

Forward versus backward semantic priming: What movement dynamics during lexical decision reveal



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Quarterly Journal of Experimental Psychology
1–6

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DOI: 10.1177/1747021818775051

qjep.sagepub.com



Abstract

Separate processes underlying forward (e.g., *crescent MOON*) and backward (e.g., *office POST*) priming have previously been inferred from button-press lexical decision response times, with an automatic prospective mechanism and a strategic retrospective mechanism presumed responsible for forward and backward priming, respectively. We tracked hand/mouse kinematics during lexical decision, and found that forward, backward, and symmetrical (e.g., *cat DOG*) priming exhibited different movement trajectories, with the effect of forward priming emerging earlier than that of backward priming and with symmetrical priming taking the lead around the time when the backward priming effect came online. The findings provide strong converging evidence for different mechanisms driving forward and backward priming, and demonstrate that continuous kinematic measures can shed light on cognitive processes as they unfold in real time.

Keywords

Semantic priming; associative priming; mouse tracking; continuous kinematic measures

Received: 30 November 2017; revised: 7 April 2018; accepted: 9 April 2018

Responding to a target stimulus (e.g., *DOCTOR*) is usually facilitated when it is preceded by a semantically or associatively related stimulus (i.e., the prime; for example, *nurse*) relative to when the preceding stimulus is unrelated (e.g., *table*), a phenomenon referred to as semantic priming (Meyer & Schvaneveldt, 1971; for reviews, see McNamara, 2005; Neely, 1991). Semantic priming has been most commonly investigated using the speeded lexical decision task (LDT) in which the subject judges whether a target letter string is a word or a nonword. In forward priming, the prime-to-target associative strength is high but the target-to-prime associative strength is low (e.g., *crescent MOON*), whereas in backward priming, it is the reverse (i.e., only the target-to-prime association is high; for example, *office POST*). In symmetrical priming, both the prime-to-target and the target-to-prime associations are high (e.g., *cat DOG*).

Theoretical explanations of semantic priming can be broadly divided into whether the putative mechanism is initiated before (prospective) or after (retrospective) the target onset. Among *prospective* theories, the most well known is spreading activation: The presentation of a prime activates its semantic representation, and activation automatically spreads to the representations of related words, which facilitates their subsequent processing or

recognition (Collins & Loftus, 1975). Another prospective theory is expectancy-induced priming, a slower, consciously controlled mechanism in which the subject uses the prime to strategically generate an expectancy for related targets (Neely, 1977).

Although prospective theories can explain priming when the forward prime-to-target associative strength is high, they cannot account for backward priming (Chwilla, Hagoort, & Brown, 1998; Kahan, Neely, & Forsythe, 1999; Koriat, 1981; Thomas, Neely, & O'Connor, 2012). To accommodate backward priming, *retrospective* priming mechanisms assume that after the target onset, the prime is retrieved and the semantic properties of the target and prime are assessed or combined. According to the semantic matching account, retrieving the prime and checking

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whether it is related to the target facilitate lexical decision because if the pair is found to be related, the target is necessarily a word (nonwords cannot be related to primes; Neely & Keefe, 1989). An alternative account is that upon presentation of the target, a compound cue comprising the target and prime is formed; if the pair is related, the cue will have higher familiarity than if the pair is unrelated, which in turn facilitates word responding for related targets (Ratcliff & McKoon, 1988). Whereas semantic matching is assumed to be relatively slow-acting and require attention, the formation of a compound cue is assumed to be automatic and the process is the same whether the direction of priming is forward or backward.

The traditional dependent measure in the LDT is the response time (RT) it takes to make the appropriate button-press response, but a limitation of measuring discrete responses is that it fails to offer a window into the time-course of underlying processes that drive the ultimate response (the button press). On the contrary, continuous kinematic measures (e.g., hand movements as the subject responds) have been shown to provide fine-grained information about the temporal dynamics of the decision process (e.g., Abrams & Balota, 1991; Spivey, Grosjean, & Knoblich, 2005) and can yield theoretical insights. For instance, instead of button-press responses, Bangert, Abrams, and Balota (2012) asked subjects to move their hands from the bottom of the screen to touch either a target area at the top left or right of the screen to indicate their word/nonword responses. They found interactive effects of stimulus degradation and word frequency during the early portion of subjects' movements, thus calling into question prevailing theory that the two factors are additive and affect different stages of the word recognition process based on Sternberg's (1969) additive factors logic (Yap, Balota, Tse, & Besner, 2008).

Using the traditional LDT, Thomas et al. (2012) found that RT priming effects were amplified for backward and symmetrical prime–target pairs when targets were visually degraded, particularly at the slowest portion of the response distribution, which suggests the compensatory strategic engagement of a slower acting retrospective semantic matching mechanism during challenging conditions. Forward priming, however, was unaffected by degradation, which is consistent with such priming being mediated largely by prospective mechanisms. The aim of the present study was to shed more light on the mechanisms underlying semantic priming by examining the dynamics of real-time hand/mouse movements during lexical decision (Barca & Pezzulo, 2012; Freeman & Ambady, 2010). Specifically, can we find more direct evidence of a retrospective priming mechanism for backward and symmetrical priming even under clear/non-degraded conditions? If forward priming is driven primarily by automatic spreading activation and backward priming by strategic semantic matching, then the priming effect in terms of movement

trajectory should emerge earlier in forward than backward priming (even if the final RT ends up being the same across the two conditions). Also, if symmetrical priming reflects a combination of the two mechanisms, then there should also be evidence for that in the movement time-course.

Method

Subjects

In total, 53 undergraduates participated for course credit or cash payment. Three left-handed subjects were excluded from analysis, one subject was excluded for not following task instructions (high error rate), and data from another subject were excluded due to a computer error. All other subjects self-reported as being right-handed, as being native English speakers, and as having normal or corrected-to-normal vision.

Stimuli

A total of 180 prime–target word pairs and 180 prime–nonword pairs were drawn from the set developed by Thomas et al. (2012).¹ There were 60 related pairs each for the forward, backward, and symmetrical priming conditions. The prime-to-target associative strength was high (.56; Nelson, McEvoy, & Schreiber, 1998) and the target-to-prime associative strength was zero in the forward condition, and vice versa in the backward condition (target-to-prime: .54). In the symmetrical condition, both the prime-to-target and target-to-prime associative strengths were high (.57 and .60, respectively). Within each condition, half of the pairs had their primes re-paired with a different target to form an unrelated pair. Across conditions, targets were equated on several psycholinguistic variables (see Thomas et al., 2012, for details). Eight different counterbalancing lists were created. The “word” button was either on the top left or top right of the screen (with the “nonword” button on the opposite side). As a result, there were 16 counterbalancing conditions (eight lists \times two possible button positions). The presentation order of the stimuli was randomised for each subject.

Procedure

Subjects were seated in individual booths in front of computers and wore sound attenuating headphones for the duration of the experiment. The experiment was run using MouseTracker software (Freeman & Ambady, 2010). Subjects were instructed that for each trial, they would begin by using the mouse to click a start button at the bottom centre of the screen, and that each trial would begin with a fixation cross, followed by a blank screen, then a lowercase word, followed by another blank screen, and finally an uppercase string of letters. Subjects were told

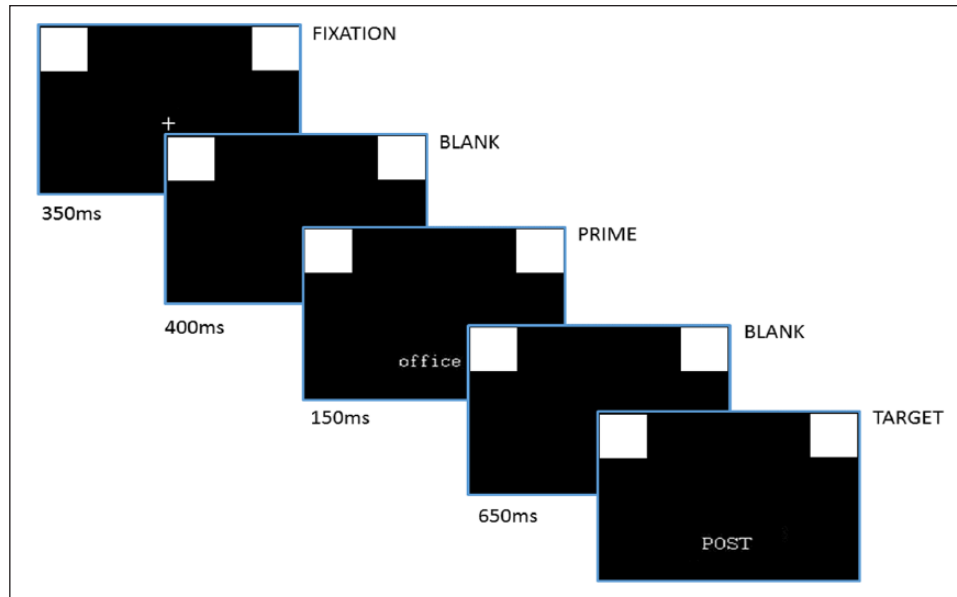


Figure 1. The sequence and timing of events in a single trial. Instructions informed subjects which of the two white buttons to click on for word and nonword targets before practice and experimental trials began.

that their task was to decide whether or not the uppercase string letters formed an English word, and to respond by clicking on one of the buttons on the top corners of the screen. They were encouraged to complete each trial as quickly as possible, but to maintain high accuracy. If they selected an incorrect response, a red “X” would briefly appear in the centre of the screen. In addition, subjects were informed that if they took too long to start moving the mouse or too long to complete a trial, they would receive pop-up messages encouraging them to speed up. Subjects completed 20 practice trials before beginning the experiment.

All stimuli appeared in the centre of the screen in white, 18-point Courier New Font, on a black background. On each trial, a fixation cross appeared for 350 ms, followed by a 400-ms blank screen, a 150-ms prime, another blank screen for 650 ms, followed by the target (see Figure 1). The target remained on the screen until the subject selected a button. After a selection was made, the screen was blank again until the subject pressed the start button to begin the next trial. The entire task took approximately 25 min to complete.

Results

For our analyses,² we focused on word target trials that were correctly recognised (erroneous responses comprised <1% of trials). We also excluded trials in which the time taken (from target onset) for initiation of movement exceeded 1000 ms or the final RT (clicking on the appropriate button on the screen) exceeded 2000 ms, in order to increase the likelihood that the hand/mouse movements

reflect cognitive processes that were unfolding during lexical decision. Approximately 98% of trials were included.

RTs

Although not our primary dependent measure of interest, we analysed response latency from the onset of the target to the selection of the correct button on the screen. Overall, there was a significant main effect of prime type (related or unrelated), with significantly faster RTs in the related condition, $F(1, 47)=77.74, p<.001$. There was also an interaction between prime type and associative direction (backward, forward, or symmetrical), $F(2, 94)=4.32, p=.016$. Pairwise comparisons revealed that the benefit of symmetrical primes was significantly larger than that for backward and forward primes ($t_s>2.43, p_s<.02$; see Table 1 for means). The priming effects for the backward and forward conditions were equivalent, $p>.70$. An item-level analysis revealed similar patterns. Again, related primes had significantly faster RTs, $F(1, 175)=35.68, p<.0001$. There was also a marginally significant interaction between prime type and associative direction due to a larger priming effect in the symmetrical condition, $F(2, 175)=2.41, p=.093$. This marginal interaction was driven by the symmetrical priming effect being larger than forward priming ($t(116)=2.05, p=.043$, as well as backward priming ($t(116)=1.74, p=.08$). Backward and forward priming effects were equivalent, $p>.85$.

Hand/mouse kinematics

The time window within which to evaluate movement dynamics was based on the average initiation time of the

Table 1. Mean RTs in milliseconds (SDs in parentheses) and priming effect (with 95% confidence intervals) as a function of associative direction.

	RT	% trials dropped	Priming effect	<i>p</i> value
Backward				
Related	1083 (144.7)	2.2 (1.5)	26 ± 13.3	<.001
Unrelated	1109 (150.7)	2.4 (1.4)		
Forward				
Related	1036 (147.5)	1.3 (0.02)	21 ± 16.0	.011
Unrelated	1057 (147.3)	2.7 (0.04)		
Symmetrical				
Related	1034 (141.5)	2.2 (3.1)	51 ± 14.9	<.001
Unrelated	1085 (148.7)	3.4 (4.8)		

RTs: response times; SDs: standard deviations.

Thomas et al. (2012) found backward, forward, and symmetrical priming effects of 30, 32, and 52 ms, respectively.

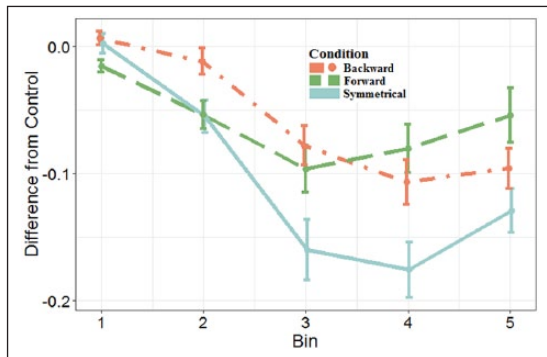


Figure 2. Priming effect (difference between related prime and its control) in terms of distance of the cursor from the word button as a function of time bin. Negative values indicate related condition being relatively closer to the button than its control. Errors bars reflect ± 1 SEM.

subjects. There was no main effect of prime type, $F(1, 47) = 1.513, p = .23$, or associative direction on average initiation time, $F(2, 94) = 0.374, p = .69$. There was also no interaction between prime type and associative direction regarding initiation time, $F(2, 94) = 0.93, p = .40$. Average initiation times for backward, forward, and symmetrical-related conditions were 294, 300, and 294 ms, respectively. Their control conditions had similar initiation times (305, 298, and 298 ms, respectively). Analysis by items revealed the same results: There was no main effect of prime type, $F(1, 175) = 0.547, p = .461$, or of associative direction, $F(2, 175) = 0.298, p = .743$, and no interaction between prime type and associative direction, $F(2, 175) = 0.899, p = .41$. Mouse movements for each trial were measured from 300 ms after target onset until 800 ms. Although subjects tended to take longer than 800 ms to complete a trial, there is evidence that the cognitive activity associated with lexical decision is completed by 800 ms (e.g., in Thomas et al.,

2012, average button-press RT was ~ 600 ms). Thus, mouse movements recorded after this time would be unlikely to reflect online processing. The distance of the mouse cursor from the target button on the screen was calculated for every 20-ms sample. The MouseTracker software scales all mouse cursor positions into a standard coordinate space ($x = [0, 1]; y = [0, 1.5]$). For each prime type in each condition, distances were averaged for each of five 100-ms bins between 300 and 800 ms. For each bin, unrelated prime distances were subtracted from their related prime, within subjects. This resulted in a measure of the relative difference between the related prime and its respective control across the five bins. Due to significant RT priming effects in all conditions, one would expect an overall advantage, but the question of interest is whether the time-course of these priming effects differs across associative directions.

There was a main effect of associative direction, $F(2, 94) = 4.60, p = .012$. This effect was driven by the symmetrical priming condition having a larger benefit over its control than backward ($p = .008$) and forward ($p = .014$) priming. There was also a main effect of bin, $F(2.46, 115.54)^3 = 59.37, p < .001$. Importantly, there was a significant interaction between associative direction and bin, $F(4.31, 202.49) = 4.76, p = .001$. Figure 2 shows the mean priming effect across time. The forward priming condition had a significant advantage over its control from the very first bin, $t(47) = 3.09, p = .003$. The advantage of forward priming over its control in the first bin was also larger than that conferred by backward priming, $t(47) = 2.47, p = .017$, and was marginally larger than that for symmetrical priming, $t(47) = 1.80, p = .078$. In the second bin, both forward and symmetrical priming conditions had significant advantages over their controls ($ts > 4.2, ps < .001$), and larger advantages than that of backward priming ($ts > 2.45, ps < .019$). Forward and symmetrical priming effects were not significantly different, $t(47) = 0.08, p = .94$. Also, the backward priming condition did not have significant advantage over its control in the second bin, $t(47) = 1.09, p = .28$. Backward priming gained a significant advantage over its control only in the third bin onwards, $t(47) = 5.01, p < .001$. Symmetrical priming exhibited a larger effect over the other two priming conditions by the third bin, $ts > 2.21, ps < .032$, which is consistent with the RT advantage that symmetrical priming has over forward and backward priming.

An analysis by items obtained results convergent with the subject-level analysis. There was a main effect of bin, $F(1.93, 338.23) = 32.71, p < .0001$. There was also a main effect of associative direction, $F(2, 175) = 3.57, p = .03$, due to symmetrical priming having a larger effect than forward and backward priming. Crucially, there was again a significant interaction between associative direction and bin, $F(8, 700) = 5.36, p < .0001$. The forward priming condition had a significant advantage over its control from the first bin,

$t(59)=2.36, p=.021$. The advantage of forward priming over its control in the first bin was also larger than that conferred by backward priming, $t(118)=2.43, p=.017$, and symmetrical priming, $t(116)=2.29, p=.024$. In the second bin, both the forward and symmetrical priming conditions showed a robust advantage over their controls, $t_s > 3.14, p_s < .003$. Forward priming had a significantly larger advantage than backward priming, $t(118)=2.58, p=.011$. Symmetrical priming had a marginally significant advantage over backward priming, $t(116)=1.92, p=.058$. Forward and symmetrical priming advantages were not significantly different from one another, $t(116)=.23, p=.82$. Backward priming did not have a significant advantage over its control in the second bin, $t(59)=1.13, p=.26$. Only in the third bin onwards did backward priming gain a significant advantage over its control, $t(59)=3.71, p<.001$. Also, symmetrical priming had a larger effect over the other two priming conditions by the third bin, $t_s > 2.64, p_s < .01$.

Although the average initiation times were not different across conditions, there was nonetheless variability in initiation times across trials and subjects. A supplementary analysis of the data at the trial level was conducted using linear mixed effects models (lme4 package in R; Bates, Maechler, Bolker, & Walker, 2015) to assess the possible influence of initiation time. Prime type, associative direction, bin, and initiation time were entered as fixed effects, and random intercepts of items and subjects were also included. Significance was evaluated using t -values of regression coefficients with Satterthwaite approximation of the degrees of freedom (Kuznetsova, Brockhoff, & Christensen, 2015). Most important for the present purposes, there was a significant three-way interaction between prime type, associative direction, and bin, $\beta = -.0109, t(40820)=3.03, p=.002$. Follow-up post hoc tests were conducted by examining within each bin the main effects and two-way interaction between prime type and associative direction. The pattern of results obtained in the previous subject- and item-level analyses was replicated. For instance, forward priming had an advantage over its control from the very first bin, $\beta = -.0424, t(2713.1)=-2.48, p=.0133$. In the second bin, both forward and symmetrical priming were significant relative to their controls, $\beta = -.0699, t(2713.4)=-4.42, p<.0001$, and $\beta = -.0702, t(2634.1)=-4.22, p<.0001$, respectively. In the third bin, backward priming finally had an advantage over its control, $\beta = -.0584, t(2646.5)=-3.70, p=.0002$, and symmetrical priming had a greater effect than both forward and backward priming, $\beta = -.0464, t(5461)=-3.02, p=.0026$ and $\beta = -.0579, t(5379)=-3.66, p=.0003$, respectively. In other words, our supplementary analysis suggests initiation time did not have an appreciable influence on the pattern of results.

Discussion

We tracked subjects' hand/mouse movements as they performed a lexical decision by moving a cursor from the bottom centre of the screen to click a button in either the top left or right corner. Half the target words were preceded by a related prime, and the relationship was either in the forward direction only, backward direction only, or symmetrical. In terms of button-press RTs, the effects of forward and backward priming were about the same while symmetrical priming was about double the size. However, the mouse movement trajectories revealed that the effect of forward priming emerged earlier than that of backward priming—in the forward priming condition, the position of the cursor was significantly closer to the word button from the first bin (out of five) onwards, relative to its control, whereas in the backward priming condition, the advantage only appeared from the third bin. Symmetrical priming was apparent from the second bin, and by the third bin onwards, it had the lead.⁴

Our findings suggest that different processes may underlie forward and backward priming. The earlier emergence of a priming effect in the forward than backward condition is best accommodated by a fast-acting prospective mechanism (e.g., spreading activation; Collins & Loftus, 1975) and a relatively slow retrospective mechanism (e.g., semantic matching; Neely & Keefe, 1989) driving forward and backward priming, respectively. The timing of when symmetrical priming emerged as the clear leader coincided with when the effect of backward priming surfaced, suggesting that symmetrical priming benefits from a combination of the two mechanisms. It is less clear how a compound cue theory that disregards the direction of the prime–target relationship (Ratcliff & McKoon, 1988) can explain the results. Importantly, our results nicely replicate part of Thomas et al.'s (2012) experiment (in terms of RTs) and provide strong converging evidence of the separate mechanisms that drive semantic priming under normal conditions. More generally, our study adds to the literature on how kinematic measures can provide a useful window into online decision processes.

Acknowledgements

We thank Casidhe Bethancourt, Megan Cheng, Spencer Chu, Song Heui Cho, and Zihan Li for assisting with data collection; George Wolford for helpful discussions regarding data analysis; and Tom Heyman and an anonymous reviewer for helpful comments on an earlier version of the manuscript. We are also grateful to Jon Freeman and his lab for helpful advice on using MouseTracker.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Open Practices



The data from the present experiment are publicly available at the Open Science Framework website: <https://osf.io/wcrd2/>.

Supplementary Material

Open Practices Disclosure is available at journals.sagepub.com/doi/suppl/10.1177/1747021818775051.

Notes

1. We discovered during data analysis that two word pairs in the symmetrical-related prime condition contained the incorrect prime (resulting in having only unrelated pairs for these two target words). We excluded all trials with these two target words from subsequent analysis, approximately 1% of word trials. Including them in the subject-level analysis (as unrelated word pairs) did not meaningfully change any of the results.
2. The data from the present experiment are publicly available at the Open Science Framework website: <https://osf.io/wcrd2/>.
3. A Greenhouse–Geisser correction was applied whenever the assumption of sphericity was violated.
4. As to why a symmetrical priming advantage was not observed in the first bin, we think it could be due to noise in the data. It is clear though that in the second bin, the symmetrical priming effect was robust and equivalent to the forward priming effect, whereas the backward priming effect had not yet emerged.

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