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The Onset and Time Course of Semantic Priming During Rapid Recognition of Visual Words

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In 2 experiments, we assessed the effects of response latency and task-induced goals on the onset and time course of semantic priming during rapid processing of visual words as revealed by ocular response tasks. In Experiment 1 (ocular lexical decision task), participants performed a lexical decision task using eye movement responses on a sequence of 4 words. In Experiment 2, the same words were encoded for an episodic recognition memory task that did not require a metalinguistic judgment. For both tasks, survival analyses showed that the earliest observable effect (divergence point [DP]) of semantic priming on target-word reading times occurred at approximately 260 ms, and ex-Gaussian distribution fits revealed that the magnitude of the priming effect increased as a function of response time. Together, these distributional effects of semantic priming suggest that the influence of the prime increases when target processing is more effortful. This effect does not require that the task include a metalinguistic judgment; manipulation of the task goals across experiments affected the overall response speed but not the location of the DP or the overall distributional pattern of the priming effect. These results are more readily explained as the result of a retrospective, rather than a prospective, priming mechanism and are consistent with compound-cue models of semantic priming.

Public Significance Statement

Semantic priming refers to the facilitation in the processing of a word when it is preceded by a related word. The current study found that the earliest observable effect of semantic priming on eye movements during single-word reading occurred approximately 260 ms after the target word was first seen. The magnitude of the effect increased as a function of target-word reading time. Average word reading times were slower when readers made word–nonword discriminations compared with when they encoded each word for a subsequent memory task, but the onset and time course of the priming effect did not differ across tasks. These results suggest that the preceding context of a word has a greater influence on its recognition when the process of recognition is more effortful (i.e., for more difficult words), irrespective of the task-based goals of the reader.

Keywords: semantic priming, ocular response tasks, lexical decision, response-time distributions, eye tracking during word reading

Semantic priming refers to facilitation in the processing of a word when it is preceded by a related word. Meyer and Schvaneveldt (1971) first demonstrated this effect for response times in the lexical decision task (LDT), in which participants make speeded judgments categorizing letter strings as words or nonwords. Since then, semantic priming has become a staple phenomenon in the study of cognition (McNamara, 2005; Neely, 1991). Its effects are robust, as measured in a variety of isolated-word recognition tasks including LDT, word naming, and semantic categorization (de Wit & Kinoshita, 2014, 2015a; Hutchison et al., 2013; Neely, 1976, 1991). Patterns of priming have played a fundamental role in the development of models of language processing and memory (J. R. Anderson, 1983; Collins & Loftus, 1975; Masson, 1995; McNamara, 1992; McRae, de Sa, & Seidenberg, 1997; Plaut & Booth, 2000; Ratcliff & McKoon, 1988; Rumelhart, McClelland, & PDP Research Group, 1986), and semantic priming effects are often used as a tool for assessing other cognitive and psychological phenomena (McNamara, 2005).

The nature of the mechanisms by which semantic relations affect word recognition times continues to be a topic of investigation. A substantial body of the research on semantic priming has focused on distinguishing automatic and strategic priming effects (e.g., Hutchison, 2003; Neely, 1976, 1991), in which automatic processes are defined as fast and unaffected by intention or aware-

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ness, and strategic processes as slower, intentional, and consciously controlled (Posner & Snyder, 1975). In addition, substantial efforts have been made to distinguish prospective priming processes, those that begin *before* the target word in a prime-target pair is encountered (Balota, Yap, Cortese, & Watson, 2008; Neely, 1976; Yap, Balota, & Tan, 2013), from retrospective priming processes that only begin *after* a target word has been encountered (Neely & Keefe, 1989). As discussed by Thomas, Neely, and O'Connor (2012), the prospective–retrospective distinction is neither parallel nor orthogonal to the automatic–strategic distinction. Prospective priming may result from the automatic preactivation of a prime word's related targets (Balota et al., 2008; Hutchison, Neely, & Johnson, 2001; Neely, 1976) or from strategic processes that generate expectations about the target based on the semantic properties of the prime (e.g., Becker, 1980; Neely, Keefe, & Ross, 1989). Similarly, retrospective priming processes may occur because the prime-target relation contributes to the development of a compound cue that can facilitate retrieval of the target word (Ratcliff & McKoon, 1988), or because prime-target relations are strategically recruited to facilitate target resolution. For example, during lexical decision, the presence of a prime-target relationship can be used as a strategic cue that the target is a real word, a strategy referred to as retrospective semantic matching (Forster, 1981; Neely, 1976; Neely et al., 1989; Stanovich & West, 1983) or postlexical coherence checking (de Groot, 1984).

Distributional Effects of Semantic Priming

Analyses of the effect across the full reaction time (RT) distribution have generated new insights regarding the time course and underlying cognitive mechanisms of semantic priming. Ex-Gaussian distributions are typically a good fit for distributions of RTs in both isolated word recognition tasks and eye movements during sentence reading (Balota & Yap, 2011; Balota et al., 2008; Staub, 2011; Staub & Benatar, 2013; Staub, White, Drieghe, Hollway, & Rayner, 2010; White & Staub, 2012). The ex-Gaussian distribution is a convolution of a Gaussian and an exponential distribution described by three parameters (Ratcliff, 1979). The mean and standard deviation of the Gaussian portion of the distribution are described by μ and σ, respectively, and τ represents mean and standard deviation of the exponential component of the distribution. Changes in μ reflect distributional shifts that maintain the general shape of the distribution, changes in σ represent changes in RT variability of the Gaussian component of the distribution, and changes in τ represent changes in the exponential component of the distribution, which reflects the amount of skew. Although the resulting distributions are shaped somewhat differently, an increase in the σ and/or τ parameters reflects an increase of the magnitude of the effect across the slow tail of the distribution. The ex-Gaussian distribution is not based on a theory of response time, so the mapping of distributional parameters to cognitive processes must be supported with additional theoretical and empirical evidence (Balota & Yap, 2011; Matzke & Wagenmakers, 2009). Nonetheless, ex-Gaussian parameter estimates allow us to capture effects of experimental manipulations across the RT distribution.

Recent literature on the effects of semantic priming on response-time distributions has reported several distinct patterns. In some cases, semantic priming has been found to affect only estimates of μ, indicating a shift of the RT distribution between the related- and unrelated-prime conditions. Balota and colleagues (2008) found semantic priming resulted in a distributional shift (affecting only μ) for both speeded pronunciation (at both short and long stimulus-onset asynchronies [SOAs]) and LDTs (at relatively long SOAs; see also Yap et al., 2013). This distributional shift was interpreted to reflect a prospective priming mechanism. According to the prospective priming account, the prime preactivates its related targets, which results in a processing head start for related targets compared with unrelated targets. This head start mechanism would yield a semantic priming effect that is constant across the RT distribution. A pattern of semantic priming resulting solely from a distributional shift was also observed by de Wit and Kinoshita (2014, 2015a) for responses in a semantic categorization task. Similarly, the authors ascribe the distributional shift to a processing head start for related targets. According to this account, the semantic categorization decision is based on a process of evidence accumulation (see Norris & Kinoshita, 2008). The task-relevant (i.e., category-diagnostic) features of related primes overlap with those of the target, allowing the accumulation of relevant evidence about the category membership of the target to begin earlier on related compared with unrelated trials. Importantly, this account was proposed specifically for the semantic categorization task; the authors observed a different distributional pattern of priming during LDT and propose a different, task-specific mechanism in each context. In summary, patterns of semantic priming reflected solely in a distributional shift (estimates of the μ parameter) are generally considered to reflect a prospective priming process in the form of a metaphorical processing head start, although accounts vary on the precise mechanism by which this head start is established.

Nonetheless, in the majority of cases, semantic priming has been observed to affect not only μ, but both μ and either σ or τ, with the resulting distribution reflecting semantic priming effect for both fast and slow responses, and the magnitude of the effect increasing as a function of response time. Balota and colleagues (2008) found that LDTs with a short SOA (250 ms) showed a priming effect on μ and σ, and when targets were visually degraded, semantic priming affected μ and τ (Balota et al., 2008; Yap et al., 2013; both experiments used an 800-ms SOA). De Wit and Kinoshita (2015a) also observed a combination of μ- and τ-based priming for a LDT with visually intact targets at a short SOA using a high proportion of related trials. Furthermore, the distributional pattern of priming can be affected by individual differences in vocabulary knowledge. Yap, Tse, and Balota (2009) found that semantic priming affected both μ and τ for low-vocabulary individuals on low-frequency targets, whereas high-vocabulary individuals showed priming in the form of a distributional shift only (μ effect), regardless of target frequency (see also Hutchison, Heap, Neely, & Thomas, 2014). This pattern combining a distributional shift and increasing effects in the slow tail of the distribution has been argued to reflect a mixture of prospective and retrospective influences of the prime. Balota and colleagues (2008) proposed that the $\mu+\sigma$ and $\mu+\tau$ effects of semantic priming reflect a "race" between bottom-up processing of the target (aided by the prospective influence of the related prime) and retrospective utilization of the prime to facilitate target processing. The authors suggest that the increased magnitude of the priming effect on slow responses (effects on the σ or τ parameter) is considered to reflect a greater reliance on related prime information for targets that are more difficult to process, for example, because they are visually degraded (Balota et al., 2008; Yap et al., 2013), or in the case of low-frequency targets for low-vocabulary individuals (Yap et al., 2009). Importantly, this mechanism does not necessarily reflect a conscious reliance on the prime, as a similar pattern of $\mu+\tau$-based priming was observed when primes were highly masked and thus unavailable for conscious processing (Balota et al., 2008; but see de Wit & Kinoshita, 2015b).

De Wit and Kinoshita (2015a, 2015b) have proposed a somewhat different account for the $\mu+\tau$-based pattern based on Ratcliff and McKoon's (1988) compound-cue model. According to their account, slow responses allow more time for the prime to affect responses through the LDT-specific mechanism of retrospective semantic matching. While the target is being processed, information about the prime-target relationship is added to the developing compound cue, the collection of cues used to make the lexical decision. More direct evidence that semantic priming depends on a retrospective process is provided by Thomas et al. (2012), who showed that the finding of greater priming for visually degraded targets in the slow tail of the distribution was observed *only* for targets with a strong backward association, meaning that the prime was a strong associate of the target, but not vice versa (e.g., *small–shrink*), and symmetrically associated pairs (e.g., *east–west*), but not for pairs that shared only strong forward associative connections (e.g., *keg–beer*; see also Hutchison et al., 2014). These findings support the notion that the increase in priming across the RT distribution depends on an active process of retrospective recruitment of information about the prime or the target-to-prime relationship in service of target–word recognition, a process that cannot begin until after the target word is encountered. Although de Wit and Kinoshita (2015a, 2015b) have proposed that such retrospective use of prime information takes place specifically in service of the word–nonword discrimination component of the LDT, similar data patterns have been observed in speeded naming tasks, which do not require a word–nonword discrimination, when targets were visually degraded (Balota et al., 2008; Thomas et al., 2012). In sum, although analyses of semantic priming effects have in some cases shown only a distributional shift, a substantial body of research shows a distributional shift plus changes in skew, thereby suggesting that semantic priming is a combination of prospective and retrospective influences.

Task Goals and Response Speed

Although ex-Gaussian distribution fits provide information about the development of semantic priming as a function of target processing time, interpretation of this information must take task factors into account. First, responses in most isolated word recognition tasks are relatively slow. For both manual lexical decisions (LDs) and speeded naming tasks, response times average around 600 ms (Balota & Chumbley, 1984; Balota et al., 2007; McNamara, 2005), whereas reading times for the same words presented in a sentence take only half that time or even less (Inhoff, 1984; Morris, 1994; Rayner, 1998). This is an important consideration, especially when interpreting effects of priming as function of response time. A second, related concern is that manual key presses, and arguably even vocal naming, are not familiar ways of responding to recognition of written words. The response of moving the eyes from one word to the next during reading is highly practiced for skilled readers, so that there is a tight link between word recognition and saccade execution (Engbert, Nuthmann, Richter, & Kliegl, 2005; Gordon, Plummer, & Choi, 2013; Rayner & Pollatsek, 1989; Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2006). In contrast, isolated word recognition tasks require participants to use a far less practiced response mode together with response mappings that have little connection to natural reading.

Ocular LDTs (Hoedemaker & Gordon, 2014a) eliminate the unusual manual response mappings typically used in LDTs with a more natural eye movement response that leads to much faster RTs. In Hoedemaker and Gordon's (2014a) study, participants read a sequence of three- letter strings and were instructed to move their eyes from one letter string to the next if the letter string was a word, but to keep their eyes still and press a button if the letter string was a nonword. Semantic relatedness of the first (prime) and second (target) words of the sequence in each trial was manipulated. Mean target processing times in the ocular LDT were shorter than those typically observed in the manual LDT. Average lexical decision time for target words not preceded by a related prime was 384 ms, compared with 595 ms for the same words in the English Lexicon Project ([ELP], Balota et al., 2007; average speeded naming time for the same words in the ELP was 599 ms). Nonetheless, ocular response times were found to be highly sensitive to lexico-semantic word characteristics. First, across all words in the study, the word frequency effect was marginally stronger for ocular lexical decisions ($R^2 = .27$) than for the ELP's manual lexical decisions ($R^2 = .18$). Second, gaze durations in the ocular LDT showed a statistically robust 23-ms priming effect. The magnitude of this effect was smaller in absolute terms than the 34-ms effect observed for the same prime-target pairs in the manual LDT experiment from which the stimuli were adapted (Lupker & Pexman, 2010, Experiment 4), but when considered as a proportion of the response time in the unrelated condition, the ocular effect was slightly larger than the effect observed with manual response times (6.0% of the 384-ms baseline response time in the ocular task compared with 5.6% of the 606-ms baseline in Lupker and Pexman's [2010] manual task). In sum, the ocular LDT has an advantage over the manual LDT because its response mapping (a forward saccade to indicate successful recognition of a word) closely resembles that of normal reading while maintaining the task goals of an LDT and showing robust sensitivity to lexico-semantic word characteristics. As a result, this task allows us to assess a portion of the word recognition response time distribution that is not accessible to manual response tasks.[1]

Mean target processing times in the Hoedemaker and Gordon's (2014a) ocular LDT showed a robust semantic priming effect. However, contrary to the results of prior literature using manual response tasks, Hoedemaker and Gordon did not observe a priming effect on μ. Instead, the semantic priming effect was concentrated in estimates of τ, indicating that the prime effect primarily affected

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[1] As only nonwords demand a key press response, the ocular LDT somewhat resembles a go/no-go LDT (although in the ocular LDT, words also demand a response: a forward saccade). Comparison of yes/no and go/no-go LDTs has shown that RTs are strongly correlated across the tasks, if slightly faster in the go/no-go version, suggesting the two types of tasks are highly similar (e.g., Chiarello, Nuding, & Pollock, 1988; Perea, Rosa, & Gómez, 2002). Specifically, Perea et al. (2002) found no difference in the magnitude of the semantic priming effect across the two types of tasks.

slower responses, with the influence of the prime increasing gradually as a function of response time. As discussed, previous observations of priming effects on μ (indicating a distributional shift) have been interpreted to reflect a metaphorical head start or prospective priming mechanism. However, the faster response times afforded by the ocular response mode allowed a portion of the LDs to be completed before the time needed to show significant priming, showing that the observation of a distributional shift depends in part on the response time floor that is dictated by the measure that is used. Furthermore, ex-Gaussian analyses provide information about the development of semantic priming over time, but they do not provide an estimate of the earliest moment at which the prime has an effect on behavior. Survival analysis of fixation durations during reading complements ex-Gaussian distribution fits by providing information about the earliest time point at which effects such as priming may be detected (Reingold, Reichle, Glaholt, & Sheridan, 2012). With this method, survival curves are computed for each 1-ms bin over a time window by determining the proportion of fixations that are slower than the time of the bin (i.e., fixations that "survive," as they have not yet been terminated by a saccade). The earliest point at which there is a discernable difference between the curves for two different conditions is known as the divergence point (DP). Using a combination of ex-Gaussian and survival analyses, Reingold, Sheridan, and colleagues have found that a variety of factors have relatively fast-acting effects on first-fixation duration during normal reading (DPs ranging from 139 ms to 145 ms), including word frequency (Reingold et al., 2012), predictability (Sheridan & Reingold, 2012a), and lexical ambiguity (Sheridan & Reingold, 2012b).

Current Study

The current study follows Hoedemaker and Gordon (2014a) in using fast ocular responses to determine the minimum duration at which semantic priming affects behavioral responses to word recognition (using survival analysis), and to assess how the influence of the prime varies as a function of response time (using both survival and ex-Gaussian analyses) and task-based goals. Experiment 1 uses the ocular LDT (Hoedemaker & Gordon, 2014a) in order to establish the DP and distributional pattern of semantic priming when the metalinguistic judgment of lexical status is indicated by movement of the eyes. Experiment 2 tests participants with the same set of words as Experiment 1, but replaces the LDT with an episodic recognition task in which each word in a trial set must be encoded in preparation for an episodic recognition probe immediately following the set. The episodic recognition task allows us to access an even earlier portion of the response time distribution than is available using ocular LDTs, and analyses of the DP and distributional pattern of priming across tasks allows us to distinguish between the effects of task goals and response speed. If the distributional pattern of effects observed in manual LDTs (priming reflected in both μ and σ or τ) reflects a retrospective matching procedure applied specifically in service of the word–nonword discrimination task (Balota et al., 2008; de Wit & Kinoshita, 2015a, 2015b), we should not observe this effect on single-word reading times when the task only requires encoding for subsequent episodic recognition. In an attempt to further distinguish between prospective and retrospective priming mechanisms, we adapted Thomas et al.'s (2012) approach and varied the degree of forward and backward association strength. As discussed, prospective priming mechanisms are hypothesized to rely on forward (prime-to-target) associative connections, whereas retrospective priming mechanisms make use of backward (target-to-prime) associations. Therefore, an effect of either forward or backward association strength would provide further evidence for a prospective or retrospective priming mechanism, respectively.

Experiment 1

Experiment 1 uses the ocular LDT to assess the onset and distribution of semantic priming in an LDT. As in Hoedemaker and Gordon (2014a), participants were presented with sets of letter strings, and on each string, made a lexical decision by moving their eyes to the next string in the set to indicate "word" and by keeping their eyes still and pressing a button to indicate "nonword." The task and stimulus presentation in the current experiment were identical to those used by Hoedemaker and Gordon, except that the current experiment presented sets of four words instead of three. The current experiment had three goals: to establish the extent to which this new stimulus set shows the distributional pattern of priming during ocular LDT observed by Hoedemaker and Gordon, to determine the earliest point at which an effect of priming may be observed on fixation durations in the ocular LDT, and to assess how the strength of the forward and backward prime-target connections affects the magnitude of the priming effect. The results of Hoedemaker and Gordon lead to the prediction that the magnitude of the priming effect will increase across the slow tail of the distribution, supporting the notion that priming depends on a mechanism that relies on the availability of target information. Hoedemaker and Gordon did not observe μ-based priming, indicating that a portion of LDs was completed faster than the time needed for priming to affect response time. Based on these earlier findings, the DP of the semantic priming was predicted to occur after the start of the distribution, allowing a portion of responses to occur before the DP. Together, these results would provide evidence for a priming mechanism that depends mostly on information about the target. Thomas et al. (2012) found that priming effects observed in the degree of distributional skew crucially depend on the presence of target-to-prime (backward) associative connections, suggesting the effect depends on a retrospective priming process. Consistent with this hypothesis, we expect greater priming for items with stronger backward associative connections.

Method

Participants. A total of 33 undergraduate students from the University of North Carolina at Chapel Hill participated in the experiment for course credit. All participants were native speakers of English with normal or corrected-to-normal vision. One participant was excluded from all analyses because of high skipping rates (over 40% of trials included at least one skip), leaving a total of 32 subjects in the analysis.

Materials and design. The stimulus words were presented in sets of four, with the experimental primes and targets appearing in the first and second position of each set. For the purpose of all three experiments in the current study, a total of 160 associatively related prime-target pairs were selected from the Semantic Priming Project's (SPP's) lexical decision database (Hutchison et al., 2013) on the basis of showing strong associative priming in the SPP study (mean standardized priming effect: z = .42, SD = .20, range = .20–1.10). In addition, the prime-target pairs were selected to represent a range of forward (.01–.83) and backward (.00–.82) association strengths based on the Nelson, McEvoy, and Schreiber (1998) association database. The word frequency of primes and targets is reported as the log10 of the number of occurrences per 51 million (SUBTLEXus; Brysbaert & New, 2009) and averaged 3.02 (range 1.30–4.87), mean length was 5.96 letters (range = 4–14 letters), and mean orthographic neighborhood size was 4.14 (range = 0–28 neighbors). All experimental pairs are provided in the Appendix. To keep the duration of the LDT in the current experiment under 45 min while accommodating the use of filler trials required for the LDT design, a total of 120 experimental prime-target pairs were randomly selected from the full set. For the selected pairs the mean standardized priming effect was z = .42 (range = .20–.97), primes and targets had a mean word frequency of 3.04 (range = 1.3–4.87), mean length was 6.08 letters (range = 4–14) and mean orthographic neighborhood size was 4.18 (range = 0–28). To create the stimulus lists, each prime was repaired with a different prime's related target in order to create a set of unrelated prime-target pairs. The related and unrelated pairs were divided into two lists that were shown to difference participants. Each list contained every target, half preceded by a related prime and half preceded by an unrelated prime, and no words were repeated within a list.

A word or a pronounceable nonword was added in the posttarget position for each prime-target pair, so that half of the related and half of the unrelated pairs were followed by a nonword. For those pairs followed by a word in the third position, a word or nonword was added in the fourth and last position, distributed equally across related and unrelated trials. Filler trials were added so that on 20% of the trials (60 trials per list), a nonword appeared in the first (prime) position, and on 40% of the trials (120 trials per list), a filler word appeared in the first position, followed by a nonword in the second (target position). As a result, there was always a .5 probability of a nonword appearing in the second, third, or fourth position, given that the previous position contained a word. The filler words were selected from the Nelson et al. (1998) association database, and nonwords were selected from the ELP (Balota et al., 2007). The experimental and filler words were equivalent in mean frequency, $t(446) = -.77$, $p = .44$, and the experimental words, fillers, and nonwords were equivalent in word length, $F(2, 715) = 1.54$, $p = .22$, and orthographic neighborhood size, $F(2, 715) = 1.61$, $p = .20$.

Procedure. Eye movements were recorded in a dimly lit room from the participant's dominant eye using an SR EyeLink 1000. Eye dominance was determined using the Miles or "hole-in-the-hand" test (Miles, 1929; Roth, Lora, & Heilman, 2002). Chin and forehead rests were used to minimize head movements. The stimuli appeared on a 22-in. Samsung LCD monitor at a viewing distance of 57 cm, with a 120-Hz refresh rate and a 1680 × 1050 display resolution. Use of a 20-point monospace font rendered each letter about 11 pixels wide; 1° of visual angle spanned approximately three characters. A 9-point calibration procedure preceded each experimental session. After initial calibration, each experimental session started with 10 warm-up trials. These warm-up trials did not contain any of the words used in the experimental list and were excluded from all analyses. Following the warm-up trials, all experimental trials were presented in random order in a single block. Each experimental session lasted approximately 30 min.

Operation of the gaze-contingent display is depicted in Figure 1. The start of each trial was marked by a fixation point on the left side of the screen. Once this point was fixated, the next screen appeared containing four masks made up of hash marks. The first mask appeared six blank character spaces to the right of the fixation point, and the subsequent masks were separated by two blank character spaces. Gaze-contingent invisible boundaries were placed between each mask. The gaze contingencies were set to prevent parafoveal processing and rereading of the nonfixated words. Each word was unmasked only when the eyes entered its region on the screen from left to right. Once the eyes left the word across the right boundary (thus simultaneously entering the next region and unmasking the next word), the mask reappeared and the word was no longer visible regardless of whether the participant made any regressive eye movements. Participants were instructed to read the four words silently, and for each letter string, decide whether it was a word or a nonword. Each time they decided a letter string was a word, they were to indicate this by moving their eyes as quickly as possible to the next letter string in the set (or to the final hash mark in the case of the fourth word). They were instructed to keep their eyes still and use a speeded key press on a hand-held console each time they decided the string was a nonword. This key press ended the trial. In the case of a correct decision on the final word, the words "Correct! Please press the button to proceed to the next trial" appeared in response to fixating the final fixation point. The word "INCORRECT!" was presented after an incorrect eye movement (i.e., making a forward saccade to

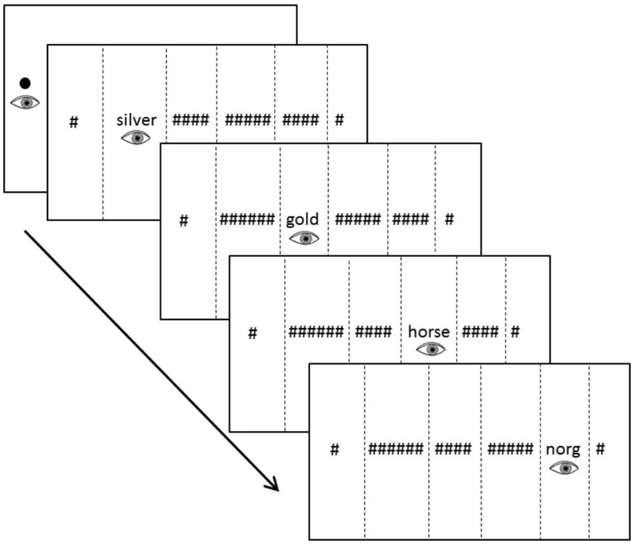

Figure 1. Presentation of stimuli in the ocular lexical decision task (Experiment 1) on the gaze-contingent display. For each letter string in the set, participants were instructed to move their eyes to the next string to indicate "word" and to hold their eyes still and press a button to indicate "nonword." The dashed vertical lines represent the invisible boundaries used to trigger the gaze-contingent display changes. Gaze contingencies were set up to prevent rereading of previously seen words and preview of upcoming words.

the next letter string in cases in which the currently fixated string was a nonword) or an incorrect button press (i.e., pressing the button while fixating a real word). Any incorrect response ended the trial, regardless of which word position had been reached at that moment.

Analysis of eye movements. Fixations shorter than 80 ms and within 1° of a longer, immediately subsequent fixation were merged with the longer fixation by an automatic procedure in the EyeLink software. Trials on which either the prime or the target was skipped (6.4% of critical trials) were removed from the analyses, as were trials on which a boundary was inadvertently triggered by a blink (.7% of critical trials) or because the eye fixated on or very near the boundary instead of on the word (4.9% of critical trials). Trials on which the participant regressed from the target back to the (then masked) prime, rather than progressing to the posttarget word, were also removed (.2% of trials). The excluded trials were distributed equally across the related and unrelated conditions, with an average of 51 usable critical trials remaining in each condition. When brief delays in the display change caused a word to be unmasked slightly after the onset of the first fixation on a word (13.9% of words), the time stamp of the fixation onset was adjusted to reflect the onset of the word display, excluding any time the participant was fixating the mask rather than the word; the adjustments averaged 7 ms (range = 1–71 ms). Finally, a reading time cutoff was determined at three standard deviations above the mean for each position in the triplet in each relatedness condition. Gaze durations longer than the relevant cutoff were removed, affecting 1.8% of all words on critical trials, equally distributed across the related (1.7%) and unrelated (1.8%) trials.

Gaze duration (GZD) is the sum of all first-pass fixation durations on a word. In the context of the ocular LDT, GZD was interpreted as a measure of both encoding and lexical decision time. Results for two other widely used measures of first-pass reading are reported for completeness. *Single-fixation duration* (SFD) is the fixation duration for those words that received only one first-pass fixation. *First-fixation duration* (FFD) is the duration of the first fixation on a word regardless of the total number of fixations on that word. However, GZD is our primary measure of interest for several reasons. First, GZD is widely used as a measure of lexical encoding in eye-tracking studies of reading (Inhoff, 1984; Morris, 1994; Rayner, 1998), and although there are arguments for using SFD or FFD instead of GZD, both measures also have substantial drawbacks. Although SFD may be the most straightforward eye movement measure of word encoding, limiting our analyses to trials in which the target received a single fixation would result in a large amount of data loss (the target received more than one fixation on over 30% of all critical trials). Previous studies examining distributional effects of lexical characteristics on eye movements sometimes focus on FFD instead of GZD, but this measure can be considered less stable than GZD, as the decision to refixate a word may be influenced by nonlexical factors such as the initial landing position within the word or other oculomotor targeting errors (Rayner, 1998). Finally, because participants were instructed to indicate a "word" decision by moving their eyes to the next letter string, GZD in this context is operationally equivalent to button press RT during manual LDT.

Survival curves were computed for GZD and FFD on the target word in the related and unrelated conditions. For each 1-ms time bin within a 1 ms to 1,040 ms window, the proportion of reading times that was longer than the time bin was considered the proportion of "surviving" fixations. Survival curves were computed separately for each participant, and the averaged curves are presented in Figure 2 (top row). The confidence interval (CI) Divergence Point Analysis (DPA) procedure of Reingold and Sheridan (2014), which uses bootstrap resampling of the data (Efron & Tibshirani, 1994), was used to determine the earliest time bin at which the proportion survival differed as a function of relatedness condition; see also Reingold and Sheridan (2014) for additional DPA bootstrapping procedures, and Inhoff and Radach (2014) for an alternative DPA procedure. On each of 10,000 bootstrap iterations, the collection of data for each condition within each participant was randomly resampled with replacement, and the individual participant survival curves were computed and averaged across participants. For each bootstrap iteration, the DP was determined as the first bin in a run of five consecutive bins on which the proportion survival in the unrelated condition was at least 1.5% greater than in the related condition (following the criteria recommended by Reingold & Sheridan 2014). Subsequently, the 10,000 DP estimates were rank ordered and the median of all DPs was used as the DP estimate for the sample. The 250th and 9,750th observed DP values were taken as the lower and upper bound of the 95% CI.

Ex-Gaussian parameter estimates for target-word reading times were obtained separately for each participant in each relatedness condition using the QMPE v2.18 program (Cousineau, Brown, & Heathcote, 2004) for quantile maximum probability estimation. Quantile estimates were calculated by ranking RTs for each participant in each condition from fastest to slowest, and dividing them into 11 equally spaced bins. Ten observed quantile estimates were then generated by taking the average of the slowest trial in one bin and the fastest trial in the next bin. This approach to distributional analysis has the advantage that data from all participants is represented equally across the 10 quantiles, thereby effectively standardizing the effect across the distribution. As such, these analyses avoid the problems typically associated with of interpreting effects across individuals, groups, or items with different baseline response latencies (Faust, Balota, Spieler, & Ferraro, 1999; Hutchison, 2003).

Results

Mean accuracy across subjects on all (critical and filler) trials was 98% for words (range = 84%–100%) and 85% for nonwords (range = 69%–99%). These levels of accuracy are similar to those found in the English Lexicon Project for these particular words (words = 97%; nonwords = 86%). For GZD and FFD, the average number of correct trials per participant available for analysis after trimming was 49 in each condition. The average number of available single-fixation trials was 33 in the unrelated condition and 35 in the related condition. Table 1 presents word reading times on the prime, target and third-word across relatedness conditions. Mean GZD was 440 ms (SD = 62 ms) for unrelated words across all three positions (i.e., target words [second position] in the related-prime condition were excluded). Average ocular LD times were significantly faster than manual LDs (M = 635 ms, SD = 68), $t(299) = 56.97$, $p < .001$, and speeded naming times (M = 623 ms, SD = 46), $t(299) = 52.7$, $p < .001$, for the same words in the

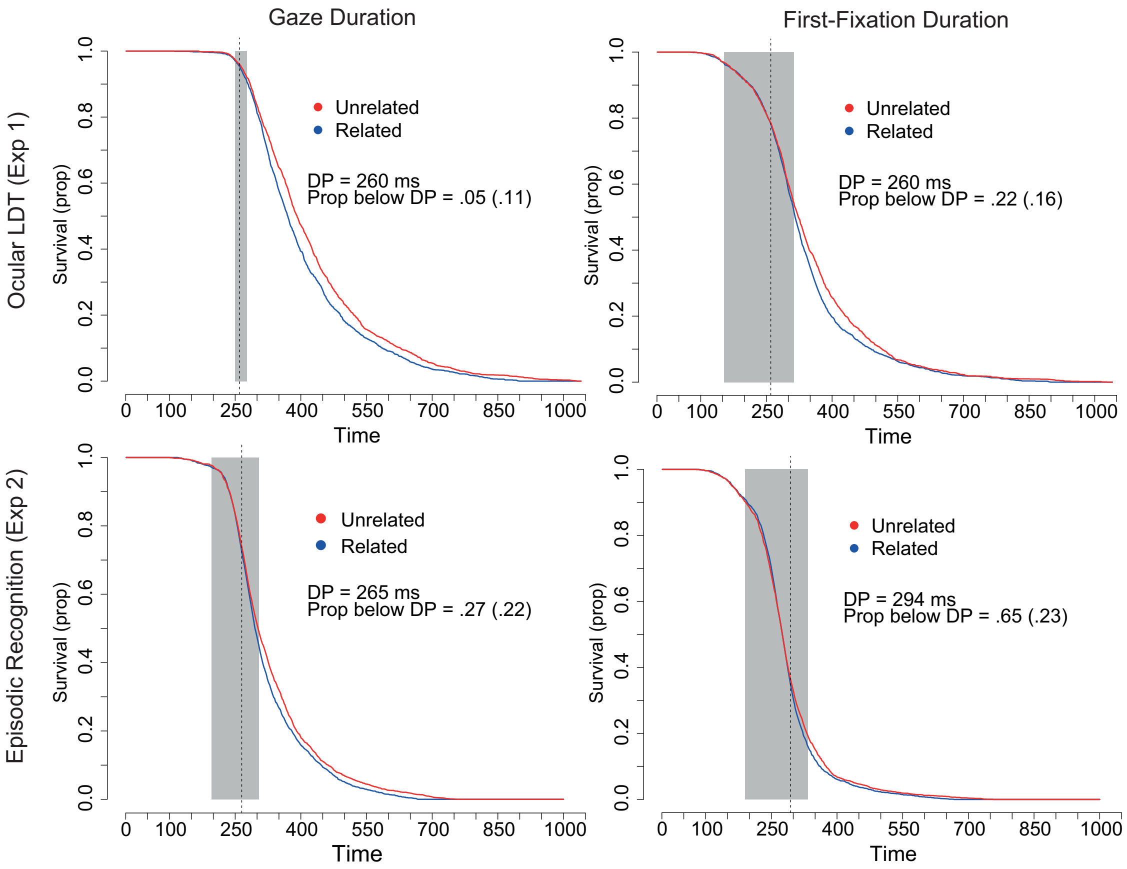

Figure 2. Survival plots for gaze duration and first-fixation duration in Experiments 1 and 2. The dashed line presents the divergence point (DP). The gray boxes represent the 95% confidence interval of the divergence point. LDT = Lexical Decision Task; Exp = Experiment; Prop = Proportion. See the online article for the color version of this figure.

ELP. Mean GZDs on individual words were correlated with manual response times in the ELP, $r = .59$, $R^2 = .34$ $p < .001$ ($N = 300$), but the effect of SUBTLEX frequency (Brysbaert & New, 2009) on response times was greater for ocular LDs, $r = -.60$, $R^2 = .36$, $p < .001$ ($N = 300$), than manual LDs, as observed in the ELP database, $r = -.49$, $R^2 = .24$ ($N = 300$), Fisher's $z = 2.61$, $p < .01$ ($N = 300$). The average manual response time to nonwords (correct responses only, trimmed to exclude RTs more

Table 1
Word Reading Times in Experiment 1

		Word position		
Measure	Condition	Prime	Target	Posttarget
Word GZD (*SD*)	Unrelated pairs	451 (82)	425 (80)	417 (71)
	Related pairs	459 (89)	398 (76)	431 (82)
	Mean	455 (85)	411 (79)	424 (77)
	Priming		27*	−14*
Word FFD (*SD*)	Unrelated pairs	250 (59)	349 (67)	330 (64)
	Related pairs	254 (68)	333 (66)	332 (69)
	Mean	252 (63)	341 (66)	330 (66)
	Priming		16*	−2
Word SFD (*SD*)	Unrelated pairs	388 (83)	397 (81)	377 (69)
	Related pairs	386 (86)	372 (73)	385 (74)
	Mean	387 (84)	384 (77)	381 (71)
	Priming		25*	−8

Note. All times in are in milliseconds. Asterisks indicate a significant effect. GZD = gaze duration; FFD = first-fixation duration; SFD = single-fixation duration.

than three standard deviations above the mean for that word position) was 710 ms ($SD = 137$).

Semantic priming. Target-word reading times showed a significant effect of relatedness, such that ocular LDs for targets were faster in the related compared with the unrelated condition across all eye movement measures, GZD: $t_1(31) = 4.65$, $p < .001$, $t_2(119) = 6.73$, $p < .001$; SFD: $t_1(31) = 4.04$, $p < .001$, $t_2(119) = 4.90$, $p < .001$; FFD: $t_1(31) = 3.44$, $p < .01$, $t_2(119) = 4.08$, $p < .001$. Consistent with the priming effect on target-word RTs, accuracy rates were higher for related ($M = 98\%$) compared with the unrelated ($M = 96\%$) target words, $t_1(31) = 2.16$, $p < .05$, $t_2(119) = 2.56$, $p < .05$. Regression analyses within individual participants showed that priming on the target was greater for prime-target pairs with higher forward association values for SFD, $t(31) = -2.78$, $p < .01$, and FFD, $t(31) = -3.63$, $p < .01$, and the effect was marginal for GZD, $t(31) = -1.84$, $p = .08$. Priming did not vary as a function of backward association strength (ts < 1).

GZDs on the posttarget word showed a reversed effect of prime-target relatedness, such that posttarget reading times were longer after a related compared with an unrelated prime-target pair, $t_1(31) = -2.44$, $p < .05$, $t_2(59) = -2.28$, $p < .05$, though this effect was not significant for SFD, $t_1(31) = -1.39$, $p = .17$, $t_2(59) = -.75$, $p = .45$, or FFD, $t_1(31) = -.32$, $p = .75$, $t_2(59) = -.50$, $p = .62$. Response accuracy on the posttarget word also showed a reversed effect of relatedness, such that accuracy was lower following a related (M = 96%) compared with an unrelated (M = 97%) prime-target pair, an effect that reached significance by subjects, $t_1(31) = -2.25$, $p < .05$, but not by items, $t_2(59) = 1.64$, $p = .12$.

Survival analysis. The DP for GZDs in the current experiment was estimated to occur at 260 ms (95% CI [250, 277]). This analysis indicates that the earliest point at which a semantic priming effect could be detected was 260 ms. For FFD, the DP was also estimated at 260 ms (95% CI [153, 312]). For each individual participant, we computed the proportion of target-word reading times (across related and unrelated conditions) that were faster than the DP of the sample. Averaged across participants, .05 ($SD = .11$) of GZDs were faster than the GZD DP, and .22 ($SD = .16$) of FFDs were faster than the FFD DP.[2]

Ex-Gaussian distribution fits and quantile analyses. The quantile estimates for GZD and FFD are plotted in Figure 3. There was a main effect of relatedness on GZD, $F(1, 31) = 19.4$, $p < .001$, SFD, $F(1, 29) = 12.69$, $p < .001$, and FFD, $F(1, 31) = 8.0$, $p < .01$. For GZD and FFD, there was also a significant interaction between quantile and relatedness, indicating that the effect of relatedness increased across the slow tail of the distribution (GZD: $F[1, 31] = 5.6$, $p < .05$; FFD: $F[1, 31] = 8.3$, $p < .01$). The effect was not significant for SFD, $F(1, 29) = 2.66$, $p = .11$. In order to ensure that the interaction did not depend entirely on effects occurring only in the slowest tenth quantile (which showed a great deal of variability), the ANOVA was repeated including only the first nine quantiles. The results remained the same regardless of 10th quantile inclusion.

Table 2 shows the average ex-Gaussian parameter estimates for GZD and FFD generated by the QMPE program (SFD did not yield a large enough number of observations to allow for ex-Gaussian distribution fits). The parameter estimates were used as dependent variables in a paired-samples t test. There was no effect of relatedness on μ, GZD: $t(31) = 1.66$, $p = .11$, FFD: $t(31) = -1.37$, $p = .18$, or σ, GZD: $t(31) = -.58$, $p = .57$, FFD: $t(31) = -.05$, $p = .96$. Estimates of τ showed a significant effect of relatedness on FFD, $t(31) = 2.54$, $p < .02$, indicating an increase in priming across the slow tail of the distribution. This effect did not reach significance for GZD, $t(31) = 1.62$, $p = .12$. However, the effect was significant when two subjects with the worst ex-Gaussian model fits (computed as the average discrepancy between the observed and estimated quantile estimates across the first nine quantiles, excluding the often-noisy 10th quantile) were excluded from the model,[3] $t(29) = 2.54$, $p < .05$.

We also assessed the effect of prime-word reading time on the distribution of target-word reading times. To do this, we ranked each participant's prime-word GZDs within relatedness conditions and divided these into five equally sized bins. We computed each participants' average target-word reading time for each prime-reading time bin in each condition,[4] and used a 5 (bins 1–5) × 2 (related vs. unrelated) ANOVA to assess the effect of prime-word reading time on the magnitude of the target-word priming effect. As can be observed in Figure 4, besides the main effect of relatedness that was already established (GZD: $F[1, 31] = 23.0$, $p < .001$; FFD: $F[1, 31] = 9.7$, $p < .01$), target-word reading times were positively correlated with prime-word GZD, reflecting a within-trial "rhythm" effect (GZD: $F[1, 31] = 56.1$, $p < .001$; FFD: $F[1, 31] = 22.3$, $p < .001$). However, the magnitude of the priming effect on target-word reading times did not vary as a function of the amount of time spent on the prime, Fs < 1. Supplementary analyses showed these results were not affected by the time stamp corrections applied to account for the occasional brief delays in the gaze contingent display change.

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[2] Additional analyses of the ocular LDT data presented in Hoedemaker and Gordon (2014a, Experiment 1) showed similar results. In this experiment, the DP of the semantic priming effect occurred at 270 ms for GZD and 272 ms for FFD. The proportion of responses faster than the DP was 14% ($SD = 12\%$) for GZD and 42% ($SD = 14\%$) for FFD.

[3] Collapsed across the first nine quantiles and relatedness conditions, the average discrepancy between predicted and observed quantile estimates across subjects was 6.83 ms (range = 1.01 to 12.41), not including the two worst-fit subjects, who had an average discrepancy of 14.21 and 15.06 ms. When the two worst-fit subjects were excluded from the model, there was no effect of relatedness on μ ($M = 7$ ms), $t(29) = 1.10$, $p = .28$, and no effect of relatedness on σ ($M = -6$), $t(29) = -1.43$, $p = .17$. The pattern of results for first-fixation duration did not change as a result of excluding the two worst-fit subjects.

[4] Note that this approach differs from the distributional analysis of the target-word priming effect as a function of target-word reading time. In the latter analysis, sorting responses by target-word reading times necessarily results in smooth, increasing distributions. In the current analysis, target-word reading times are sorted as a function of prime-word reading times, meaning the resulting function is not necessarily increasing or smooth, and accordingly warrants a less-detailed assessment. For this reason, the results are plotted and analyzed using five bins rather than 10. In addition, target priming as a function of prime-word reading time is plotted as the average reading time in each bin (see Figure 4) rather than quantile estimates of reading time (e.g., Figure 3). In the analysis of the semantic priming effect as a function of target-word reading time, when the target-word reading times were sorted from fast to slow, the quantile estimates were computed as the mean of the slowest RT in one bin and the fastest RT in the next bin. In the analysis of target priming as a function of prime-word reading times, target RTs are ordered nonconsecutively, such that the quantile estimate is less meaningful than the bin average.

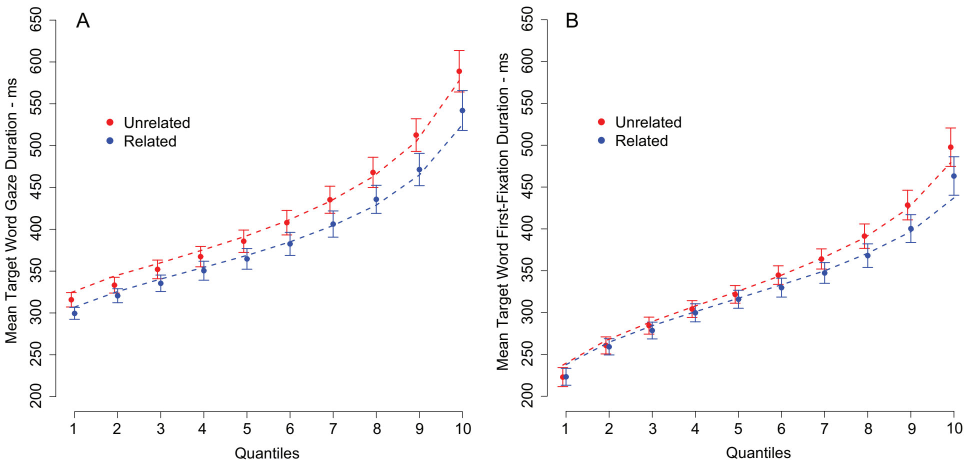

Figure 3. Quantile plot for mean gaze durations (Panel A) and first-fixation durations (Panel B) on the target word in the ocular lexical decision task (Experiment 1) when the target was preceded by a related or an unrelated prime. Quantile estimates were calculated by ranking RTs for each participant in each condition from fastest to slowest, and dividing them into 11 equally spaced bins. Ten observed quantile estimates were then generated by taking the average of the slowest trial in one bin and the fastest trial in the next bin. Quantiles are arranged from fastest to slowest on the x-axis. Error bars show the standard error of the quantile value across subjects and the dashed lines represent predicted quantile values based on mean parameters of the estimated ex-Gaussian distribution. See the online article for the color version of this figure.

Discussion

Consistent with Hoedemaker and Gordon (2014a), we observed a robust semantic priming effect in the ocular LDT, even though average word reading times were much shorter than those typically observed using manual-response or speeded-naming tasks. In addition, the word frequency effect was stronger for ocular LDs in the current experiment than for manual LDs in the ELP (Balota et al., 2008), confirming that this measure is sensitive to lexical properties. DP analysis revealed that the earliest detectable influence of the prime on target-word reading times, whether measured for GZD or FFD, occurred around 260 ms after the target word was fixated. The timing of this DP is roughly consistent with the time scale of semantic priming as observed using electroencephalography. Typically, the ERPs associated with target-word processing in LDT are shown to begin diverging between 200 and 250 ms, with the effect peaking in the N400 region (e.g., Bentin, McCarthy, & Wood, 1985; Holcomb, 1988), although in some cases, the effect is not reported to emerge until 300 ms after the onset of the target (J. E. Anderson & Holcomb, 1995; Holcomb & Neville, 1990; Rossell, Price, & Nobre, 2003).

A possible concern about these data is that fast ocular responses include a high proportion of guesses, which would explain why the priming effect was attenuated in the fast tail of the distribution. The accuracy data showed a bias to respond "word" (higher error rates for nonwords than words), as might be expected if participants adopted a liberal criterion for moving their eyes to the next letter string. However, this word bias was similar in magnitude to that found for manual LDs for the same words in the ELP (Balota et al., 2007), suggesting that response bias contributes equally to ocular and manual LD responses. Importantly, there was no relationship between individuals' nonword error rates and the extent to which the effect of relatedness within participants was expressed in effects of priming on either μ (GZD: $r = .26$, $p = .15$; FFD: $r = .11$, $p = .56$) or τ (GZD: $r = -.07$, $p = .69$; FFD: $r = -.03$, $p = .86$). Therefore, participants who adopted a more conservative strategy did not show greater μ-based priming than participants

Table 2
Ex-Gaussian Parameter Estimates in Experiment 1

		Parameter		
Measure	Condition	Mu	Sigma	Tau
GZD (*SD*)	Unrelated	324 (70)	27 (30)	104 (55)
	Related	313 (65)	30 (31)	87 (48)
	Priming	11	−3	17
FFD (*SD*)	Unrelated	267 (57)	54 (34)	82 (64)
	Related	275 (60)	54 (34)	58 (54)
	Priming	−8	0	24*

Note. All times in are in milliseconds. Asterisks indicate a significant effect. GZD = gaze duration; FFD = first-fixation duration.

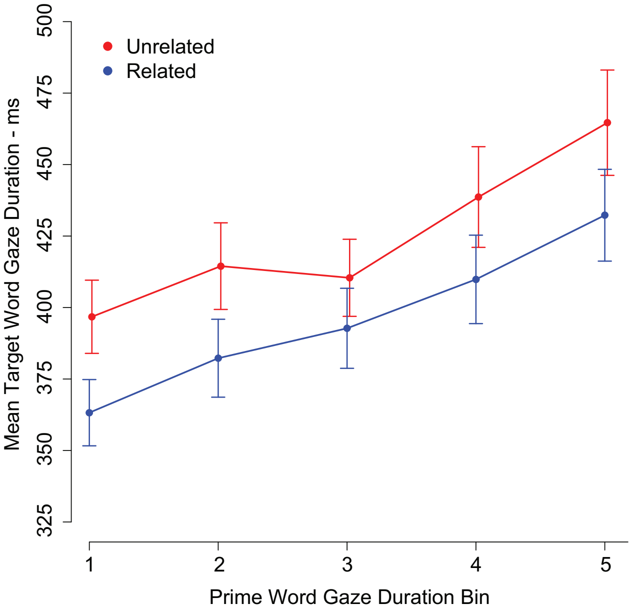

Figure 4. Mean target-word gaze durations as a function of the gaze duration on the prime word on the same trial in Experiment 1. For each participant in each condition, trials were divided into five bins based on prime-word gaze duration. Average target-word gaze duration in each bin and condition was plotted. Error bars represent the standard error of the bin mean across subjects. See the online article for the color version of this figure.

who adopted a more liberal strategy. In addition, incorrect eye movement responses (moving one's eyes from a nonword onto to the next letter string) were slower on average (*M* = 548 ms, *SD* = 151 ms) than correct eye movement responses (i.e., moving one's eyes from a word onto the next letter string). This suggests that incorrect classifications of nonwords as words were not by fast guesses or an inability to suppress fast, involuntary forward saccades. A final indication that reading times in the ocular LDT reflect LDT-related processes (rather than guesses) is the fact that we observed a reverse priming effect on the posttarget (slower reading times following a related prime-target pair). This result replicates the findings in Hoedemaker and Gordon (2014a), and suggests participants adopted a stricter decision criterion following words that were easier to process by virtue of having been preceded by a related prime. Such criterion adjustments have also been observed in manual LDTs in the form of first-order sequential effects (Perea & Carreiras, 2003) and frequency blocking effects (Glanzer & Ehrenreich, 1979; Lupker, Brown, & Colombo, 1997).

The 11-ms effect of priming on estimates of μ did not reach statistical significance, and therefore the results of the ex-Gaussian analysis did not provide clear evidence that semantic priming caused a distributional shift, an outcome that is consistent with the results of Hoedemaker and Gordon (2014a), in which the priming effect on μ was 5 ms and not statistically significant. However, across participants, only 5% of GZDs were faster than the 260-ms DP. This suggests that semantic priming affected the majority of ocular LD responses, including many of those in the fast tail of the distribution. As mentioned, additional analyses of the ocular LDT data presented in Hoedemaker and Gordon showed a DP of 270 and, on average, 14% of responses were faster than the DP. Thus, although this experiment and Experiment 1 of Hoedemaker and Gordon showed similar DPs, GZDs in the earlier experiment were slightly faster than in the current data, resulting in a clear attenuation of the priming effect in the fast tail of the distribution. Taken together, these results suggest that the DP of the semantic priming effect is quite stable across experiments and measures (e.g., GZD and FFD), but that the observed distributional pattern based on ex-Gaussian distribution fits varies depending on the response time floor of a particular task. Response times are faster for ocular compared with manual LDTs, and the greater speed of responding is accompanied by attenuation or elimination of the priming effect in the fast tail the ocular RT distribution. Comparison of the current and previous ocular LDT experiment shows that even small differences in baseline response times (in this case, likely by average word frequency being lower in the current experiment than in Experiment 1 of Hoedemaker and Gordon) can also affect interpretations of the distributional pattern of priming.

The priming effect on estimates of τ reached significance once two participants with poor model fit were removed from the data. The notion that the magnitude of the priming effect increased as a function of response time is also supported by the quantile analysis, which shows a significant increase of the effect across quantiles. As discussed, there is no a priori mapping between distributional parameters and cognitive processes. However, the analysis of priming as a function of prime-word reading times (as opposed to target-word reading times) provides important information about the possible mechanisms driving the skew-based priming effect. Consistent with Hoedemaker and Gordon (2014a), participants adopted a within-trial rhythm such that prime and target-word reading times within a trial were positively correlated. As shown in Figure 4, target reading times increased across the slower prime reading time bins, a pattern that is consistent with the previous finding. However, the magnitude of the priming effect did not increase as a function of prime reading time bin, which indicates that the magnitude of the priming effect increases with target response latency as a function of target-specific processing effort rather than trial-general processing. When target-word reading time is elevated by factors that are not specifically related to target-word difficulty (such as general within-trial rhythm as also measured on prime reading time), there is no corresponding increase in priming. However, when target-word reading time is elevated by target-specific factors, we observe a greater influence of the prime. These results support Balota et al.'s (2008) account of skew-based priming effects as reflecting greater utilization of the prime when target processing is more effortful, showing that the account applies also in cases in which processing effort is related to properties of the target itself (word frequency and length being likely candidates to affect processing difficulty) rather than visual degradation.

Thomas et al. (2012) proposed that active recruitment of prime information in service of target-word recognition on more difficult trials depends crucially on the availability of target-to-prime backward associative connections. That relationship between the magnitude of priming and the strength of backward association between prime and target was not observed in this experiment. Instead, the data provide some evidence that the magnitude of priming increased with increases in the strength of the *forward* association between prime and target, but that the magnitude of priming did not vary with the strength of *backward* associative connections. This pattern is not consistent with a mechanism in which retrospective priming is characterized as dependent on backward associations that are not available until the target word had been at least partially recognized. However, it does not rule out alternative memory-search models of priming, such as compound-cues models, that do not depend specifically on an active search for target-to-prime relations. The implications of this hypothesis will be explored in more detail in the General Discussion.

Experiment 2

The goal of Experiment 2 was to assess the extent to which the pattern of priming found in the ocular LDT depends on LDT-specific processes, and to explore the distribution of the priming effect in a task with an even lower response time floor. Participants read sets of four words on the same gaze-contingent display used in Experiment 1, and on each trial indicated whether a subsequently presented episodic recognition-memory probe word had been among that trial's four words. As such, the goal of the reader was to encode primes and targets (as well as fillers) for the purpose of a relatively easy recognition-memory task. We refer to this task as the episodic-recognition task, as the only explicit response required from the participant is a yes/no recognition memory judgment to the probe word following each trial. However, the main measure of interest, word reading time on the primes and target, reflects word encoding time. Word encoding times in the episodic-recognition task do not reflect the metalinguistic judgment required by an LD, and forward saccades reflect an implicit decision that the word has been sufficiently encoded rather than an explicit task-based response. Whereas the ocular LDT might have encouraged backward checking for semantic relations (prime-target relatedness provided a reliable indication that the target was a word), such strategies are not applicable in the episodic recognition task. The episodic-recognition task was adapted from Brysbaert (1995), who applied it to investigate sequential effects on the encoding of Arabic numerals, and from Hoedemaker and Gordon (2014b), who used it to study encoding of words. Using a similar paradigm, Deacon, Hewitt, Yang, and Nagata (2000) obtained a significant N400 effect of semantic priming both when the prime was masked and when it was not masked; this suggests that the task is well suited for the investigation of semantic priming effects on the encoding of words. If priming in the ocular LDT is driven entirely by the metalinguistic decision-making processes required by the LDT, we would not expect to see an effect of priming on target-word reading times in the recognition task. Alternatively, if the magnitude of the priming effect primarily depends on response time, the faster word reading times afforded by the current task will shift the distribution relative to the DP of the priming effect, resulting in a larger proportion of responses that is faster than the DP, and thus not affected by priming. The observation of a τ-based priming effect would indicate that the influence of the prime increases for slower responses even when the decisions regarding when and where to move the eyes are driven by processes of general word recognition rather than a metalinguistic judgment.

Method

Participants. A total of 33 undergraduate students from the University of North Carolina at Chapel Hill participated in the experiment for course credit. All participants were native speakers of English with normal or corrected-to-normal vision. One participant was excluded from all analyses because his or her raw target-word reading times were more than two standard deviations above the grand mean. Two additional participants were excluded because of unusually high skipping rates (at least one word was skipped on over 40% of trials), leaving a total of 30 participants in the analyses.

Materials and design. All 160 associatively related pairs selected for the current study were used in Experiment 2. As in Experiment 1, each prime was repaired with a different prime's related target in order to create a set of unrelated prime-target pairs (for the 120 pairs that were also used in Experiment 1, the same unrelated pairings were maintained across experiments). The related and unrelated pairs were divided into two lists presented to different participants, and each list contained every target, half preceded by a related prime and half preceded by an unrelated prime. No words were repeated within a list. As in Experiment 1, the prime and target always appeared in the first and second positions of the set. A third and fourth word were added to each experimental pair to create sets of four. These filler words were a subset of those used in Experiment 1 and did not differ from the experimental words in length, $t(636) = .09$, $p = .93$, frequency, $t(636) = 1.43$, $p = .15$, or orthographic neighborhood size, $t(636) = 1.01$ $p = .31$. A new-word probe (i.e., a foil) was presented on half of the trials containing a related and half containing an unrelated prime-target pair. Old-word probes were presented on the other half of the trials and were randomly selected from each of the four positions equally often. The old and new probes did not differ in mean length, $t(158) = 1.10$, $p = .27$, frequency, $t(158) = .88$ $p = .38$, and orthographic neighborhood size, $t(158) = -.75$, $p = .46$.

Procedure. The equipment was identical to that used in Experiment 1. Participants read each set of four words on a gaze-contingent display while their eye movements were monitored. Gaze contingencies were set up the same way as in Experiment 1. Participants were instructed to read all four words silently before pressing a key on a hand-held console using the index finger of their right hand. A probe word was presented on a new screen appearing after the key press at a 0-ms delay. The participant's task was to indicate whether the probe had been among the trial's four words or not, indicating "yes" or "no" via a speeded key press on the same console. No words from the trial were visible while the probe was up, and the probe remained visible until a response was made. Participants received accuracy feedback after every trial.

Analysis of eye movements. Fixations shorter than 80 ms and within 1° of a longer, immediately subsequent fixation were merged with the longer fixation by an automatic procedure in the EyeLink software. One item was removed from all analyses by a stimulus error. Trials on which either the prime or the target was skipped (11.5% of trials) were removed from the analyses, as were trials on which a boundary was inadvertently triggered by a blink (.5% of trials) or because the eye fixated on or very near the boundary instead of on the word (7.7% of trials). Finally, trials on which the participant regressed from the target back to the (then masked) prime rather than progressing to the posttarget word were also removed (.2% of trials). The excluded trials were distributed equally across conditions, with an average of 63 and 64 trials per participant remaining in the related and unrelated conditions, respectively. When brief delays in the display change caused a word to be unmasked slightly after the onset of the first fixation (14.8% of words), the time stamp of the fixation onset was adjusted to reflect the onset of the word display, excluding any time the participant was fixating the mask rather than the word, resulting in an average adjustment of 7 ms (range = 1–86 ms). Finally, a reading time cutoff was determined at three standard deviations above the mean for each position in the set in each relatedness condition. GZDs longer than the relevant cutoff were removed, affecting 1.7% of all words, equally distributed across the related (1.6%) and unrelated (1.8%) trials.

Results

One prime-target pair was excluded from all analyses by a stimulus error. Mean accuracy for the recognition probe responses was 98% (range = 93%–100%). Accuracy was slightly higher for new probes (*M* = 98%) compared with old probes (*M* = 97%), and following trials with a related (*M* = 98%) compared with an unrelated (*M* = 97%) prime-target pair. After trimming, there was a per-participant average of 63 and 62 trials available for the analysis for GZD and FFD in the unrelated and related condition, respectively. The average number of single-fixation trials available in each condition was 50. Table 3 presents reading times across the prime, target, and third-word position. Mean GZD was 334 ms (*SD* = 27 ms) for unrelated words across all three positions (i.e., not including target words in the related-prime condition). Mean GZDs on individual words were correlated with manual response times in the ELP (Balota et al., 2007), $r = .36$, $p < .001$, $R^2 = .13$ ($N = 479$), and negatively correlated with SUBTLEX (Brysbaert & New, 2009) log10 word frequency, $r = -.32$, $R^2 = .10$, $p < .001$ ($N = 479$).

Semantic priming. Table 3 shows the mean reading times for the target words across relatedness conditions. There was a main effect of relatedness, so that reading times for the target word were shorter in the related compared with the unrelated prime condition for GZD, $t_1(29) = 4.09$, $p < .001$, $t_2(158) = 3.36$, $p < .01$, and SFD, $t_1(29) = 2.71$, $p < .05$, $t_2(158) = 2.11$, $p < .05$. There was a marginal effect of relatedness on FFD in the by-subjects analysis, but the effect was not significant by items, $t_1(29) = 1.87$, $p = .07$, $t_2(158) = 1.38$, $p = .17$. In contrast to the ocular LDT, there was no evidence that participants adjusted their criterion for when to move the eyes as a function of the relatedness of the previous word (all *t*s < 1). Regression analyses within individual participants showed that priming on the target word was not affected by forward or backward association strength (all *t*s < 1).

Survival analysis. Survival curves were computed for GZD and FFD in the same way as Experiment 1. Averaged survival curves for the sample are plotted in Figure 2 (bottom row). The DP for GZDs in the current experiment was estimated to occur at 265 ms (95% CI [196, 304]), indicating that the earliest GZD at which a semantic priming effect could be detected was 265 ms. For FFD, the DP was estimated at 294 ms (95% CI [190, 333]). Averaged across participants, .27 (*SD* = .22) of GZDs and .65 (*SD* = .23) of FFDs were faster than the DP.

Distribution analyses. We used the same procedure as in Experiment 1 to obtain quantile and ex-Gaussian parameter estimates for target-word reading times. The quantile estimates for GZD, SFD, and FFD are plotted in Figure 5. Consistent with the analysis of condition means, there was a significant main effect of relatedness on GZD, $F(1, 29) = 14.9$, $p < .01$, and SFD, $F(1, 28) = 4.5$, $p < .05$, but this effect was not significant on FFD, $F(1, 29) = 1.6$, $p = .22$. Crucially, there was an interaction between quantile and relatedness, indicating that the effect of relatedness increased with reading time for all three eye movement measures (GZD: $F[1, 28] = 18.6$, $p < .001$; FFD: $F[1, 29] = 5.6$, $p < .05$; SFD: $F[1, 28] = 4.5$, $p < .05$). Excluding the 10th quantile, GZD and FFD continued to show a significant relatedness by quantile interaction (GZD: $F[1, 29] = 15.0$, $p < .01$; FFD: $F[1, 29] = 4.8$, $p < .05$), but the effect on SFD was no longer significant, $F(1, 28) = 2.5$, $p = .13$.

Average ex-Gaussian parameter estimates are shown in Table 4. Relatedness did not affect estimates of μ for GZD, $t(29) = -.60$, $p = .55$, SFD, $t(28) = -1.19$, $p = .24$, or FFD, $t(29) = -.32$, $p = .75$. Similarly, there were no effects of relatedness on σ (all *t*s <

Table 3
Word Reading Times in Experiment 2

Measure	Condition	Prime	Target	Posttarget
Word GZD (*SD*)	Unrelated pairs	330 (61)	329 (63)	343 (63)
	Related pairs	323 (53)	319 (56)	344 (62)
	Mean	327 (57)	324 (59)	343 (62)
	Priming		10*	−1
Word FFD (*SD*)	Unrelated pairs	250 (40)	285 (47)	285 (42)
	Related pairs	248 (39)	281 (43)	286 (42)
	Mean	249 (39)	283 (45)	285 (42)
	Priming		4	−1
Word SFD (*SD*)	Unrelated pairs	287 (46)	305 (52)	310 (47)
	Related pairs	283 (44)	299 (47)	312 (49)
	Mean	285 (45)	302 (49)	311 (48)
	Priming		6*	−2

(Prime, Target and Posttarget are printed under the spanning header "Word position".)

Note. All times in are in milliseconds. Asterisks indicate a significant effect. GZD = gaze duration; FFD = first-fixation duration; SFD = single-fixation duration.

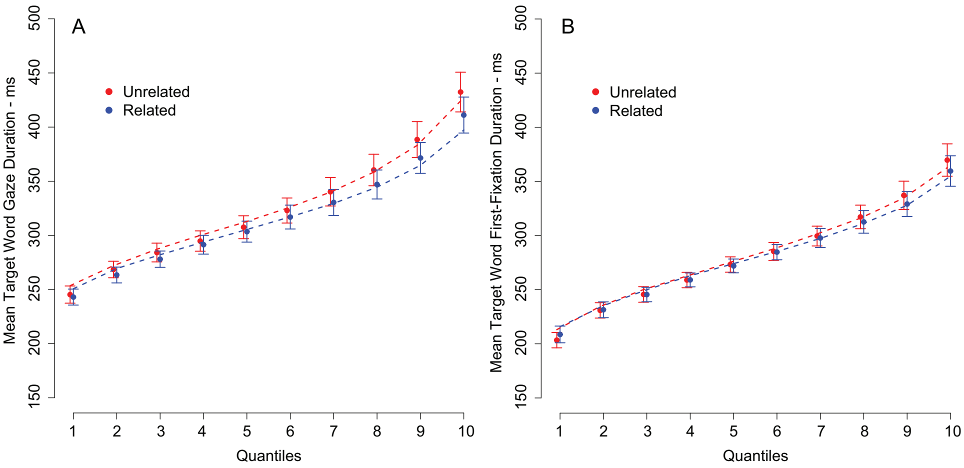

Figure 5. Quantile plot for mean gaze durations (Panel A) and first-fixation durations (Panel B) on the target word in the ocular recognition task in Experiment 2 when the target was preceded by a related or an unrelated prime. Quantiles are arranged from fastest to slowest on the x-axis. Error bars show the standard error of the quantile value across subjects and the dashed lines represent predicted quantile values based on mean parameters of the estimated ex-Gaussian distribution. See the online article for the color version of this figure.

1). In contrast, for GZD, the estimates of τ were significantly larger in the unrelated compared with the related condition for GZD, $t(29) = 3.02$, $p < .01$, and SFD, $t(28) = 2.32$, $p < .05$, but not FFD, $t(29) = .75$, $p = .46$.

The distributional effect of prime-word reading time on the magnitude of the target-word prime effect was assessed the same way as in Experiment 1. The results are presented in Figure 6. As in Experiment 1, this analysis confirmed the already-established effects of relatedness (GZD: $F[1, 29] = 16.4$, $p < .001$; FFD: $F[1, 29] = 4.6$, $p < .05$), and prime-target "rhythm" effects, such that target reading times increased as a function of within-trial prime reading times (GZD: $F[1, 29] = 26.8$, $p < .001$; FFD: $F[1, 29] = 43.9$, $p < .001$). Also consistent with the results of Experiment 1, the ocular recognition memory task did not show an interaction between prime reading time bin and the magnitude of the target-word priming effect, *F*s < 1, meaning the magnitude of the priming effect on the target word did not vary as a function of time spent processing the prime. Supplementary analyses showed these results were not affected by the time stamp corrections applied to account for the occasional brief delays in the gaze contingent display change.

Comparing semantic priming across LDT and recognition tasks. Figure 7 shows the priming effects in Experiments 1 and 2 as a function of the baseline RT (mean response time for each quantile in the unrelated condition). The plot shows that response times are faster and the priming effect is smaller in the episodic recognition memory task than in the LDT, but the magnitude of the priming effect increases with response time in both tasks. For those portions of the distributions in which the response times in the two tasks are approximately equal, the effect of priming is only slightly larger in the LDT than in the recognition task and appears to increase at a similar rate. For a more direct comparison of the priming effect across tasks while controlling for baseline response latency, we performed a matched bin analysis (cf. Thomas et al., 2012). First, we selected those bins from Experiments 1 and 2 with similar across-subject average quantile estimates in the unrelated condition (Bins 2, 4, 5, and 7 in Experiment 1; Bins 7, 8, 9, and 10 in Experiment 2). Average GZD across selected bins in the unre-

Table 4
Ex-Gaussian Parameter Estimates in Experiment 2

Measure	Condition	Parameter		
		Mu	Sigma	Tau
GZD (*SD*)	Unrelated	270 (52)	35 (30)	60 (33)
	Related	272 (53)	35 (28)	47 (33)
	Priming	–2	0	13^{*}
FFD (*SD*)	Unrelated	247 (42)	45 (28)	37 (29)
	Related	249 (30)	42 (20)	33 (35)
	Priming	–2	3	4
SFD (*SD*)	Unrelated	257 (29)	28 (17)	47 (41)
	Related	260 (33)	29 (19)	38 (37)
	Priming	–4	–1	9^{*}

Note. All times in are in milliseconds. Asterisks indicate a significant effect. GZD = gaze duration; FFD = first-fixation duration; SFD = single-fixation duration.

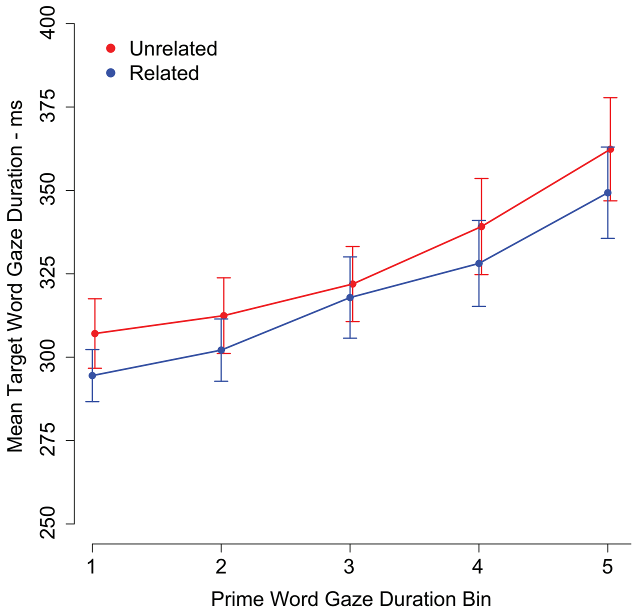

Figure 6. Mean target-word gaze durations as a function of the gaze duration on the prime word on the same trial in Experiment 2. For each participant in each condition, trials were divided into five bins based on prime-word gaze duration, and average target-word gaze duration in each condition was plotted for each bin. Error bars represent the standard error of the bin mean across subjects. See the online article for the color version of this figure.

lated condition was the same in both experiments at 380 ms. Subsequently, a 2 (Experiment 1 vs. Experiment 2) × 2 (related vs. unrelated) by-subjects ANOVA showed that the magnitude of the priming effect in the selected bins did not differ across Experiments, $F(1, 60) < 1$. The same results were obtained when we simply compared the seven fastest bins in Experiment 1 (average GZD on targets in unrelated pairs = 371 ms), with the slowest five bins in Experiment 2 (average GZD on targets in unrelated pairs = 369 ms), showing no difference in priming as a function of experiment, $F(1, 60) = 1.4$, $p = .24$.

DPs. Figure 2 plots the survival curves for Experiments 1 and 2. The DP estimates for GZD are strikingly similar across the LDT (260 ms) and recognition task (265 ms). As the DP for each experiment fell within the 95% CI (Reingold & Sheridan, 2014) of the other experiment, we conclude that the fastest response for which a semantic priming effect could be detected did not differ as a function of the metalinguistic requirements of the task. This was true for both GZD and FFD.

In contrast, across participants, the proportion of reading times that were faster than the DP was significant larger in the recognition task (Experiment 2 = 27%) than the LDT (Experiment 1 = 5%), $t(60) = 5.1$, $p < .001$. Similarly, the proportion of FFDs that were faster than the DP was larger in the recognition task (Experiment 2 = 65%) than in the LDT (Experiment 1 = 22%), $t(60) = 8.7$, $p < .001$.

Discussion

The episodic recognition task showed a robust semantic priming effect, even though word reading times were substantially faster than those observed in the ocular LDT (Experiment 1). Word reading times in the current task were correlated with manual LD responses in the ELP and showed a significant effect of word frequency, indicating that word encoding in this task is sensitive to the lexico-semantic properties of stimuli. In the current task, participants encoded each word for a subsequent recognition memory task, so that moving the eyes from one word to the next likely reflected the decision that a word had been learned sufficiently for that purpose. However, in contrast to the ocular LDT, we did not observe evidence for criterion adjustment in the form of slower reading times following a related prime-target pair, supporting the notion that word reading times in the episodic recognition task represent time allocated to lexico-semantic encoding and do not reflect an explicit response.

Interestingly, the ocular LDT and episodic recognition tasks yielded similar estimates of the onset and time course of the semantic priming effect. In Experiment 2, the earliest influence of the prime on GZDs in the word recognition task was detected at 265 ms (compare with 260 ms in Experiment 1 of this article and 270 ms for Experiment 1 of Hoedemaker & Gordon, 2014a); further, 27% of responses were shorter than this DP, meaning that those responses were not affected by the semantic prime-target relationship. Thus, without the requirement of a metalinguistic judgment, the distribution of word reading times in the episodic-recognition task was overall faster than the distribution of times for LDTs, but the minimum amount of time necessary for the prime to influence behavior has not changed.

Semantic priming had a significant effect on estimates of τ for GZD, and quantile analyses showed a significant increase in the magnitude of the priming effect as a function of response time for both GZD and FFD. This result strongly undermines the claim that τ-based priming in the LDT is the result of an LD-specific pro-

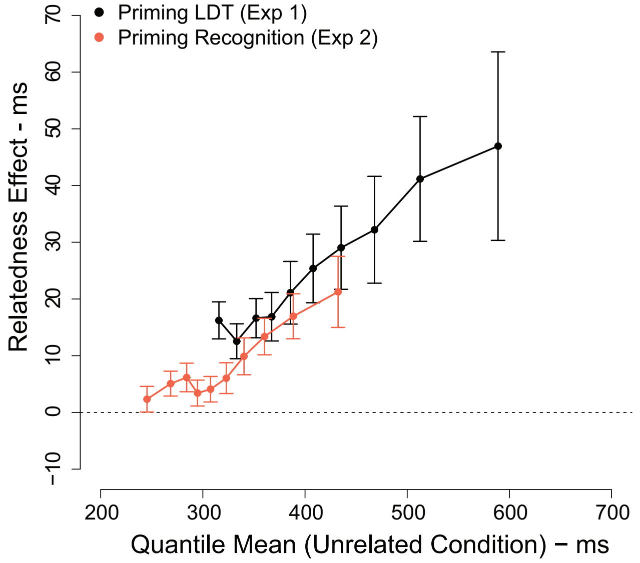

Figure 7. Mean priming effect (gaze duration in the unrelated–related condition) by baseline response latency (average gaze duration in the unrelated condition) in Experiments 1 and 2. Error bars represent the standard error of the mean. LDT = Lexical Decision Task. See the online article for the color version of this figure.

cessing mechanism operating specifically in service of the word–nonword discrimination. The episodic recognition memory task in Experiment 2 does not involve an LD, yet τ-based priming is observed on target-word reading times. This finding is consistent with previous findings of increased skew-based priming (using visually degraded targets) on speeded naming tasks (Balota et al., 2008; Thomas et al., 2012), which also do not involve a metalinguistic judgment.

Additional analyses support the notion that the skew-based priming effect reflects increased influence of the prime for more difficult targets. When trials were sorted by prime processing time instead, the distribution of target reading times continued to show an increase across prime-based bins (representing the within-trial rhythm effect), but the Priming × Bin interaction that was seen for binning based on target response times was no longer observed. Consistent with Experiment 1, this finding indicates that the mechanism responsible for increasing the influence of the prime on trials with slower target reading times is more likely related to processing effort associated with the difficulty of target identification itself, rather than other factors that may also increase processing time, such as a general slowness on that particular trial. Taken together, these results implicate a retrospective priming mechanism, as the magnitude of the priming effect is influenced by processes that can only begin to operate once the target has been encountered. The magnitude of the priming effect was not affected by the strength of forward or backward associations, suggesting that priming depended more strongly on the availability of the memory representation of the prime itself rather than specific associative connections between the prime and the target.

General Discussion

This study used fast ocular responses to determine the onset and distributional patterns of semantic priming in an LDT (Experiment 1) and an episodic recognition-memory task (Experiment 2). Word reading times in the ocular LDT reflect overt responses to the metalinguistic, task-induced goal of making a lexical decision. In contrast, word reading times in the recognition task reflect a process of word encoding that does not include a metalinguistic decision-making component. Of course, the episodic recognition task is unlike normal reading, as it requires participants to encode each word for the purpose of a memory task, so that word reading times may reflect the decision that a word has been sufficiently learned in addition to processes of lexico-semantic encoding (Gordon, Hendrick, & Foster, 2000). However, the task allowed us to assess semantic priming in a task that does not require an explicit word–nonword decision and has a much lower response time floor than the ocular LDT. Comparison of Experiments 1 and 2 showed that even though the tasks differed in regard to the explicit task goals and response mappings, the onset and distributional pattern of the semantic priming effect were remarkably similar across experiments. Across tasks, survival analysis indicated that the earliest observable priming effect occurred around 260 ms, and distributional analyses showed that the magnitude of the semantic priming effect increased as a function of response time. When controlling for baseline RTs in a matched-bin analysis (cf., Thomas et al., 2012), the magnitude of the priming effect in the LD and episodic-recognition tasks did not differ.

Prior studies applying distributional analyses to semantic priming in isolated word recognition tasks with manual responses have consistently found a distributional shift, indicating that semantically related primes affect both fast and slow responses. This distributional shift has been interpreted to reflect a processing head start (Balota et al., 2008; Yap et al., 2013; for semantic categorization, see de Wit & Kinoshita, 2014, 2015a), and as supporting the widely held belief that priming during visual word recognition is driven by the rapid prospective activation of related targets triggered by the prime. However, the current study shows that the observation, or lack thereof, of a distributional shift is strongly affected by the response time floor of the measure. Across studies of manual LDT, response times in the fastest bin range between 400 and 500 ms (Balota et al., 2008; Yap et al., 2013; de Wit & Kinoshita, 2015a, 2015b), meaning that almost all manual LDs are slow enough to last beyond the 260-ms priming threshold identified here. In contrast, ocular response tasks have a lower response time floor, so that a larger proportion of responses can be completed before enough time has passed for the influence of the prime to emerge. Similarly, combined use of ex-Gaussian distribution fits and survival analysis showed that apparent task-related differences in priming between the LDT and recognition task were primarily by confounded differences in overall RTs. Survival analysis showed that in both tasks, the earliest observable priming effect occurred around 260 ms, meaning the explicit task goals had an effect on the location of the distribution in relation to the priming threshold rather than on the threshold itself. In other words, the LDT requirement resulted in slower overall RTs, but it did not affect how rapidly prime information was observed to affect target-word processing.

For both tasks, the magnitude of priming increased with increasing response times, indicating that skew-based semantic priming effects do not depend on the specific requirement to make a word–nonword decision (cf. de Wit & Kinoshita, 2015a, 2015b). Instead, these results are consistent with a limited set of previous findings showing greater priming for slower responses in both LDT and naming tasks (Thomas et al., 2012; Balota et al., 2008, for visually degraded targets only). Thomas and colleagues (2012) provide two possible explanations for this finding. According to the decision-level account, detection of a semantic relationship between the target and the prime increases confidence in the response and reduces the criterion to begin responding. According to the alternative lexical-level account, detection of a prime-target relationship reduces the amount of visual information required to determine the correct response, thereby speeding up word recognition and reducing response times. In the current study, word reading times in the ocular recognition task did not reflect an explicit, task-related decision, reducing the plausibility of the decision-level account. This leaves the lexical-access account, suggesting that the related prime can facilitate the lexico-semantic processing stage of word recognition during reading independently from the specific task-induced goals of the reader.

In both experiments, our interpretation of the skew-based priming effect as reflecting greater target processing effort is supported by the analysis of target-word reading times as a function of prime processing time. When target responses were sorted as a function of prime processing time, target-word reading times increased across bins, but we did not observe a significant Priming × Bin interaction. Therefore, it appears that the prime becomes an increasingly important contributor of information when word recognition is more effortful. This interpretation is consistent with different potential priming mechanisms. According to Thomas et al.'s (2012) lexical-access account, related primes reduce the amount of visual information necessary to correctly recognize the target. The current findings suggest that this results in a greater benefit for difficult than for easy to recognize targets.

These results are also consistent with the compound-cue model of semantic priming (Ratcliff & McKoon, 1988). According to this model, during the process of word recognition, the target item combines with elements of the surrounding context (including the prime) to form a "compound cue." During LDT, the strength or degree of familiarity of the compound cue is used to discriminate between words and nonwords. As also discussed by de Wit and Kinoshita (2015a, 2015b), the notion that the compound cue gradually develops over the course of word recognition time fits nicely with the observed skew-based effects of semantic priming. The current study shows that this account applies not only in the context of the LDT but also when the task does not involve a metalinguistic decision and instead encourages a more general goal of word recognition, as does the episodic recognition task. Compound-cue models have sometimes been criticized for being unable to account for priming effects on tasks, such as speeded naming (e.g., Neely, 1991), that do not require a decision that is based on a familiarity criteria (McNamara, 2005). However, McNamara (2005) has argued that compound-cue models can explain priming in speeded naming tasks if naming is considered to involve mapping written words to their meaning, with the ease of this mapping affected by the context of the time-evolving compound cue. Interestingly, the EZ Reader model, one of the most influential models of eye movements during reading, posits that "familiarity" plays an important role in determining when to initiate the planning and execution of a saccade to the next word (Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 2003). Specifically, according to the EZ Reader model, the first stage of word recognition consists of a "familiarity check," assessing how quickly a word is likely to be recognized. If recognition is deemed imminent, the system initiates programming of the next forward saccade. If we assume that word familiarity is the main engine driving forward saccades, and therefore word reading times in both the LDT and recognition task, the compound-cue model can explain the skew-based priming effects observed in both tasks. Regardless of the specific task goals of the reader, the related prime causes the degree of familiarity (i.e., the strength of the compound cue) for the target word to develop more strongly or more quickly, resulting in earlier saccades to the next word. On slower trials, the compound cue has more time to develop, resulting in stronger priming effects than on faster trials. In an alternative (but not mutually exclusive) conceptualization of the two stages of word recognition in the EZ Reader model, initial processing is based primarily on orthographic information followed by semantic processing in a subsequent stage (Reichle & Sheridan, 2015; Reingold & Rayner, 2006; Reingold, Yang, & Rayner, 2010). The notion that semantic processing follows the initial processing stage is consistent with the observation that faster responses show smaller effects of semantic priming.

Thomas et al. (2012) observed an increase the magnitude of the priming effect in slower bins only for prime-target pairs with a backward (target-to-prime) association, supporting the notion that the increase in priming across the RT distribution reflects the retrospective recruitment of prime information when target processing is more effortful. In contrast, the current study found greater priming for items with stronger forward (prime-to-target) associations in the ocular LDT (Experiment 1) and no effects of associative strength (forward or backward in the episodic recognition task; Experiment 2). This difference may have occurred because Thomas et al. manipulated associative direction as a categorical variable, comparing the distributional priming effect for prime-target pairs with forward, backward, and symmetrical associative connections. In contrast, the current study treated forward and backward associative strength as continuous predictors, assessing differences in the mean effect of priming as a function of associative strength in each direction. Nonetheless, if is indeed the case that the skew-based priming effect does not depend on the strength or availability of backward associative connections, our results may indicate that skew-based effects of priming do not necessarily reflect a process by which participants are actively checking for a relationship between the target and the prime. Instead, the prime and target may combine to form a compound cue that supports target identification independent of the direction of the association. Finally, the observation that the magnitude of priming increases when target recognition is more effortful does not necessarily mean that prime information is strategically or consciously recruited. Recent evidence of an inhibitory priming effect suggests that primes may affect target processing even when this is not strategically desirable (Heyman, Hutchison, & Storms, 2016). Therefore, the magnitude of the semantic priming effect may be greater when target processing is more effortful even when this does not improve task performance.

The finding that semantic priming primarily affects estimates of τ, whereas the μ effect depends strongly on response speed, may seem to contrast with Staub's (2011) finding that word predictability during sentence reading affected estimates of μ but not τ. However, the availability of parafoveal preview during sentence reading likely has important consequences for the timing with which these effects were observed (see also Hoedemaker & Gordon [2014a] for further discussion of how distributions of fixation durations during sentence reading may differ from those in ocular response tasks). Reingold et al. (2012) showed that the DP of the word frequency effect occurred earlier when target preview was available, so that without preview, the frequency effect emerged only as a change in distributional skew but when preview was available the frequency effect emerged as both a shift and a change in skew. However, masking preview of the target in the current study allowed us to control when target processing could be initiated and investigate the onset and time course of the priming effect from this point onward. It also makes the current results more easily comparable with manual isolated word recognition studies, which typically do not provide preview of upcoming target words.

Conclusion

The use of the fast, well-practiced ocular response mode in an isolated word recognition task allowed us to investigate a portion of the fast tail of the response time distribution that is not accessible using manual response tasks. The current study showed it takes a minimum of about 260 ms from the onset of the target before an effect of relatedness can be reliably detected in eye movement behavior, and magnitude of the semantic priming effect increased as a function of response time. Overall, responses were slower when the task required an explicit, metalinguistic judgment compared with when words were encoded for recognition. However, the onset and time course of the priming effect did not change as a function of these changes in the goals of the task. These results are consistent with Thomas et al.'s (2012) lexical access account, by which the presence of a related prime facilitates the lexico-semantic processing stage of word recognition. More generally, these results are consistent with the compound-cue model of semantic priming (Ratcliff & McKoon, 1988), by which the prime and the target combine to form a time-evolving retrieval cue that supports the process of semantic word identification, and the influence of the prime increases in cases in which target identification is more effortful.

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(*Appendix follows*)

Appendix

Stimuli

Unrelated prime	Related prime	Target	Posttarget	Final word	Probe
mischief	foggy	unclear	instructor	apron	nerve
foggy	mischief	trouble	appliance	king	foggy/mischief
concern	foundation	base	engineer	sweet	prince
foundation	concern	worry	diagram	color	worry
alter	purpose	reason	pencil	tennis	afternoon
purpose	alter	change	endurance	milk	endurance
demon	community	neighborhood	business	kite	city
community	demon	devil	newspaper	pony	pony
violet	myth	legend	detergent	pulp	beige
myth	violet	purple	asleep	ugly	myth/violet
contemporary	gorgeous	beautiful	signal	hand	cupcake
gorgeous	contemporary	modern	orchid	berry	modern
adorable	roam	wander	admission	band	circus
roam	adorable	cute	rabbit	apartment	rabbit
marsh	journal	diary	competition	twig	body
journal	marsh	swamp	cheesecake	clean	clean
defrost	simple	easy	couch	hammer	spicy
simple	defrost	thaw	juice	personal	simple/defrost
blame	combination	mixture	kitchen	sofa	tournament
combination	blame	accuse	honor	germ	accuse
dish	pile	stack	museum	fruit	virus
pile	dish	plate	treasure	acorn	treasure
vote	courage	bravery	hurricane	recycle	song
courage	vote	elect	brunch	mystery	mystery
rush	teenager	adolescent	headlight	prize	purse
teenager	rush	hurry	environment	snail	teenager/rush
choice	characteristic	trait	diamond	category	mallet
characteristic	choice	decision	injury	inventor	decision
small	sale	bargain	award	dictionary	park
sale	small	little	surgeon	happy	surgeon
weird	helper	assistant	haircut	pear	maple
helper	weird	strange	pasta	slow	slow
pick	middle	center	battle	diagnosis	club
middle	pick	choose	church	saucer	middle/pick
loving	boring	dull	bicycle	soda	wave
boring	loving	caring	library	giant	caring
garbage	careful	cautious	energy	canvas	camp
careful	garbage	trash	salad	shape	salad
disappear	dinner	supper	classroom	clock	walk
dinner	disappear	vanish	peach	heat	heat
goodbye	ending	beginning	nominate	soldier	temperature
ending	goodbye	hello	watch	mint	ending/goodbye
pull	once	never	ring	moist	faith
once	pull	shove	curtain	nose	shove
construct	victim	murderer	snow	race	fern
victim	construct	destroy	criticize	wedding	criticize
stand	hungry	full	mosquito	wood	container
hungry	stand	fall	guest	women	women
move	mend	break	calculate	vase	camel
mend	move	stay	crown	elbow	mend/move
float	opposite	same	tuxedo	plead	banquet
opposite	float	sink	chicken	sleigh	sink
relax	loss	gain	graph	golden	bonus
loss	relax	tense	perfume	design	perfume
expert	thick	thin	iron	none	coin
thick	expert	novice	vitamin	tower	tower
public	reject	accept	smoke	walrus	lawyer
reject	public	private	world	button	reject/public

(*Appendix continues*)

Appendix (*continued*)

Unrelated prime	Related prime	Target	Posttarget	Final word	Probe
part	solution	problem	secret	vanilla	tape
solution	part	whole	musician	question	whole
basement	student	teacher	education	peanut	card
student	basement	attic	humid	cousin	humid
failure	frown	smile	kiwi	risk	breakfast
frown	failure	success	family	medical	medical
finish	fake	real	rodent	friend	helicopter
fake	finish	start	restroom	candy	fake/finish
learn	deep	shallow	degree	sled	act
deep	learn	teach	cruel	menu	teach
guilty	rough	smooth	cafeteria	marry	lecture
rough	guilty	innocent	cake	waitress	cake
above	death	life	place	police	mansion
death	above	below	telescope	pond	pond
closing	best	worst	sock	cube	rug
best	closing	opening	lunch	season	best/closing
white	winner	loser	treatment	tooth	partner
winner	white	black	human	party	black
tight	borrow	lend	restaurant	loft	jewelry
borrow	tight	loose	school	delete	school
more	buyer	seller	fossil	mouse	laundry
buyer	more	less	society	patient	patient
blackboard	airport	plane	mentor	crowd	bridge
airport	blackboard	chalk	government	twilight	airport/blackboard
century	blanket	warm	pressure	organize	pen
blanket	century	year	coffee	scientist	year
compulsion	cobra	snake	donate	anchor	volunteer
cobra	compulsion	obsession	quiz	forest	quiz
electrician	danger	scary	reward	shower	flag
danger	electrician	wire	author	cream	cream
torch	interrupt	rude	leaf	allergy	sour
interrupt	torch	fire	mail	gallery	interrupt/torch
tuba	homework	study	corn	sell	federal
homework	tuba	instrument	football	doctor	instrument
whiskey	safari	jungle	onion	receipt	log
safari	whiskey	booze	talent	worm	talent
astronaut	cookbook	recipe	request	bench	acid
cookbook	astronaut	space	heart	editor	editor
secretary	europe	asia	mattress	garden	kid
europe	secretary	boss	smart	sleep	europe/secretary
balcony	compass	direction	broken	clay	expand
compass	balcony	ledge	canoe	stapler	ledge
chemistry	wings	bird	fence	town	mice
wings	chemistry	science	leader	stone	leader
angel	clarinet	flute	bump	hug	ballot
clarinet	angel	heaven	realistic	dusk	dusk
mammal	spring	summer	mustard	wolf	sky
spring	mammal	whale	dorm	magnet	spring/mammal
lettuce	disaster	earthquake	cabinet	bed	metal
disaster	lettuce	tomato	office	chime	tomato
mute	mars	planets	knock	alarm	loud
mars	mute	deaf	touch	bride	touch
angle	celery	carrot	chair	male	electricity
celery	angle	geometry	captain	grab	grab
cauliflower	relative	aunt	casino	hawk	miner
relative	cauliflower	broccoli	single	nest	relative/cauliflower
thief	washcloth	towel	against	dirt	farmer
washcloth	thief	steal	decay	wrong	steal
quench	hands	feet	confident	patio	chipmunk
hands	quench	thirst	penny	eagle	penny
smell	lobster	crab	spatula	trip	vacuum

(*Appendix continues*)

Appendix (*continued*)

Unrelated prime	Related prime	Target	Posttarget	Final word	Probe
lobster	smell	taste	wand	nutrition	nutrition
prickly	hero	superman	play	copy	detail
hero	prickly	cactus	light	neck	hero/prickly
child	emergency	ambulance	guard	safe	sneeze
emergency	child	baby	tube	kick	baby
image	goal	achieve	information	piano	sneaker
goal	image	mirror	feather	alligator	feather
honest	language	english	program	president	clap
language	honest	truth	palace	today	today
drug	congress	senate	attorney	normal	wound
congress	drug	cocaine	jump	siren	congress/drug
lizard	glass	window	match	cabbage	pepper
glass	lizard	reptile	plant	glue	reptile
cents	meat	steak	symptom	soil	geography
meat	cents	dollars	marathon	consequence	marathon
lion	court	judge	tulip	shrimp	oak
court	lion	tiger	literature	theater	theater
toilet	artery	vein	reporter	soap	mild
artery	toilet	bathroom	cave	bagel	artery/toilet
minutes	egypt	pyramid	dance	passport	bus
egypt	minutes	hours	ladder	uncle	hours
clam	silk	satin	surprise	uniform	tuna
silk	clam	oyster	mushroom	home	mushroom
flower	pain	headache	glove	math	hospital
pain	flower	rose	muffin	leave	leave
weather	knife	fork	sand	oval	gym
knife	weather	climate	performance	fuel	knife/weather
house	conditioner	shampoo	tour	professor	detective
conditioner	house	brick	national	taxi	brick
lime	embarrass	blush	ankle	campus	sheriff
embarrass	lime	lemon	creature	parrot	creature
write	beard	mustache	marker	insurance	parking
beard	write	print	famous	gate	gate
hear	pancakes	syrup	apology	flyer	koala
pancakes	hear	listen	necklace	disk	hear/pancakes
volcano	armor	knight	month	certificate	job
armor	volcano	erupt	burn	sunset	erupt
noun	army	navy	trial	sword	studio
army	noun	verb	algebra	midnight	algebra
lightning	duck	quack	vocabulary	lamp	hotel
duck	lightning	thunder	garage	run	run

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