconscious activation of primes is short-lived (Greenwald et al., 1996). Consistently, our results showed that a substantial effect due to subword priming was as strong as, if not stronger than, that of semantic priming. Again, careful examination of target word processing after a prolonged visible prime may be a more sensitive way to probe the priming effect.

However, the question still remains as to how the target (suppressed) word interacts with the neural networks activated by the prime word. Another issue is describing how a suppressed primed (related) word is able to overcome suppression faster than an unrelated word.

If we take a simplistic view of our data and infer that one process occurs before or after another, we would be suggesting that word form and semantic processing occurs before the neural site of interocular suppression. However, the answer is not so simple. Although it is likely that interocular competition starts at V1 when the two eyes' input converges, it is believed that the competition is a multistage process (Blake & Logothetis, 2002; Freeman, 2005; Nguyen et al., 2003; Tong et al., 1998). Thus, it is possible that a representation of the invisible word under interocular suppression, however degraded and rudimentary, is still available at higher-level brain areas and influences the rivalry dynamics via feedback to the early processing stages, particularly when the suppressed word has word-parts in common with or is semantically related to the prime word.

Previous studies using the masking paradigm have demonstrated that the semantic and phonological information of words can be extracted in the absence of awareness (see Neely, 1991 for a full review), suggesting that masked words are represented in part of the cerebral networks for semantic and phonological processing (Bowers, Vigliocco, & Haan, 1998; Greenwald et al., 1996). Indeed, recent brain imaging studies have demonstrated that unseen masked words activate extrastriate, fusiform, and precentral regions (Dehaene et al., 2001), and even the amygdala (Naccache et al., 2005). In a more recent brain imaging study, it was shown that both subliminal and supraliminal primes evoked strong orthographic repetition effects in occipito-temporal areas extending to the visual word form area (VWFA) (Kouider, Dehaene, Jobert, & Le Bihan, 2007), an area located in the left inferior temporal cortex reported in several studies of subliminal priming during reading (Dehaene et al., 2004, 2001; Devlin, Jamison, Matthews, & Gonnerman, 2004).

Although there is still controversy as to whether ventral areas respond to interocularly suppressed (as compared to backward masked) stimuli (Almeida, Mahon, Nakayama, & Caramazza, 2008; Fang & He, 2005), some recent brain imaging studies have found that the ventral stream, including the fusiform face area (FFA) and the parahippocampal place area (PPA), can be weakly activated by or have special activation patterns in response to suppressed stimuli (Jiang & He, 2006; Sterzer, Haynes, & Rees, 2008), similar to what has been found with the masking paradigm (Kouider, Eger, Dolan, & Henson, 2009). Nevertheless, the current study suggests that the suppressed target words are able to reach regions involved in processing the word form and semantic information of words. There is a timing advantage in gaining awareness if the prime word is related (either semantically or shares subword components) to the target word, and it is likely that multiple brain areas interact with each other to facilitate an awareness advantage for related targets.

In conclusion, the networks involved in processing the visible prime are able to strengthen the signal of the suppressed words that are either semantically related or share subword components, resulting in shortened suppression durations for related targets. How this is specifically accomplished still remains open for investigation, but this behavioral finding suggests that information from the suppressed words is able to interact with the neural networks activated by the prime word.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.concog.2009.02.003.

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