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Effects of Repetition Priming on Recognition Memory: Testing a Perceptual Fluency–Disfluency Model

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Five experiments explored the effects of immediate repetition priming on episodic recognition (the "Jacoby–Whitehouse effect") as measured with forced-choice testing. These experiments confirmed key predictions of a model adapted from D. E. Huber and R. C. O'Reilly's (2003) dynamic neural network of perception. In this model, short prime durations pre-activate primed items, enhancing perceptual fluency and familiarity, whereas long prime durations result in habituation, causing perceptual disfluency and less familiarity. Short duration primes produced a recognition preference for primed words (Experiments 1, 2, and 5), whereas long duration primes produced a preference against primed words (Experiments 3, 4, and 5). Experiment 2 found prime duration effects even when participants accurately identified short duration primes. A cued-recall task included in Experiments 3, 4, and 5 found priming effects only for recognition trials that were followed by cued-recall failure. These results suggest that priming can enhance as well as lower familiarity, without affecting recollection. Experiment 4 provided a manipulation check on this procedure through a delay manipulation that preferentially affected recognition followed by cued-recall success.

Keywords: perceptual fluency, familiarity, priming, criterion shifts, recognition memory

When irrelevant sources of information enter into a memory retrieval process, they can produce effects (either positive or negative) on both true and false memories. For instance, they can increase the retrieval of previously seen items and boost recognition responses for targets, producing a greater tendency to call a studied item "old." These irrelevant sources can also elicit false memory, or the tendency to call a foil item "old" (we employ the terminology of *foils* in referring to nonstudied distractors). For instance, past research found that simple perceptual manipulations can induce false memories, such as through immediate repetition priming (Jacoby & Whitehouse, 1989), immediate semantic priming (Lewandowsky, 1986), enhanced visual clarity of a test word (Whittlesea, Jacoby, & Girard, 1990), or fragment completion prior to testing (e.g., Luo, 1993; Watkins & Peynircioglu, 1990). In the current research, we investigate the claim that changes in recognition memory with immediate priming are due to changes in perceptual fluency.

Fluency is alternately defined as the speed or ease with which information is extracted from a stimulus (e.g., Fazendeiro, Winkielman, Luo, & Lorah, 2005; Jacoby, 1991; Jacoby, Kelley, & Dywan, 1989; Jacoby & Whitehouse, 1989; Johnston, Dark, & Jacoby, 1985; Johnston, Hawley, & Elliot, 1991; Lindsay & Kelley, 1996; Rajaram, 1993; Verfaellie & Treadwell, 1993; Whittlesea, 1993), and it has been suggested that fluency is an adaptive heuristic for a wide variety of judgments because it captures relevant statistics of the environment (e.g., Hertwig, Herzog, Schooler, & Reimer, in press). For instance, a fluency-based account of both recognition memory and long-term repetition priming has been supported through the modeling of reaction time data in both tasks (e.g., Berry, Shanks, & Henson, 2008). In the current situation, we examined immediate repetition priming with less than a second between a prime and the recognition trial. For this immediate priming of recognition, it has been proposed that increased perceptual fluency produces increased recognition responses to both studied and nonstudied items because it boosts familiarity, which is then (mis)attributed to a previous study episode (Jacoby, 1991; Kelley & Lindsay, 1993).

Under some conditions, immediate priming can actually decrease recognition responses to the primed item, thus reducing both true and false memories. For instance, Jacoby and Whitehouse (1989) found that immediate subliminal repetition priming

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increased false recognition of primed words, but when primes were presented supraliminally, this effect was reversed, with lower recognition rates for primed words. This reversal in the direction of priming was attributed to strategic discounting of fluency. In other words, supraliminal primes also enhanced target fluency, but participants strategically adjusted their responses against the recognition of primed words. Casting doubt on a strategic interpretation, Joordens and Merikle (1992) found the same pattern of results even when all primes were presented supraliminally, with greater prime duration producing the priming reversal. However, it is possible that short duration primes receive less attention and are discounted less than long duration primes (Debner & Jacoby, 1994). For instance, Merikle and Joordens (1997) replicated the positive priming effect on recognition responses with weakly attended primes and reversed the effect with strongly attended primes.

The primary question we ask is whether perceptual habituation, which is considered to be an automatic process, can explain the transition from positive to negative priming of recognition responses (i.e., we term this recognition crossover as a function of prime duration the "Jacoby–Whitehouse effect"). Importantly, we do not deny the existence of strategic discounting, but instead we question whether it is needed to explain this phenomenon. In place of a strategy-based explanation of these priming reversals, we propose a more constrained, quantitatively specified and testable habituation model. This alternative explanation is tested by using methodologies designed to minimize strategies and by assessing specific quantitative predictions that arise from a computational model of perceptual habituation. This model was previously developed to explain perceptual identification experiments in which short duration primes resulted in a perceptual preference for primed words (e.g., a tendency to identify a primed test word regardless of whether or not it was the briefly flashed target word), whereas long duration primes resulted in a perceptual preference against primed words (Huber, 2008; Huber, Shiffrin, Lyle, & Quach, 2002; Huber, Shiffrin, Lyle, & Ruys, 2001; Huber, Shiffrin, Quach, & Lyle, 2002; Weidemann, Huber, & Shiffrin, 2005, 2008). Because the direction of repetition priming is readily reversed as a function of prime duration in perceptual tasks, this leads us to ask whether perception may explain both positive and negative priming in a recognition task. Therefore, we extended the model of perceptual habituation to the task of episodic recognition. To provide data that constrain this model, we manipulated prime duration while examining forced-choice recognition with conditions in which the prime does not match either choice word, the prime matches the correct target word, or the prime matches the incorrect foil word.

Testing the hypothesis that perceptual habituation and its effect on familiarity can explain recognition priming requires several methodological controls. More specifically, there are a variety of strategic factors that might vary with prime duration, such as directly responding based on prime identity, changes in recognition bias, and the use of recollection during recognition. Both the original perceptual identification studies of Huber and colleagues (Huber, Shiffrin, Lyle, & Quach, 2002; Huber, Shiffrin, Lyle, & Ruys, 2001; Huber, Shiffrin, Quach, & Lyle, 2002), and the currently reported episodic recognition studies, reduced strategic responding based on prime identity by presenting prime words at supraliminal durations to equate for prime awareness. All experiments included an equal mix of trials that primed the correct answer and trials that primed the incorrect answer, and participants were explicitly instructed that primes were just as likely to indicate the incorrect response. Critically, all experiments gave participants trial by trial accuracy feedback on their recognition decisions to ensure that they fully understood that there could be no useful strategy in relation to the priming manipulations.

Another form of strategic responding is a simple bias (i.e., adopting a different criterion for primed words vs. unprimed words). As pointed out by Wixted and Stretch (2000), signal detection theory as applied to yes/no data cannot differentiate between criterion shifts and shifts in the memory distributions. Fortunately, the need for a response criterion can be eliminated with forced-choice testing, which is assumed to involve a direct comparison between target and foil (Green & Swets, 1966; Macmillan & Creelman, 2005). In keeping with this assumption, forced-choice testing and single item old/new testing do not always produce similar results. For instance, the phenomenon referred to as "the revelation effect" (Watkins & Peynircioglu, 1990), in which old/new recognition is boosted by revealing a disguised item, was eliminated when tested with forced-choice testing (Hicks & Marsh, 1998). This finding led to the conclusion that the revelation effect arises from strategic criteria shifts rather than a change in the signal that underlies recognition (although see Major & Hockley, 2007).[1]

Besides controlling for responding based on prime identity and controlling for changes in bias, differential use of recall during a recognition test is another factor that needs to be controlled in order to test the claim that perceptual habituation can automatically produce discounting of the familiarity response. For instance, there may be a greater tendency to rely on recall (either to accept or reject) following long duration primes that are identical to a test item, particularly because recall is known to be a slower process than recognition (e.g., Nobel & Shiffrin, 2001). Dual-process theories of recognition often term the recall-like process during recognition "recollection," which is distinguished from "familiarity" (e.g. Jacoby, 1991; Jacoby & Dallas, 1981; Mandler, 1979, 1980; Norman & O'Reilly, 2003; Yonelinas, 1994, 1997; see Yonelinas, 2002, for a review). Because the process of recalling (or recollecting) involves retrieval of missing information rather than the strength of response, we assume that it is unaffected by perceptual fluency or by perceptual habituation. Therefore, our account supposes that prime-induced changes in recognition primarily occur through changes in familiarity rather than changes in recollection both following short prime durations that result in positive priming as well as following long prime durations that result in negative priming. The question of whether familiarity is reversed following long duration primes has never been addressed in the literature, and testing this prediction is one goal of the reported experiments.

[1] Besides demonstrating the usefulness of forced-choice testing, the revelation effect is relevant because one might interpret priming of recognition as a form of revelation effect in which people experience a "revelation" when a previously seen subliminal target is then unveiled as an easily seen test item. However, we note this account does not apply to the current experiments, which always used supraliminal targets.

To measure the recollection and familiarity components of recognition, many researchers rely on participants' reports of subjective experience during memory tasks (i.e., metamemory). For example, the remember–know procedure of Tulving (1985) instructs participants to indicate whether a recognized test item was remembered or simply known. With this paradigm, Rajaram (1993) found that subliminal repetition priming increased know but not remember responses for subliminal primes. Woollams, Taylor, Karayanidis, and Henson (2008) replicated this result and found that remember versus know trials were indicative of different event-related potential (ERP) waveform components. Similar to these priming effects, Lindsay and Kelley (1996) found that presenting three rather than two letters in a fragment completion task selectively increased know responses. However, these studies did not address the issue of recollection versus familiarity in the case of supraliminal repetition priming. Because supraliminal primes might induce strategic forms of responding that could bias metacognitive judgments, we addressed this issue by using the classic distinction between recognition and recall (e.g., Humphreys et al., 2003; Mandler, 1980), which is a performance measure that should be relatively insensitive to response strategies. Therefore, some of the reported experiments followed each single item recognition response with a cued-recall attempt that used the recognition target as the cue for paired associate recall. Cued-recall success was used to break recognition trials into two types. Because this is not a commonly used procedure, we validated its use with separate manipulations that preferentially affected recognition trials that were followed by cued-recall success (recollection) or cued-recall failure (familiarity).

Next, we briefly describe the perceptual habituation model as applied to familiarity. Further details appear in Experiment 6 and in the Appendix.

The Pre-Activation/Habituation Model

Huber and O'Reilly (2003) proposed a model of perceptual fluency that may provide an explanation of the Jacoby–Whitehouse effect without relying on a change from automatic to strategic processes as a function of prime duration. Fluency, in the context of this model, is the time it takes for a stimulus representation to achieve maximum activation. The dynamics of this model explain the build up of activation in the face of the current stimulus. This lingering pre-activation from recently seen words provides a "head start" to the process of identifying a primed test word (perceptual fluency for the primed item). However, if the prime is viewed excessively long (e.g., seconds), then the head start is reduced by the habituation of the perceptual response, which reduces the magnitude of lingering pre-activation. Furthermore, a large degree of habituation can even produce a disfluency (slow identification) for primed words. Lingering habituation can make it difficult to rapidly identify a primed test item, and so a primed test item is at a relative disadvantage in the decision process, and the alternative response is preferred. It is important to note that pre-activation and habituation are two different mechanisms, and both can exist simultaneously. For instance, there may be pre-activation that provides a head start to a primed item, but, because of habituation, it may be that the primed test item is disfluent and slow to activate despite its head start. This habituation model was designed to handle perceptual identification (e.g., Huber, 2008), but because habituation is found with many perceptual and conceptual responses, similar dynamics may exist for familiarity. Furthermore, familiarity might be directly influenced by the perceptual response. We refer to this account as the pre-activation/habituation model because short duration primes produce pre-activation (positive priming), whereas long duration primes produce an offsetting habituation (elimination of positive priming or even negative priming).

To evaluate the applicability of this account to recognition memory, we extended the model by adding a familiarity layer (see Figure 1) that is driven by the perceptual response, and we report these simulation study results as Experiment 6. Beyond the qualitative prediction that the negative priming effect with long duration primes is the result of lowered familiarity rather than a response strategy, application of the model revealed important and novel quantitative predictions. These predictions are discussed more fully in Experiment 6 and are summarized briefly here. By including habituation within the familiarity response itself, there is a difference in the prime duration needed to induce disfluency when comparing priming for targets that differ in familiarity. This is because a prime that is more familiar activates more quickly but also habituates more quickly. In other words, a previously studied word is more quickly placed into a disfluent state by its presentation as a prime. There are two important predictions that follow from this effect, and both of these are tested and confirmed in the reported experiments: (a) stronger memories (e.g., longer study durations) will habituate more quickly and will more readily

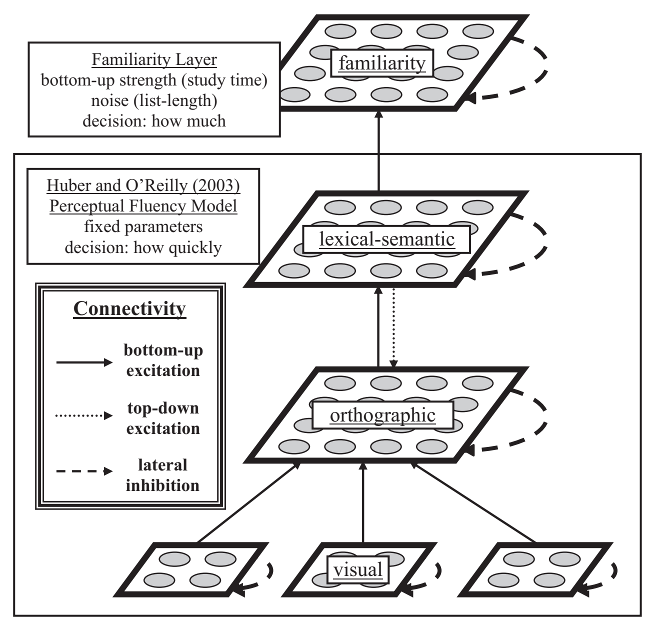

Figure 1. The architecture of the pre-activation/habituation model as applied to episodic familiarity. The portion within the box shows the original perceptual model of Huber and O'Reilly (2003) that was applied to priming of perceptual identification. This portion remained unchanged, and the output of the lexical–semantic layer was fed into an episodic familiarity layer that captured the difference between studied and nonstudied words through connection strength. Habituation dynamics were assumed to exist in the familiarity response as well, revealing that weaker memories more quickly saturate.

produce negative priming; and (b) the cost of presenting the target as a long duration prime will be greater than the benefit of presenting the foil as a long duration prime (i.e., an asymmetry between the cost and benefit of priming) because a familiar target will more quickly enter a disfluent state than will a less familiar foil.

Experiment 1

Experiment 1 explored whether the Jacoby–Whitehouse effect of prime duration would exist when forced-choice testing and trial by trial accuracy feedback were employed to minimize strategic responding. Study durations were individually tailored to place recognition performance at 75% to provide greater sensitivity to priming effects. A failure to find an interaction between priming and prime duration under these conditions would suggest that the Jacoby–Whitehouse effect as previously measured with yes/no testing was due to a decision strategy or criterion shifts. In contrast, the pre-activation/habituation model supposes that prime duration directly affects the familiarity response and predicts an interaction between prime duration and priming condition (i.e., a lessening of familiarity with increasing prime duration) even though the role of decision criteria is eliminated by using forced-choice testing.

Method

Participants. Twenty-four university undergraduates participated individually for class credit.

Materials and procedure. One thousand 5-letter words were used in the present study. All words had a minimum written language frequency of four as defined by Kučera & Francis (1967) and were randomly selected without replacement on each trial.

Participants studied lists of words presented on a computer screen, with each study list immediately followed by a forced-choice recognition test list. Each study list contained 18 words presented one at a time, and each forced-choice list contained 12 pairs of words, presented one pair at a time. The 12 tested targets were drawn from the middle of the study list to minimize primacy and recency. There were 3 prime types: neither-primed, target-primed, or foil-primed. In the neither-primed condition, the prime word did not match either the target or the foil. Each trial tested one of two prime durations: 100 ms (short) or 1,000 ms (long).

The experiment consisted of 3 different segments: initial practice, adjustment of study duration to obtain 75% threshold accuracy, and experimental lists. Practice consisted of one study list followed by one test list. The duration of study list items was 1,000 ms per item during practice, primes were always short duration (100 ms), and the forced-choice practice condition was always the neither-primed type.

The threshold segment consisted of 5 study and test lists to find the study duration that placed recognition at 75% accuracy. The study duration for the first list in this segment was 1,000 ms. After each forced-choice test list, study duration was decreased if 11 or 12 recognition judgments were correct, remained the same if 9 or 10 judgments were correct, or increased if 8 or fewer were correct. The first potential change in study duration was ±417.0 ms, the second was ±250.0 ms, the third was ±167.0 ms, and the forth and fifth were ±83.3 ms. The threshold segment consisted of all short duration primes and neither-primed prime types. The average study duration across the experimental trials and across participants was 870 ms, which ranged from 167 ms to 2,125 ms across participants.

The experimental segment consisted of 4 blocks, with 5 study/test lists per block. Each forced-choice test list tested all 6 conditions (2 prime durations × 3 priming conditions) twice each, resulting in 240 total trials per participant (40 repetitions of the 6 conditions).

A single forced-choice test trial consisted of a fixation for 250 ms followed by a blank screen for 250 ms. Then, a single prime word was presented in the center of the screen prior to forced-choice recognition. The prime word was followed by a 500-ms pattern mask, and then forced-choice (a pattern mask was needed to eliminate visible persistence, ensuring a minimal exposure for a briefly presented prime). The forced-choice words were presented to the left and right of center. Left/right position of the target was fully counterbalanced. Participants decided whether the right or left word appeared in the study list through a keyboard response. Accuracy feedback was presented after every test trial. The order of trials within a test list was randomly determined. Because all of the primes were above the threshold for conscious awareness, a fully informed design was used. Prior to the experimental lists, participants received instructions that there could be no effective strategy that used the primes in determining recognition responses.

Results and Discussion

Means and standard deviations for recognition accuracy in Experiment 1 are shown in Figure 2. A 2 (prime duration) × 3 (prime type) repeated measures analysis of variance (ANOVA) revealed a significant main effect of prime duration, $F(1, 23) = 5.22$, $MSE = .004$, $p < .05$; and a significant main effect of prime type, $F(2, 46) = 3.96$, $MSE = .007$, $p < .05$. Importantly, there was a significant

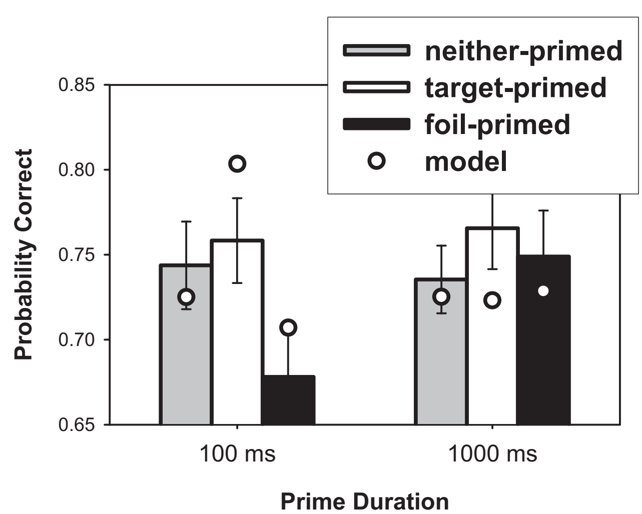

Figure 2. Mean forced-choice recognition accuracy as a function of prime duration and prime type in Experiment 1. Error bars represent standard error of the mean. The circles are the result of fitting the pre-activation/habituation to these data as outlined in Experiment 6 with the parameters that appear in Table 1.

interaction between prime duration and prime type, $F(2, 46) = 5.96$, $MSE = .004$, $p < .01$. Tests of simple effects revealed a significant effect of prime type for short duration primes, $F(2, 22) = 10.97$, $p < .001$; but not for long duration primes ($F < 1$). Pairwise comparisons of the short prime duration effects revealed that accuracy was greater in the target-primed condition than in the foil-primed condition ($p < .001$) and also that accuracy was greater in the neither-primed condition than the foil-primed condition ($p < .005$).

Replicating the Jacoby–Whitehouse effect, as revealed by the interaction between priming and prime duration, we found that short duration primes produced a recognition preference for primed words, suggesting that increased perceptual fluency was misattributed to episodic recognition. Furthermore, these effects were eliminated following long duration primes. As seen in the circles of Figure 2 that show the pre-activation/habituation model (see Experiment 6 for details), a reasonable account of all three prime types is provided, and model behavior for the target-primed condition compared with that for the foil-primed condition clearly demonstrated a positive priming effect for short duration primes that was eliminated with long duration primes. Because the behavioral results were found with forced-choice testing, supraliminal primes, and techniques that discouraged strategies, this suggests that the prime duration effect is due to a change in the signal that underlies recognition, rather than a change in response criteria.

Experiment 2

The results of Experiment 1 supported the pre-activation/habituation model's prediction that prime duration manipulations produce changes in memory retrieval rather than changes in response criteria. As seen in Figure 2, the model accounted for these data reasonably well and, as explained in Experiment 6, the prime duration effect was simulated simply by allowing the model to "view" primes for different durations, with no parameters changing between short and long duration primes. Thus, this model does not require differences in attention to primes or a change in prime awareness to produce the observed interaction between prime duration and priming condition. For this reason, supraliminal prime durations were used in all conditions to equate for prime awareness. However, as noted by Debner and Jacoby (1994), simply using prime durations that could support prime awareness does not guarantee that participants actually attend to primes to the point of awareness. Therefore, Experiment 2 included manipulations designed to create a high degree of attention to both short and long duration primes through the use of response tasks in both cases. For short duration primes (100 ms, as in Experiment 1), this secondary task was prime identification, with these identifications occurring instead of the usual recognition task on a subset of trials. This task served as a measure of prime awareness, providing direct evidence that short duration primes were attended and identified. For long duration primes, the secondary task was a nonspeeded verb rating (i.e., could the prime word be used as a verb) performed while the prime remained on screen (the verb task, which was also used in subsequent experiments, typically takes more than a second to perform). Previous experiments with priming of perceptual identification demonstrated that this verb task is equivalent to long duration attended primes (Huber et al., 2001; Huber, Shiffrin, Quach, & Lyle, 2002). Importantly, whether or not participants performed these secondary tasks was randomly mixed across trials, and so it seems likely that all primes were highly attended because at the onset of a prime word it could not be known whether a verb response or prime identification would be required.

Method

Participants. Thirty-two university undergraduates participated individually for class credit.

Materials and procedure. The same words as in Experiment 1 were used. Of these words, 48% could be verbs. Prime duration was either short (100 ms) or long, with the long duration determined by the amount of time taken on the verb task (1,984 ms on average). The verb task was nonspeeded, and the prime remained on the screen until a response was given. On average, participants were 78.7% correct in their verb-task responses.

Each test trial of the experiment proceeded as follows: First, the prime appeared in the center of the screen. For short duration trials, this word was presented for 100 ms, followed by a 500-ms mask to eliminate iconic persistence. For verb-task trials, this word remained on the screen until participants decided whether or not it could be a verb by pressing either the *YES* or *NO* key. The prompt *?verb?* appeared simultaneously with prime onset for verb-task trials, with this question displayed in yellow font above the prime. After giving a verb response, the prime was replaced by a 500-ms mask. Following the mask, two words were presented on the screen for forced-choice testing. Following short duration primes, participants made one of two potential types of judgments. If the prompt *?memory?* (in green font) appeared on the screen above the forced-choice words, participants decided which of the two words appeared in the previous study list (target recognition). If the prompt *?flash?* (in red font) appeared on the screen above the two forced-choice words, participants identified which of the two words was the same as the short duration prime (prime identification). As in Experiment 1, there were neither-primed, target-primed, and foil-primed trials following both short and long duration primes. Only target-primed and foil-primed trials were probed for prime identification forced-choice testing (because these were the only forced-choice presentations that included a repetition of the prime). Trial by trial accuracy feedback was presented to participants in relation to the verb task, the flash task, and/or the memory task as appropriate to the condition.

As in Experiment 1, there was 1 practice list, and there were 5 threshold study duration determination lists prior to the experimental segment of the procedure. Both the practice and threshold determination lists included the verb task, the memory task, and the flash task. The experimental segment consisted of 15 study/test lists broken into three blocks of 5, with no break between blocks. Each study list consisted of 18 words, and each test list consisted of 16 trials (12 target recognition trials and 4 prime identification trials, randomly positioned in the test list). The 12 target recognition trials broke down as 6 long duration verb-task primes and 6 short duration primes, with 2 trials each of target-primed, foil-primed, or neither-primed for each prime duration. The 4 prime identification trials followed only short duration primes and consisted of 2 target-primed trials (correct answer to choose previously studied word that was just primed) and 2 foil-primed trials (correct answer to choose the primed foil). All other procedures were as in Experiment 1. The average study duration was 833.8 ms and ranged from 333 ms to 2,000 ms across participants.

Results and Discussion

Figure 3 presents means for recognition accuracy as a function of prime duration and prime type. A 2 (prime duration) × 3 (prime type) repeated measures ANOVA revealed a significant main effect of prime type, $F(2, 62) = 5.78$, $MSE = .08$, $p < .01$. Importantly, it also revealed a significant interaction of prime duration and prime type, $F(2, 62) = 4.54$, $MSE = .038$, $p < .05$. Tests of simple effects across the three prime types revealed a significant effect for short duration primes, $F(2, 30) = 7.31$, $p < .005$; and long duration primes, $F(2, 30) = 4.43$, $p < .05$. Pairwise comparisons revealed that for short duration primes, recognition accuracy was greater in the target-primed condition than in the foil-primed condition ($p < .001$). Also, accuracy in the neither-primed condition was greater than accuracy in the foil-primed condition ($p < .005$). For long duration primes, accuracy in the neither-primed condition was greater than accuracy in the foil-primed condition ($p < .05$). No other comparisons were statistically significant.

Average accuracy in the prime identification task was 96% (91% for target-primed trials; 100% for foil-primed trials).[2] This high rate of accuracy indicates that participants were attending to and aware of the primes, even when they were flashed for only 100 ms. It should be noted that prime identification trials occurred only following brief primes but not after long duration primes. It is conceivable that this induced a different strategy in relation to brief primes as compared with long duration primes. However, the results were nearly identical to Experiment 1, which did not include any tasks in relation to the primes. Furthermore, performance in the prime identification task and in the verb task indicated that participants were aware of the primes regardless of prime duration, and so it is not obvious why participants would adopt two different strategies. In keeping with this interpretation, the pre-activation/habituation model produced similar results for both Experiment 1 and Experiment 2, with these effects arising purely as a function of prime viewing duration.

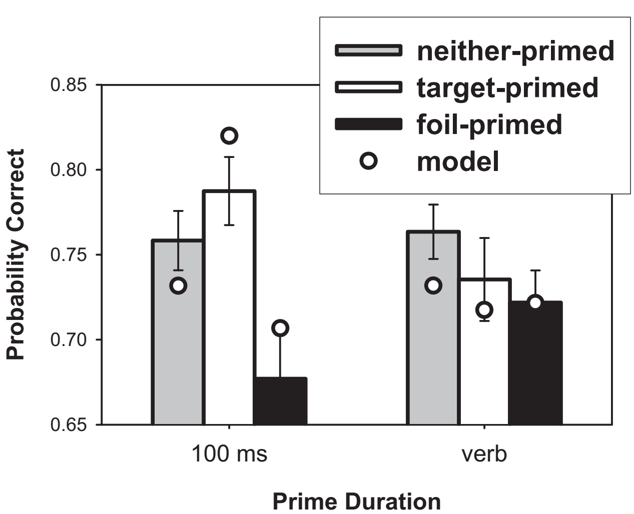

Figure 3. Mean forced-choice recognition accuracy as a function of prime duration and prime type in Experiment 2. Error bars represent standard error of the mean. The circles are the result of fitting the pre-activation/habituation to these data as outlined in Experiment 6 with the parameters that appear in Table 1.

In summary, Experiment 2 replicated the critical interaction between prime type and prime duration with forced-choice testing found in Experiment 1, even though prime awareness for short duration primes was demonstrated to be high as indicated by prime identification trials. Participants were accurate 96% of the time at prime identification following short duration primes, even though they did not know at the time of prime presentation whether they would be asked to engage in prime identification or forced-choice episodic recognition. This demonstrates that the prime duration effect exists even when there is awareness of short duration primes and even when both short and long duration primes are attended.

Experiment 3

Experiments 1 and 2 found interactions between prime duration and prime type even though participants were aware of the primes in all conditions. Furthermore, by using forced-choice recognition, these experiments demonstrated that priming effects were due to a change in memory retrieval rather than a change in response criteria. However, memory retrieval may arise from different components, such as with the distinction between familiarity and recollection, and it is not clear from these results which component is primarily responsible for the effect. By using subliminal primes, Rajaram (1993) used the remember/know procedure and found that priming preferentially affected familiarity. However, the relationship between familiarity/recollection and priming has never been examined for the situation of long duration primes, which tend to eliminate or reverse priming. This is a critical test of the pre-activation/habituation model because it predicts that positive priming, the elimination of positive priming, and even reversed priming are all due to changes in familiarity due to perceptual fluency or disfluency. Therefore, Experiment 3 replicated the prime duration manipulation of Experiment 2 while using procedures to measure recollection versus familiarity.

Due to interpretational issues surrounding the remember/know procedure (e.g., Rotello & Macmillan, 2006), particularly in the case of supraliminal primes that might induce strategies, we instead used a method based on the classic distinction between recall and recognition. Thus, recognition trials were divided into mem-

[2] The difference between prime identification rates for target-primed and foil-primed trials is most likely due to a flaw in the procedures employed during the practice and threshold lists in the initial stages of the experiment. The flash task during these stages of the experiment used only foil-primed trials (i.e., the previously studied target word was always the incorrect choice in the flash task). This most likely induced a strategy against choosing the previously studied word on flash task trials, which occasionally led participants astray during the experimental lists. Unlike the initial stages of the experiment, the experimental lists included an equal mix of target-primed and foil-primed trials, and so a strategy not to choose the previously studied word would result only in chance performance. Despite this flaw in the procedure, performance for target-primed prime identification trials was 91%, which demonstrates the ease with which the short duration primes were perceived.

ories that also supported successful recall versus memories that did not support recall. More specifically, recall was tested in the form of cued recall, with the target from the recognition response serving as a cue for a paired associate seen at study. Following study of word pairs, recognition trials were for single words, just as in Experiments 1 and 2. Each forced-choice recognition response was immediately followed by a cued-recall test using the target as a cue. We assume that recognition responses to memories that also support cued-recall success were likely to have been recognition responses based on recollection. Our prediction is that priming will primarily affect recognition followed by recall failure (i.e., familiarity-based recognition), and this will be true both for short duration primes and for long duration primes.

A secondary prediction of the pre-activation/habituation model arose from the longer study durations used in Experiment 3, which were needed to support sufficient levels of cued recall. As mentioned previously, application of the model to recognition memory supposes that items of higher familiarity more quickly become disfluent. Because Experiment 3 used longer study durations (in Experiments 1 and 2, study durations were on average 870 and 834 ms, as compared with 2,961 ms in Experiment 3), the memories in Experiment 3 should be more familiar on average. Therefore, all else being equal, it was predicted that the longer study durations in Experiment 3 would produce negative priming for the case of the verb-task prime duration even though this condition served only to eliminate priming in Experiment 2. To keep forced-choice recognition below ceiling with these highly familiar memories, the number of study words was increased from 18 to 72 (36 pairs). Thus, the design of Experiment 3 was still expected to produce approximately 75% recognition performance due to the combination of stronger memories as well as more variability in the familiarity response in light of the increased number of items on the study list (e.g., Shiffrin, Huber, & Marinelli, 1995). In other words, with a long study list, even foils may occasionally appear highly familiar by randomly matching study list items.

Method

Participants. Thirty-one university undergraduates participated individually in return for class credit.

Materials and procedure. All materials and procedures were the same as Experiment 2 except as noted, with the verb task providing a long prime duration condition. On average, the verb task took 2,524 ms to accomplish with 75.9% accuracy. Unlike Experiment 2, there were no prime identification trials following the short 100-ms prime presentations. Study lists consisted of 36 pairs of randomly matched words, and study instructions emphasized that participants should create a relationship between the two words in each pair, for instance, by forming a bizarre interacting image. Left/right study position of targets and associates was randomly counterbalanced such that any of the 72 study list words was potentially a target in forced-choice recognition. Test lists consisted of 24 pairs of forced-choice items, presented 1 pair at a time.

As with Experiments 1 and 2, the mask that followed the prime was immediately replaced with a single item forced-choice recognition test trial (even though study was for pairs, recognition was for single items). After the recognition response was given, participants were told which of the two choices was the correct target word and asked to indicate if they could recall the word paired at study with that target word. In other words, they were asked to use the target word as a cue for recall. This occurred on all trials, even if they incorrectly chose the foil in the recognition response, thus giving them a chance to perform cued recall even if they failed to recognize the target. They indicated whether they could recall the word studied with the target by pressing the *YES* or *NO* key. If they answered "yes" to this question, then they were asked to type the first letter of that word (cued-recall). Finally, participants received feedback for all their responses after every trial.

During practice, there were 2 study/test lists consisting of all verb-task neither-primed trials. Study duration was 3,000 ms for the first list. After each list, the study duration could decrease if 21 or more forced-choice recognition judgments were correct or could increase if 15 or fewer were correct. Study duration could change by 1,000 ms following the first list, 500 ms following the second list, and 250 ms following each of the experimental lists. Average study duration for the experimental lists was 2,961 ms, ranging from 1,542 ms to 5,125 ms across individuals.

The experimental segment contained 2 blocks with 3 lists per block. Each 24-trial test list used all 6 conditions (2 prime durations × 3 prime types), each occurring four times and resulting in 144 total experimental trials per participant (24 repetitions of the 6 conditions). The first and last 6 pairs from each study list in this experiment were not tested.

Results and Discussion

Figure 4 shows mean recognition accuracy as a function of prime duration (short, verb task) and prime type (neither-primed, target-primed, foil-primed). The figure also shows the breakdown of recognition accuracy into subsequent cued-recall success versus cued-recall failure.

Recognition accuracy. A 2 (prime duration) × 3 (prime type) repeated measures ANOVA revealed a significant main effect of prime, $F(1, 30) = 4.26$, $MSE = .007$, $p < .05$; and a significant interaction between prime duration and prime type, $F(2, 60) = 4.89$, $MSE = .012$, $p < .05$. Simple effects revealed no effect of prime type for short duration primes. In contrast, pairwise comparisons showed that for long duration primes, accuracy in the target-primed condition was significantly less than accuracy in the neither-primed condition ($p < .05$). In sum, the present experiment found that long duration primes (verb task) can cause perceptual disfluency for the primed items, therefore lowering recognition, and that short (100-ms) primes have no effect on recognition.

As predicted by use of longer study durations, the pattern obtained in Experiment 3 differed from the two preceding experiments. In Experiments 1 and 2, short duration primes increased recognition for the primed items whereas long duration primes (1,000 ms in Experiment 1 and verb-task primes in Experiment 2) eliminated but did not reverse this effect. In contrast, the short duration primes of Experiment 3 produced no apparent effect, but the long duration primes produced reversed priming. According to the pre-activation/habituation model, the 100-ms prime duration was already sufficient to produce a balance between fluency and disfluency, whereas long duration primes produced even greater habituation, resulting in an observable disfluency. As discussed in

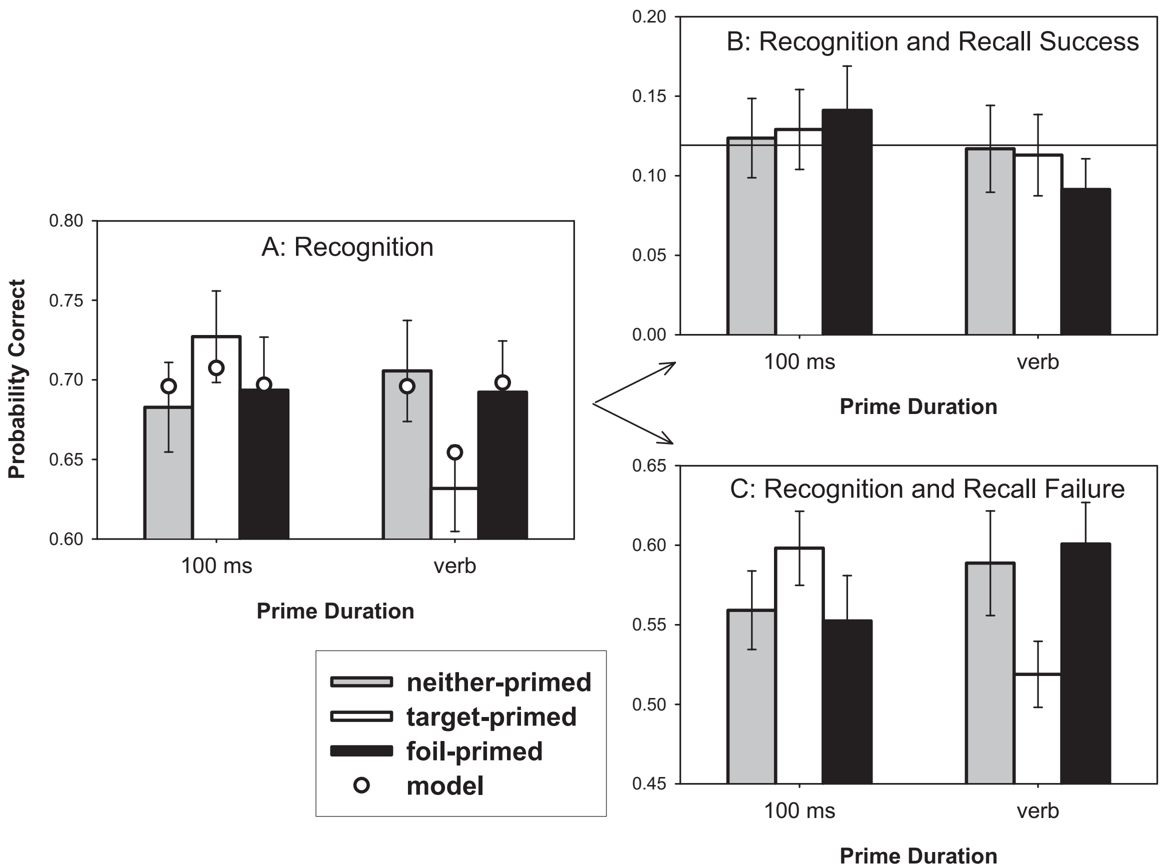

Figure 4. Mean forced-choice recognition accuracy as a function of prime duration and prime type in Experiment 3 (Panel A). This is broken down into joint probability of correct recognition followed by cued-recall success (Panel B), versus the joint probability of correct recognition followed by cued-recall failure (Panel C). Error bars represent standard error of the mean. The circles are the result of fitting the pre-activation/habituation to these data as outlined in Experiment 6 with the parameters that appear in Table 1. The horizontal line on Panel B is the average recognition followed by recall level of .119 for Experiment 3.

the simulation study (Experiment 6), the model produced this qualitative change by changing only memory strength; greater memory strength in turn produces more rapid habituation within the familiarity response.

Experiment 3 also provided a critical test of the predicted asymmetry between the costs and benefits of priming. Relative to the neither-primed condition, long duration primes decreased recognition accuracy for primed targets more than the corresponding increase for primed foils. According to the model in a situation with strong disfluency, priming of familiar targets produces greater disfluency (large costs) as compared with priming of foils (smaller benefits), considering that targets but not foils appeared on the study list. This was the first opportunity to clearly observe this prediction because the memory strengths used in Experiments 1 and 2 were insufficient to produce a sizable priming reversal.

Recognition followed by recall success. We conducted separate joint probability analyses for accurate recognition that were followed by cued-recall success or followed by cued-recall failure. This was done as a joint probability rather than a conditional probability so that recognition accuracy is broken into two parts based on recall success or failure, with these two parts adding to produce the overall probability of recognition. Also, joint probabilities are the measurement provided by the remember/know procedure, and so this breakdown will be familiar to those used to that procedure. For the joint probability of correct recognition followed by recall success, a 2 × 3 repeated measures ANOVA revealed a significant main effect of prime duration, $F(1, 30) = 4.38$, $MSE = .006$, $p < .05$. However, the critical test of the interaction between prime type and prime duration failed to reach significance ($p > .10$).

Recognition followed by recall failure. In contrast, the pattern of results for recognition followed by recall failure was the same as the pattern for recognition accuracy. Specifically, there was a significant interaction between prime duration and prime type, $F(2, 60) = 4.40$, $MSE = .017$, $p < .05$. Simple effects revealed no effect of prime type for short duration primes. In contrast, pairwise comparisons for long duration primes revealed that correct recognition was significantly greater in the foil and neither-primed conditions than in the target-primed condition (both ps = .05). As with the collapsed recognition data, we found asymmetries such that priming decreased accuracy in the target-primed condition more so than it increased accuracy in the foil-primed condition.

It is worth noting that the probability of correct recall in the cued-recall task was .13, and this is very similar to the probability of correct recognition and cued-recall success (.12). This is due to the very high conditional probability (.98) of correct recognition for trials that also resulted in correct cued recall. Assuming that priming does not affect recall, it may appear that this experiment was guaranteed to produce priming effects primarily for cued-recall-failure trials given this high probability of recognition conditioned on recall success. However, this appears to be the case only in retrospect. Instead, it might have been (a) that priming exerted an influence directly on recall, for instance by providing more opportunity to view target items; or (b) that recall was combined with familiarity to provide an aggregate measure for the recognition response (e.g., Wixted & Stretch, 2004) rather than taking precedence over familiarity, in which case priming might have influenced recognition through its effect on familiarity despite the presence of recall information.

Regardless of reasons why priming might have influenced recognition followed by recall success, the important result of Experiment 3 is the finding of negative priming following long duration primes while measuring the role of recall. This supports our claim that the Jacoby–Whitehouse prime duration effect is due to the lowering of familiarity with increased prime duration. Furthermore, this result represents the first time that the role of familiarity versus recollection has been assessed for immediate priming conditions that produce recognition reversals. However, there are two potential concerns with this conclusion from Experiment 3: (a) It relies on accepting the null hypothesis for the case of recognition followed by cued-recall success, and (b) our recognition followed by cued-recall procedure for separating recognition into two trial types has not been validated in terms of its ability to measure separate influences on each trial type. As explained below, Experiment 4 addressed both of these concerns by replicating Experiment 3 while including a second manipulation that preferentially affected recognition followed by recall success.

Experiment 4

Experiment 3 showed that priming can preferentially affect recognition trials that were followed by cued-recall failure. However, to validate this procedure, and to demonstrate that the lack of effect for recognition followed by recall success was not due to a lack of power, Experiment 4 included an additional manipulation that produced a preferential effect on recognition trials that were followed by recall success (i.e., recollection-based recognition). This was achieved by varying the delay between study and test, with one condition testing words that appeared in the list just studied (the immediate condition that replicates Experiment 3), and another condition testing words from two lists prior to the most recent study list. Both immediate and delayed targets appeared on every test list. Although the use of delay was originally motivated for other reasons, and we did not anticipate that delay would preferentially affect recollection-based recognition, the fact that delay selectively affected recognition trials that also produced accurate recall proved to be useful in validating the recognition followed by recall technique.

Method

Participants. Forty university undergraduates participated individually in return for class credit.

Materials and procedure. The materials and procedure were identical to Experiment 3, except as noted. Unlike previous experiments, study duration was not tailored to each participant and was instead set to 3 s for each pair of words. The two practice episodes consisted of 16 verb-task test trials. By testing only 16 of the 32 study word pairs, this reserved the other 16 for testing at delay. There were 8 experimental conditions, consisting of two test delays (immediate, delay) crossed with two prime types (target-primed, foil-primed) crossed with two prime durations (100 ms, verb task). On average, the verb task took 2,124 ms to accomplish with 76.9% accuracy. Because two conditions were added to the experiment, 32 of the 36 study pairs were tested (excluding the first 2 and the last 2), rather than 24. This yielded exactly the same number of trials per condition, per participant as in Experiment 3. The neither-primed condition was eliminated from this study to allow a more focused analysis of the direction of priming, rather than asymmetries between prime-induced costs and benefits. For the newly added delay manipulation, test items were either from the immediately preceding study list (immediate) or were from the list presented two lists previously (delay; i.e., there were two study lists presented between the delayed test word and the study list in which the word was originally shown). At the start of the first experimental test list, which followed the two practice lists, participants were explicitly informed that half of the test words would come from a previously studied list rather than the just studied list. With this design, the first and second test lists included test words that were studied during practice study lists. Participants were instructed to respond “old” to any test word seen previously in the experiment, regardless of which study list that word appeared on.

Results and Discussion

Figure 5 shows the mean recognition accuracy as a function of test delay (immediate, delay), prime duration (100 ms, verb task), and prime type (target-primed, foil-primed). The figure also shows the breakdown of recognition accuracy into subsequent cued-recall success versus cued-recall failure.

Recognition accuracy. A 2 (prime duration: 100 ms, verb task) × 2 (test delay: delay, immediate) × 2 (prime type: target-primed, foil-primed) repeated measures ANOVA revealed a significant main effect of test delay, $F(1, 39) = 32.71$, $MSE = .006$, $p < .001$; a significant main effect of prime type, $F(1, 39) = 15.49$, $MSE = .03$, $p < .001$; and a significant interaction between prime type and prime duration, $F(1, 39) = 4.70$, $MSE = .02$, $p < .05$. Tests of simple effects showed that for delayed test items, there were significant effects with 100-ms priming, $F(1, 39) = 5.30$, $p < .05$; and with long duration priming, $F(1, 39) = 12.74$, $p < .001$. On the other hand, for immediate test items, there was a significant effect only for long duration priming, $F(1, 39) = 12.14$, $p < .005$. Pairwise comparisons revealed that, for all three significant simple effects, recognition was greater for primed foils than for primed targets (delay, 100 ms: $p < .05$; delay, verb task: $p < .001$; immediate, verb task: $p < .001$).

These results replicated Experiment 3 by revealing significant negative priming in the immediate condition following long dura-

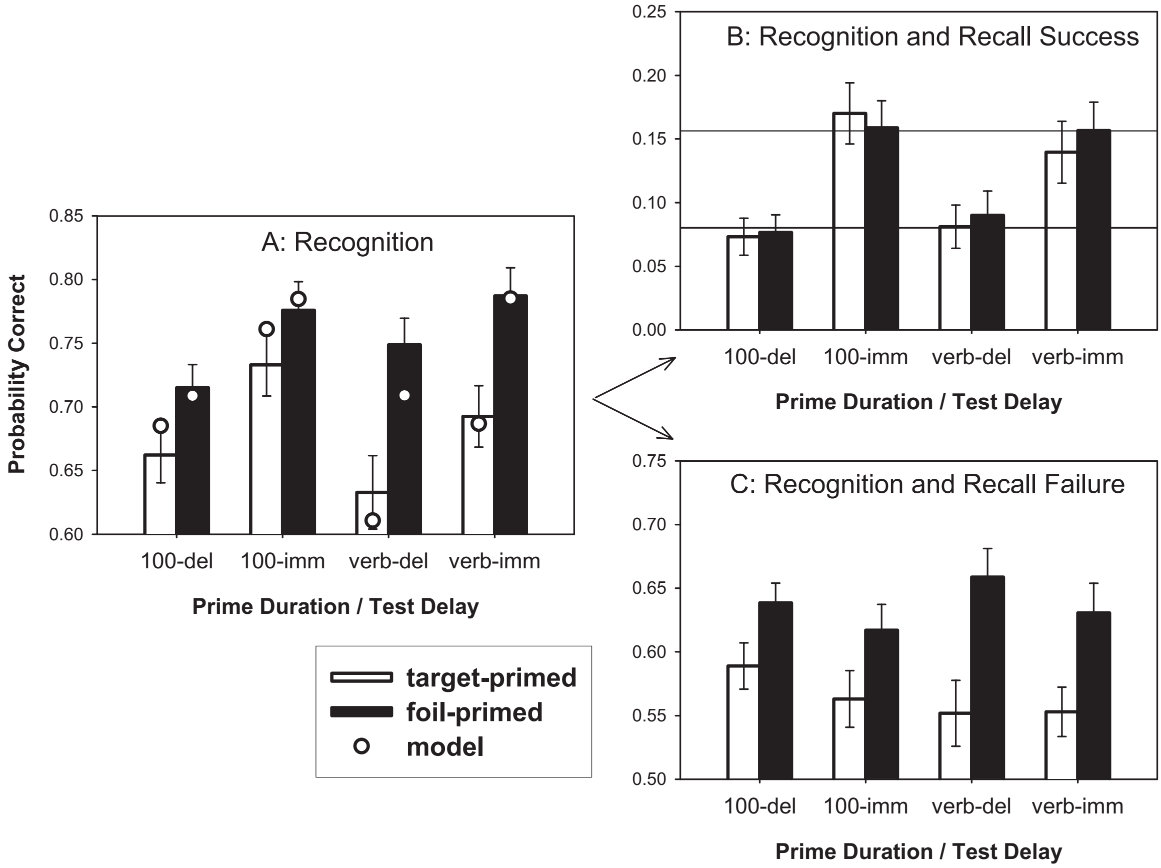

Figure 5. Mean forced-choice recognition accuracy as a function of prime duration, study-test delay and prime type in Experiment 4 (Panel A). This is broken down into joint probability of correct recognition followed by cued-recall success (Panel B), versus the joint probability of correct recognition followed by cued-recall failure (Panel C). Error bars represent standard error of the mean. The circles are the result of fitting the pre-activation/habituation to these data as outlined in Experiment 6 with the parameters that appear in Table 1. del = delay; imm = immediate. The horizontal lines on Panel B show average recognition followed by recall collapsed over prime type and prime duration (.080 for delayed and .156 for immediate).

tion primes. These results also indicate that both the delay manipulation and the priming manipulation influenced recognition. As seen next, each effect appears to map preferentially onto one of the two recognition trial types.

Recognition followed by recall success. For the joint probability of correct recognition and recall success, a 2 (prime type) × 2 (test delay) × 2 (prime duration) repeated measures ANOVA revealed a significant main effect of test delay, $F(1, 39) = 49.42$, $MSE = .009$, $p < .001$; but no interaction between prime type and prime duration, $F(1, 39) = 3.34$, $MSE = .004$, $p = .075$. There were no other main effects and no interactions (all Fs < 2.1 and ps $> .16$). As seen in Figure 5, performance was greater with immediate testing, but as with Experiment 3, priming did not affect recognition performance for these trials that were subsequently recalled. This replicates the null result of priming of recognition trials that were subsequently recalled. This result helps address issues of null hypothesis acceptance by means of replication, and, more importantly, by finding significant differences with delay, which demonstrates that this experiment contained sufficient power to observe effects for recognition trials that were subsequently recalled.

Recognition followed by recall failure. Recognition followed by cued-recall failure revealed a significant main effect of prime type, $F(1, 39) = 13.06$, $MSE = .03$, $p < .001$; but no effect of delay (delay = .61, and immediate = .59). There were no other main effects and no interactions (all Fs < 1.3 and ps $> .26$). Tests of simple effects for immediate test items revealed significant effects of both 100-ms primes, $F(1, 39) = 4.96$, $p < .05$; and long duration primes, $F(1, 39) = 6.29$, $p < .005$. Likewise, simple effects tests for delayed test items revealed significant effects of both 100-ms primes, $F(1, 39) = 4.19$, $p < .05$; and long duration primes, $F(1, 39) = 7.93$, $p < .01$. Pairwise comparisons revealed greater recognition accuracy for foil-primed trials than for target-primed trials in all four conditions (delay, 100 ms: $p < .05$; delay, verb task: $p < .01$; immediate, 100 ms: $p < .05$; immediate, verb task: $p < .02$). These results indicate that recognition followed by recall failure was impacted by priming but not by test delay. More specifically, regardless of prime duration, recognition followed by recall failure was more accurate for foil-primed trials than for target-primed trials.

Although the pre-activation/habituation model made no prediction regarding recall in general and the effect of delay on recall, this experiment provided an important validation of the recognition followed by recall procedure by demonstrating that one variable (priming) can preferentially affect recognition followed by recall failure at the same time that another variable (delay) can preferentially affect recognition followed by recall success. This also demonstrated that the design included sufficient power to find effects on recognition followed by recall success. Thus, the finding that long duration primes produced negative priming preferentially for recognition followed by recall failure (i.e., familiarity-based recognition) appears to be a reliable result.

Very few studies have examined the difference between recollection and familiarity as a function of delay. One exception is a study by Yonelinas and Levy (2002), which used a procedure somewhat similar to ours; their study tested both single item recognition and association information in the form of a subsequent question regarding the color of the studied word. However, in seeming contradiction to our results, they found that familiarity was preferentially affected by delay, but recollection was not. The key difference may be that the delays in their study were quite short, consisting of between 1 and 32 intervening study items in a continuous memory paradigm. Furthermore, although their experiment also included intervening list items, these intervening items were part of separate study lists in our design. Our use of recall tests between initial study and subsequent testing at delay may have protected target memories from retroactive interference (e.g., Jang & Huber, 2008). Furthermore, associative information in their study (e.g., ink color–word) was different in nature than the associative information in our study (e.g., word–word).

In summary, the important conclusion from Experiment 4 is that the priming effect on recognition followed by recall-failure trials (familiarity) was preferentially affected by priming, even with reversed priming following long duration primes. In contrast, recognition followed by recall success (recollection) was preferentially affected by delay, thus validating the recognition/recall procedure.

Experiment 5

In each of the previous four experiments, we observed interactions between prime duration and the direction of priming as revealed by comparisons between the target-primed and foil-primed conditions. In the case of Experiments 1 and 2, which used single items studied for less than a second, this interaction took the form of positive priming following 100-ms primes, which was eliminated following 1,000-ms primes or verb-task primes (which were viewed for several seconds). In the case of Experiments 3 and 4, which used paired items studied for 3 s, this interaction took the form of null priming (Experiment 3 and the immediate condition of Experiment 4) following 100-ms primes but took the form of negative priming following long duration primes. As predicted, the direction of change was from positive to negative priming with increasing prime duration for all experiments. Also, as predicted, the stronger memories of Experiments 3 and 4 more rapidly saturated, thus explaining why 100 ms was sufficient to eliminate positive priming. However, one lingering concern with these interactions is that they all relied on one priming condition that produced an apparent null priming result. The pre-activation/habituation model supposes that these null priming conditions are in fact a balancing act between the benefits of pre-activation (increased head start in the fluency response) versus the deficits of habituation (a depleted representation that is slow to fully reactivate as a test word). Nevertheless, interpreting null results is always a tricky matter. Therefore, Experiment 5 was designed to produce a full crossover interaction from positive to negative priming within the same study. By documenting this crossover, the midpoint that produces null priming is more sensibly interpreted as the crossing point between positive and negative priming (suggesting a balance of factors) rather than an absence of priming.

The purpose of Experiment 5 was to test the full transition from fluency to disfluency within the same experiment through manipulation of prime duration. Specifically, two very short prime durations (17 ms and 50 ms) were added to the procedure of Experiment 3.

Method

Participants. Thirty-six university undergraduates participated individually in return for class credit.

Materials and procedure. The materials and procedure of Experiment 5 were identical to those of Experiment 3 except for the following deviations. Like Experiment 4, the study durations were not tailored for each participant, but rather all participants studied word pairs for 3 s each. There was only one practice list, consisting of 16 verb-task trials, which was followed by six experimental study/test lists. In addition to the 100-ms and verb-task priming conditions used in Experiment 3, some of the primes were presented for 17 ms, and some were presented for 50 ms. The four priming conditions (17 ms, 50 ms, 100 ms, verb task) were crossed with two prime types (target-primed and foil-primed) making for eight conditions total. On average, the verb task took 2,430 ms to accomplish with 77.0% accuracy. Because two conditions were added to the experiment, 32 of the 36 study pairs were tested (excluding the first 2 and the last 2), rather than 24. This yielded exactly the same number of trials per condition, per participant as in Experiment 3. Lastly, like in Experiment 4, the neither-primed condition was eliminated because the critical comparison to assess priming effects with forced choice is between the target-primed and foil-primed conditions.

Results and Discussion

Figure 6 shows the mean recognition accuracy as a function of prime duration (17 ms, 50 ms, 100 ms, verb task) and prime type (target-primed, foil-primed). The figure also shows the breakdown of recognition accuracy into subsequent cued-recall success versus cued-recall failure.

Recognition accuracy. For combined recall-success and recall-failure trials, a 4 (prime duration: 17 ms, 50 ms, 100 ms, verb task) × 2 (prime type: target-primed, foil-primed) repeated measures ANOVA revealed a significant interaction between prime duration and prime type, $F(3, 105) = 7.31$, $MSE = .06$, $p < .001$. Tests of simple effects showed that recognition was significantly greater for primed targets than for primed foils both for the 17-ms prime duration, $F(1, 35) = 4.92$, $p < .05$; and the 50-ms prime duration, $F(1, 35) = 4.08$, $p = .051$. However, there was no difference in recognition between primed targets and primed foils following 100-ms duration primes. Because the difference at 100 ms was in the direction of positive priming, one could question

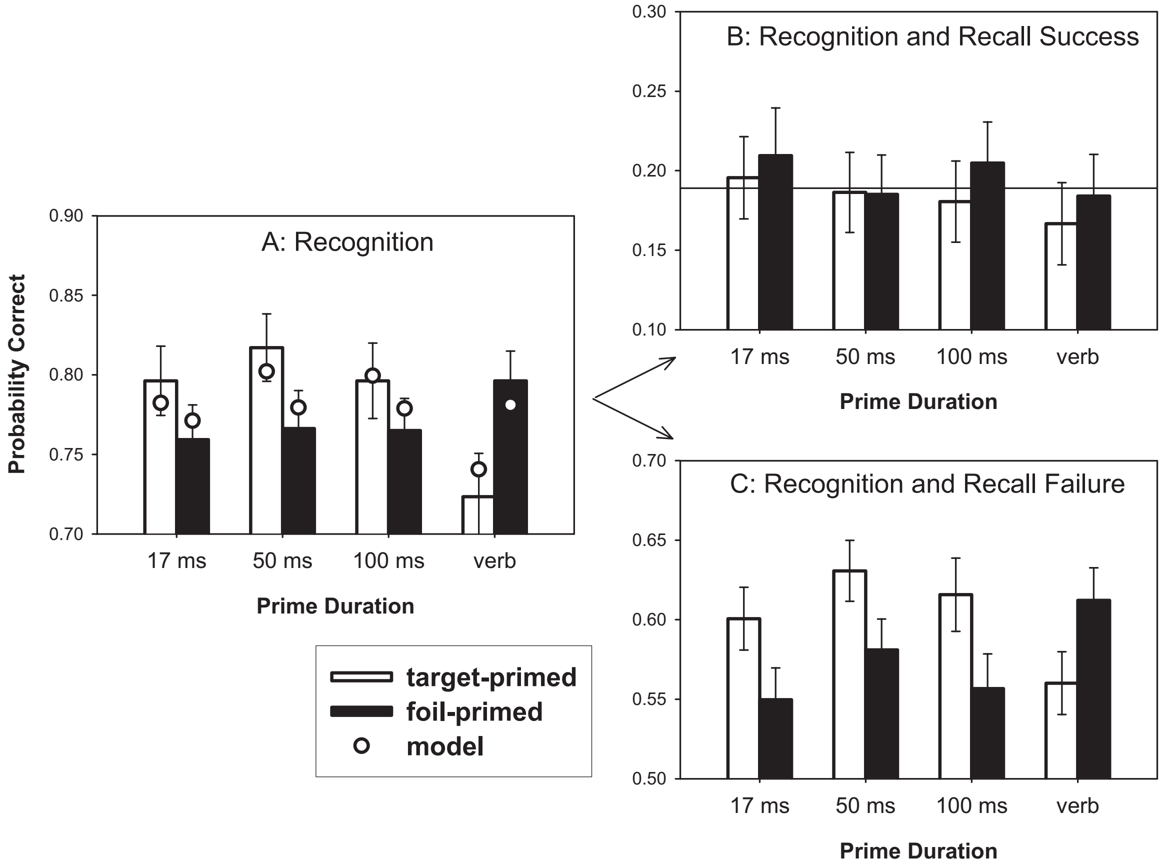

Figure 6. Mean forced-choice recognition accuracy as a function of prime duration and prime type in Experiment 5 (Panel A). This is broken down into joint probability of correct recognition followed by cued-recall success (Panel B), versus the joint probability of correct recognition followed by cued-recall failure (Panel C). Error bars represent standard error of the mean. The circles are the result of fitting the pre-activation/habituation to these data as outlined in Experiment 6 with the parameters that appear in Table 1. The horizontal line on Panel B is the average recognition followed by recall level of .189 for Experiment 5.

whether there is simply insufficient power at this duration to observe positive priming. However, this is somewhat irrelevant considering that with even longer prime durations, in the form of the verb task, recognition was greater for primed foils than for primed targets, $F(1, 35) = 8.03$, $p < .01$. Because Experiment 5 produced a crossover interaction whereby short duration primes (17 ms and 50 ms) produced a positive priming effect, but long duration primes (verb task) produced a negative priming effect, there is certain to be a true null crossing point at some intermediate prime duration. Providing converging evidence that 100 ms was indeed this crossing point, Experiment 5 replicated the results of Experiment 3, which also produced no apparent effect of priming for 100-ms duration primes.

These results are consistent with the pre-activation/habituation model, which produces a nonlinear gradual course for priming as a function of prime duration. Specifically, very short prime durations (17 ms and 50 ms) produced perceptual fluency for the primed items, thereby increasing recognition (positive priming); 100-ms prime durations produced a balance between fluency and disfluency and therefore had no effect on recognition; long duration primes (verb task) caused perceptual disfluency, thereby decreasing recognition (negative priming).

Recognition followed by recall success. For the joint probability of correct recognition followed by cued-recall success, a 4 (prime type) × 2 (prime duration) repeated measures ANOVA revealed no effect of prime duration, $F(3, 105) = 2.52$, $MSE = .10$; and no interaction between prime type, and prime duration was not significant ($F < 1$).

Recognition followed by recall failure. In contrast, the joint probability analysis for correct recognition followed by cued-recall failure revealed a pattern similar to that of recognition accuracy collapsed over recall success/failure. Specifically, a 4 (prime duration) × 2 (prime type) repeated measures ANOVA showed a significant interaction between prime duration and prime type, $F(3, 105) = 4.96$, $MSE = .05$, $p < .005$. Simple effects tests revealed that the probability of correct recognition was significantly greater for target-primed trials than foil-primed trials for prime durations of 17 ms, $F(1, 35) = 5.11$, $p < .05$; and 100 ms, $F(1, 35) = 5.82$, $p < .05$; although this difference was not significant for 50-ms primes, $F(1, 35) = 3.05$, $p = .09$. Importantly, there was a reverse priming effect for long duration primes such that recognition was greater for primed foils than for primed targets, $F(1, 35) = 4.02$, $p = .053$.

These results replicated Experiments 3 and 4 but extended these priming effects to shorter prime durations, revealing a full crossover from positive to negative priming, supporting the claim that pre-activation and habituation can balance to produce an apparent lack of priming at intermediate prime durations. As with Experiments 3 and 4, these results also suggest that priming selectively influenced the familiarity component of recognition memory, and, more specifically, that reversed priming is due to lowered familiarity.

Experiment 6: Simulation Study

To evaluate the adequacy of the pre-activation/habituation account of recognition priming, we quantitatively fit the model seen in Figure 1 to the data of Experiments 1–5, by using the activation equations and decision rule equation reported in the Appendix. The parameters for the visual, orthographic, and lexical–semantic layers of the model were the same as reported by Huber and O'Reilly (2003). These default values were originally found by fitting 40 conditions in a perceptual identification experiment, which included priming, masking, and a range of five prime durations (Huber, 2008). In addition, these default parameters were based on the same words used in the currently reported experiments. Because the current extension to the original perpetual model did not include feedback from familiarity onto lexical–semantic processing, the perceptual dynamics were unchanged from these previously published results. In other words, the millisecond by millisecond lexical–semantic responses were pre-determined by previously published model results. The basic question asked in this model-fitting exercise was whether sensible parameter values in the newly added familiarity component of the model could quantitatively capture the prime duration effects across the three priming conditions (i.e., could memory strength capture the direction of priming as well as the asymmetries between the costs and benefits of priming). In doing so, no parameter varied as a function of prime viewing duration; instead, the model was shown primes for the correct number of milliseconds as appropriate to each condition. A secondary question was whether the model could quantitatively explain the differences between Experiments 1 and 2, which used shorter lists and shorter study durations (i.e., weaker memories with less variability), versus Experiments 3–5, which used longer lists and longer study durations (i.e., stronger memories with more variability).

In the fits of Experiments 1–5, shown in Figures 2–6, there were two free parameters for each experiment as reported in Table 1. These free parameters were "structural" in nature and did not vary with prime duration. More specifically, there was one free parameter corresponding to the newly learned strength of the connection between the lexical–semantic and episodic familiarity layers for studied targets (target connection strength) and one free parameter corresponding to variability in the familiarity response. This variability parameter (performance gain) was applied as a multiplier on the difference between the familiarity of targets and foils. The resultant weighted familiarity difference was then mapped into accuracy through a sigmoidal logistic function. Target connection strength presumably relates to strength of encoding and study duration. In keeping with this supposition, best-fitting values for Experiments 3–5 were considerably higher than those for Experiments 1 and 2, reflecting the fact that study durations were more than three times as long for Experiments 3–5. Performance gain presumably corresponds to variability in the familiarity response. According to many global familiarity models (e.g., the SAM model of Gillund & Shiffrin, 1984), variability in the familiarity response increases as a function of the number of studied items, thus producing worse recognition performance for longer study lists (although see Dennis & Humphreys, 2001, for an alternative view). In keeping with this supposition, the performance gain values were much smaller (i.e., poor signal to noise, reflecting high variability) for Experiments 3–5, which used four times as many words in each study list.

Besides these two free parameters that were fit separately to the results of each experiment using chi-square goodness of fit, extension of the Huber and O'Reilly (2003) model to familiarity required a parameter for the speed of processing in the familiarity layer (i.e., the integration time constant for the temporal differential equations). Initial investigations revealed that setting this parameter to .0046 worked well in general, and this value was used for all experiments. This extension also required some level of familiarity for nonstudied foils (i.e., the strength of the connection between the lexical–semantic and familiarity layers for nonstudied foils). Again, initial investigations revealed that setting this parameter to .5 worked well in general. Therefore, one might consider these to be free parameters even though they were not optimized by any fitting routine. Considering that these 2 parameters applied to the data from all five experiments, this would adjust the number of free parameters from 2.0 to 2.4 per experiment (the conclusions regarding significant goodness of fit would remain unchanged).

Because this model is concerned only with familiarity and has nothing to say regarding recall, we did not model the recall results. Instead, we used the observed degree of correct recognition followed by recall success to factor recollection out of the recognition responses, thus providing a less contaminated measure of familiarity. The model was used to produce a measure for the proba-

Table 1
Model Parameters and Goodness of Fit

Experiment	Target connection strength	Performance gain	No. of conditions	*N* per condition	Sum of χ^2 error	Rejection probability
1	0.71	22.5	6	960	28.7	<.01
2	0.67	28.3	6	960	20.7	<.01
3	1.39	2.04	6	744	4.17	.39
4	4.08	1.42	8	984	17.2	.01
5	1.08	3.39	8	864	7.30	.29

bility of recognition and not recalling (i.e., the cleaner measure of familiarity), and this was added to the observed level of recognizing and recalling (which did not differ with priming manipulation and is nearly identical to the probability of recalling in general). Model parameters were then optimized in comparison with this reconstituted measure of recognition that was based on the sum of model predictions based on familiarity in combination with the observed level of recognition followed by recall success. Fitting was done in relation to this reconstituted total recognition because (a) total recognition was the only data available for Experiments 1 and 2 and (b) total recognition is a more reliable observation considering that it includes more data (i.e., less likely to be fitting sampling noise). In Experiments 3 and 5, recognition followed by recall did not vary as a function of condition, and so averages were taken over priming condition to provide a more reliable estimate. The horizontal line on Panel B of Figure 4 is the average recognition followed by recall level of .119 for Experiment 3, and the horizontal line on Panel B of Figure 6 is the average recognition followed by recall level of .189 for Experiment 5. In the case of Experiment 4, recognition followed by recall varied as function of delay (because recall varied with delay), and, therefore, recognition in Experiment 4 was fit by adding in the appropriate level of recognition followed by recall, as seen in the horizontal lines of Figure 5 (.080 for delayed and .156 for immediate).

As seen in Figures 2–6 and Table 1, the model provided a good qualitative and quantitative account of the data from all five experiments, and the best-fitting parameters sensibly varied as a function of study duration (target connection strength) and list length (performance gain). The ability of the model to capture the nonlinear pattern from positive to negative priming as a function of prime duration was mostly due to fluency within the perceptual layers as dictated by the default parameters. However, the connection strength parameter served to modulate the manner in which perceptual fluency affected familiarity. For the connection strength parameter appropriate to the study durations found in Experiments 1 and 2, this resulted in a transition from positive priming to a situation in which habituation roughly matched prime pre-activation, producing no difference between the target-primed and foil-primed conditions. For the connection strength parameter appropriate to the study durations found in Experiments 3 and 4, this resulted in a transition from no difference between the target-primed and foil-primed conditions to a situation of negative priming. Finally, in Experiment 5, which also included shorter prime durations, the model captured the full crossover from positive to negative priming.

In this extension of the model, familiarity is more than a passive conduit of perceptual fluency, and this proved to be important in several respects. Because the familiarity layer also includes habituation, stronger target connection strengths (i.e., the longer study durations of Experiments 3–5) produced more habituation within the familiarity response itself (above and beyond perceptual disfluency). For this reason, the 100-ms duration of Experiments 3–5 was already sufficient to saturate the familiarity response and produce a balance (i.e., null priming) between pre-activation and habituation. Besides the connection strength difference in comparing stronger versus weaker targets, the connection strength difference between targets and foils was also important in capturing these results. In particular, this explained the asymmetries for the costs versus benefits of priming for a situation of negative priming. This is particularly prominent for the long duration prime conditions of Experiment 3, in which case the neither-primed condition was greater than both the target-primed and foil-primed conditions. As seen in Figure 4, the model produced an accurate account of this asymmetry. This occurred because the priming of targets produced greater habituation (i.e., greater disfluency in the familiarity response) than did the equivalent priming of foils; the costs of priming outweighed the benefits because presentation of highly familiar target words as a prime produced more disfluency (thus hurting performance) as compared with presentation of unfamiliar foil words as a prime (which helped performance, but less so).

An examination of Table 1 reveals that, according to chi-square goodness of fit, Experiments 1, 2, and 4 were significantly bad fits, but the model cannot be rejected by the fits to Experiments 3 and 5. However, even in the case of Experiments 1, 2, and 4, the fit is still qualitatively accurate, and the model is doing well despite severe constraints (two free parameters, neither of which varied with prime duration). Experiments 1 and 2 were the only experiments that revealed positive priming while including the neither-primed condition, and in this case the model is quantitatively off for the 100-ms conditions in producing the costs versus benefits of priming; with positive priming, the model tends to produce greater benefits than costs due to greater fluency for priming targets as compared with magnitude of the fluency enhancement for priming foils. Simulating different trials with stochastically chosen levels of familiarity for targets and foils (rather than using a deterministic simulation with a performance gain parameter to map behavior into accuracy) might remedy this slight deviance from the observed data; such trial by trial variability would tend to move things in the direction of greater costs than benefits with positive priming. However, for reasons of simplicity and computational complexity, we elected to use this deterministic version of the model.

General Discussion

Data and Model Summary

We report five experiments testing the hypothesis that the direction and magnitude of repetition priming for recognition responses depends on prime duration. Furthermore, we confirm predictions that decreases as well as increases in recognition can result from changes in familiarity rather than changes in response criteria. This hypothesis, which represents an alternative to accounts of prime reversals based on prime awareness or explicit strategies, is based on a computational model that was originally designed to explain similar costs and benefits in perceptual priming (Huber & O'Reilly, 2003). We extend the original perceptual model to the case of familiarity and term this the "pre-activation/habituation model." The process of activation explains positive priming with short prime durations, and the process of habituation explains negative priming with sufficiently long prime durations. We propose that the increases in recognition responses with short duration primes as well as the decreases in recognition responses with long duration primes can be explained by the neural dynamics of perception, which produce positive or negative aftereffects depending on viewing duration. This account does not need to rely on any form of strategic responding to handle both positive and negative priming of recognition (although we do not deny that such strategies exist in some circumstances). We tested this account by adopting a methodology designed to minimize use of strategies. Specifically, all of our experiments used supraliminal prime durations, informed participants that there could be no effective strategy in relation to the primes, provided trial by trial accuracy feedback, and used forced-choice testing to eliminate the role of criterion shifts.

Experiment 1 replicated the basic Jacoby–Whitehouse effect—an interaction between prime duration and priming condition— despite implementing controls against strategic responding. Experiment 2 replicated this finding even though participants were aware of the short duration primes (as revealed by their 96% accuracy on prime identification trials). Experiments 3–5 used cued recall following recognition, revealing that priming preferentially existed for recognition trials that were followed by cued-recall failure (which we assume to be familiarity-based recognition). The literature on separating recognition into familiarity versus recollection with recognition priming has examined only subliminal primes, and so this represented the first occasion in which not only positive priming but also negative priming was found to relate to familiarity-based recognition. Experiment 4 used a delay manipulation that preferentially affected recognition trials that were followed by cued-recall success. This validated the recognition/recall procedure in terms of a manipulation check (i.e., a demonstration of sufficient power to change cued recall) and in terms of separate manipulations that preferentially affected each type of recognition. Finally, Experiment 5 revealed the full nonlinear crossover from positive to negative priming by including additional prime durations. This tested the prediction that intermediate prime durations can produce null priming due to a balance between fluency (the process of activation) and disfluency (the process of habituation).

We extended the perceptual identification model of Huber and O'Reilly (2003) to the domain of recognition memory by assuming that the speed of lexical/semantic activation influences the activation of episodic familiarity. As reported in Experiment 6 (simulation study), this was achieved by using the original perceptual fluency neural network as the driving input to episodic familiarity. The model produces a beneficial head start for a primed test word following the briefly presented prime (perceptual fluency), which leads to performance benefits in the competition taking place within the familiarity response. Because the familiarity response of a primed word is given a head start (i.e., pre-activated familiarity), it competes strongly against an unprimed word, with these effects occurring for both studied targets and nonstudied foils (i.e., producing a preference to "recognize" whichever word was primed). In this manner, increased speed of perceptual processing is translated into increased strength of familiarity. In contrast to short duration primes, longer duration primes saturate the primed word's perceptual representation, counteracting the benefits of priming. With even longer prime durations, priming can lead to perceptual disfluency, causing recognition deficits (i.e., a preference against recognizing whichever was primed). The model produces habituation through the inclusion of transient activity-dependent synaptic depression (i.e., habituation) at all levels of processing. As reported in the simulation studies of Experiment 6, the obtained data were consistent with the model across all five behavioral studies.

Application of the model revealed two important effects of memory strength due to the inclusion of habituation within the familiarity response: a predicted difference between priming weak targets and priming strong targets (Experiments 1–2 vs. Experiments 3–5) and a predicted difference between priming targets and priming foils (the priming asymmetry in Experiment 3). For Experiments 3–5, study times were more than 3 times longer than in Experiments 1 and 2, which was necessary to produce adequate levels of cued-recall success. We assume that these longer study times resulted in stronger memories—a feature that allowed a test of the model prediction that stronger memories will saturate more quickly. Consistent with this prediction, the 100-ms primes of Experiments 3, 4 (immediate condition), and 5 had no effect, whereas long duration primes decreased recognition for primed words. In contrast, both Experiments 1 and 2, which used shorter study durations, revealed positive priming in the 100-ms condition, and this was eliminated in the long duration conditions (but there was no reversal of priming). The model accounted for these differences across experiments by varying just a single memory strength parameter (performance gain also differed across experiments, but this parameter does not affect the direction of priming). For the stronger memories of Experiments 3–5, presentation of targets as short duration primes produced sufficient disfluency to counteract pre-activation. Furthermore, the long duration verb-task primes were sufficient to fully saturate the primed representation, producing a significant preference against recognizing the primed word. Experiment 3 included a baseline neither-primed condition, and the pattern of negative priming following long duration primes confirmed the prediction that the cost of priming the target outweighs the benefit of priming the foil because presenting a prime that is a target (which is more familiar) creates more disfluency as compared with a prime that is a foil (which is less familiar). Even though there was no comparison baseline condition in Experiment 5, this cost/benefit asymmetry is nevertheless revealed by noting that the average of the target- and foil-primed conditions is substantially higher for the short prime durations as compared with the long prime duration (also note that the model readily handled this only by simulating additional prime viewing).

These effects of memory strength may shed light on the recent finding that study of pictures eliminates recognition priming as compared with auditory study, which was interpreted in terms of greater use of recollection with picture study (Gallo, Perlmutter, Moore, & Schacter, 2008). Although the pre-activation/habituation model is compatible with this recollection interpretation, it also suggests an alternative possibility based on changes in memory strength. Indeed, memory strength as measured with d' was higher with picture study, which should in part produce the observed results according to the pre-activation/habituation model even if there was no change in the amount of recollection in comparing picture study versus auditory study.

Methodological Implications

This forced-choice paradigm, testing the costs and benefits of priming, could be used more broadly in the study of false memories, separating out strategic effects or criterion shifts from changes in memory retrieval. Specifically, this procedure could be applied in any paradigm with two sources of information for judgment—relevant and irrelevant—such as intervening task paradigms (e.g., fragment completion; e.g., Luo, 1993; Watkins & Peynircioglu, 1990), false fame paradigms (e.g., Jacoby, Kelley, Brown, &

Jasechko, 1989), and paradigms in which semantic familiarity is manipulated within the study list (the DRM paradigm; e.g., Deese, 1959; Roediger & McDermott, 1995). For example, Ratcliff and McKoon (1997) used forced-choice testing to explore the nature of long-term perceptual priming, and Huber et al. (2001) used forced-choice testing to explore the nature of short-term perceptual priming.

The vast majority of studies that measure the familiarity and recollection components of recognition used the remember/know procedure introduced by Tulving (1985). In contrast, the present study used a cued-recall procedure previously employed by Humphreys et al. (2003) and Mandler (1980). One potential problem with the traditional remember/know procedure is its subjectivity. More specifically, after participants receive instructions for labeling an item *remembered* or *known/familiar,* they must categorize a subjective feeling in light of these somewhat complicated instructions. However, subjective experiences may differ or correspond improperly to instructions. Furthermore, it is possible that many participants are uncertain how to categorize items as *remembered* or *known* even after reading the instructions. This could cause recollection to be contaminated by familiarity, or vice versa. Although the cued-recall procedure is likewise subject to contamination, the contamination will primarily occur in one direction—trials with cued-recall failure will reflect a mix of familiarity- and recollection-based recognition, whereas trials with cued-recall success are likely to be trials based purely on recollection. We note that this form of contamination actually works against the claim that priming preferentially affects familiarity-based recognition. Crucially, our Experiment 4 validated use of this procedure through one manipulation (delay) that preferentially affected recollection, while another manipulation (priming) preferentially affected familiarity.

Alternative Theoretical Accounts

It is important to consider possible alternative explanations of the transition from positive priming to negative priming in a recognition task. First, qualitatively similar results might arise from criterion shifts, or if participants deliberately required more or less familiarity to recognize an item as a function of the type of prime presented (Miller & Wolford, 1999). However, our use of forced-choice testing undermines this account because the decision is assumed to be based on a relative comparison between target and foil, rather than through a criterial response (this assumption of relative comparisons in forced-choice testing has recently been empirically validated in recognition memory by directly comparing yes/no and forced-choice results; Smith & Duncan, 2004).

Second, fluency-attribution theory (e.g., Jacoby, Kelley, & Dywan, 1989; Jacoby & Whitehouse, 1989) is similar to our account in proposing that perceptual fluency from brief prime presentations is misattributed to the test item, resulting in greater recognition. However, fluency-attribution theory is fundamentally different from our account by proposing that the change to negative priming for long duration primes is due to strategic discounting. On this account, when there is no confusion about the source of the target's fluency (e.g., such as with awareness of primes that are attentively processed), it is assumed that participants strategically discount fluency and shift their judgments against the primed items (Jacoby & Whitehouse, 1989). Casting doubt on the reliability of this discounting heuristic, Higham and Vokey (2000) found that in some circumstances, identifying the prime can actually induce a heuristic that boosts rather than lowers recognition for primed items. However, there are several features of the current research that are problematic for any sort of strategic recognition heuristic. First, in all our experiments, the primes were available to awareness even in the short prime duration condition, and trial by trial accuracy feedback was provided to make it clear that there could be no effective strategy that used prime identity. Despite using supraliminal primes, our studies obtained the same pattern of results as the subliminal/supraliminal study by Jacoby and Whitehouse (1989). Of course, it is possible that unattended supraliminal primes might function similarly to unconscious primes (Debner & Jacoby, 1994). Therefore, in Experiments 2–5 we increased the likelihood that participants attended to primes by introducing a verb task that was performed on some of the primes, with it not known in advance whether this task would be required. Finally, in order to make certain that participants were in fact aware and attending to short duration primes, we included a prime identification task in Experiment 2 as applied randomly to a subset of unknown trials, finding that participants correctly identified the primes in the 100-ms condition. It is possible that people adopted two different strategies; for 100-ms primes, even though they knew which choice was primed, they chose not to discount, but for long duration primes they elected to discount. However, such an explanation is not parsimonious (it requires participants adopting different strategies for every condition).

Third, the discrepancy-attribution theory (e.g., Whittlesea & Williams, 1998, 2001a, 2001b) is a general account including perceptual fluency, but also fluency through structural regularity, such as with false memory to orthographically regular nonwords (although see Cleary, Morris, & Langley, 2007, for a critique of this result). This theory states that a feeling of familiarity is experienced only when actual fluency is discrepant from expected fluency (e.g., seeing one's dentist in the subway, rather than in the dental office). In this theory, short duration primes enhance actual fluency but do not create an expectation of increased fluency. This unexpected fluency leads to a feeling of familiarity (and therefore greater recognition). On the other hand, long duration primes enhance actual fluency but also create an expectation of increased fluency, thereby eliminating the feeling of familiarity that would otherwise be caused by priming. Furthermore, long duration primes might generate an overly strong expectation of fluency. This would lead to relatively less familiarity, as compared with no priming, and, consequently, a recognition preference against the primed item. Thus, discrepancy-attribution theory also predicted that both positive priming following short duration primes as well as negative priming following long duration primes would correspond to changes in familiarity.

Despite the apparent similarity between these accounts, the discrepancy-attribution model differs from the pre-activation/habituation model by supposing that fluency is enhanced by presentation of both short and long duration primes, with expectation determining whether familiarity increases or decreases. In contrast, fluency is directly reduced in the pre-activation/habituation model. We note that the specific time course parameters in the currently reported pre-activation/habituation model were originally determined from perceptual identification experiments (Huber & O'Reilly, 2003). Furthermore, those experiments found reaction time reversals following long duration primes (Huber &

Cousineau, 2004). Because disfluency is caused by transient habituation, it should fade (i.e., hurt performance less) with even short delays. Consistent with this prediction, Bernstein (2005) found the Jacoby–Whitehouse pattern of results when primes immediately preceded test items, but these effects disappeared when a question was interposed between prime and test. Finally, providing psychophysiological evidence for a perceptual source to these effects, Huber, Tian, Curran, O'Reilly, and Woroch (in press) found that perceptual responses to a repeated target word varied as a function of prime duration (150 ms vs. 2,000 ms) as measured with early perceptual ERPs (change in N170 repetition effect) and MEG responses (change in M170 repetition effect). Furthermore, the same perceptual parameters and neural dynamics that were used in the current article also accounted for the millisecond by millisecond electrophysiological data.

Summary

The present research suggests that both increased recognition following short duration primes, as well as decreased recognition following long duration primes, arise naturally from the activation and subsequent habituation that occurs in perceptual responses. The pre-activation/habituation model provides a mechanistic account of these results and has implications for other areas of research where short versus excessive stimulus presentations result in differential effects.

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Appendix

Model Specification for the Simulation Study (Experiment 6)

This appendix briefly reports the activation equations and response rule used in the simulation study. These equations are the same as those used by Huber and O'Reilly (2003). For the neural network architecture seen in Figure 1, the representation of a word is activated regardless of when and where the word is presented, and so persistent activation from the primes boosts the response to primed targets or foils during testing. In this manner, the model suffers from source confusion in its attempt to identify words. Persistence is the direct byproduct of Equation A1, which integrates excitatory input over time. Activation of a simulated unit in the model is the result of membrane potential v. Equation A1 contains a leak current that gradually resets activation to the resting value in the absence of input, resulting in a lingering response.

$$\frac{\Delta v_i^n(t)}{S_n} = [1 - v_i^n(t)] \times \left\{ \sum_{\forall j} w_{ij} o_j^{n-1}(t) + F \times \sum_{\forall k} w_{ik} o_k^{n+1}(t) \right\} - v_i^n \times \left\{ L + I \times \sum_{\forall l} o_l^n(t) \right\}. \quad \text{(A1)}$$

Equation A1 specifies how much the membrane potential of unit i in layer n at time t changes $\Delta v_i^n(t)$ as a function of the bottom-up and top-down excitatory input found in the first set of brackets and inhibition and leak currents found in the second set of brackets. The rate of change is dictated by the integration constant for layer n (S_n). The first term within the first brackets sums bottom-up excitatory input between each sending unit j from the lower level $n - 1$ with output $o_j^{n-1}(t)$ and receiving unit i as scaled by the connection strength w_{ij}. The second term in the first brackets sums top-down excitatory input for each sending unit k. In addition, top-down support is scaled by the value F, which is less than 1.0. The second set of brackets includes a constant leak value L, and the summed output of every unit in layer n is scaled by the inhibition constant I, which is also less than 1.0. Inhibition acts as a shunt on total activation so that a layer of the network will be able to activate only a subset of the units (i.e., k-winner-take-all).

The membrane potential is the real-valued probability that the cell will spike at that particular moment in time, but the model does not actually implement spiking neurons. Therefore, each unit can be thought of as representing the summed activity of a large number of spiking cells with identical inputs and identical outputs. As with spiking neurons, there is a threshold of activation θ, which must be crossed before any activation can occur. Below this threshold, the spiking probability is 0.0, as implemented by Equation A2.

$$o(t) = [v(t) - \Theta] \times a(t); \text{ for } v(t) > \Theta$$
$$o(t) = 0; \text{ for } v(t) \leq \Theta. \quad \text{(A2)}$$

Besides persistence due to temporal integration, the other dynamic that is critical to these priming data is synaptic depression. Synaptic depression exists in most excitatory pyramidal cells in the cortex, resulting in less effective signaling across the synapse despite ongoing pre-synaptic spiking (e.g., Tsodyks & Markram, 1997). This is captured through the amplitude $a(t)$ for the magnitude of post-synaptic depolarization that occurs with each pre-synaptic action potential. Therefore, the output $o(t)$ for any synapse is the probability of a spike $[v(t) - \theta]$ multiplied by the dynamically varying amplitude as seen in Equation A2.

At the beginning of a trial, the amplitudes of all synapses start in their fully recharged state of 1.0, but then amplitude is diminished (i.e., the process of habituation) due to the various presentations within a trial, serving to dynamically reduce signaling between recently active units. This reduces the amount of prime persistence and additionally introduces reduced responsiveness (i.e., disfluency) when a word is repeated. Equation A3 specifies the manner in which amplitude $\Delta a_i^n(t)$ changes as a function of the ongoing output of the synapse $o_i^n(t)$, as scaled by a depletion parameter D, and a recovery parameter R.

$$\frac{\Delta a_i^n(t)}{S_n} = R \times [1 - a_i^n(t)] - D \times o_i^n(t). \quad \text{(A3)}$$

The depletion parameter is much larger than the recovery parameter, resulting in synapses that rapidly deplete but remain in a depleted state for a short period of time even after activation has subsided (i.e., latent depletion). Each layer of the model contains a speed of processing parameters S_n, specifying the integration time constant that applies to both Equations A1 and A3. Because lower level features (e.g., line segments) change more rapidly than higher level features (e.g., meaning), lower layers of the model are set to activate and depress more rapidly than are higher levels.

Huber and O'Reilly (2003) adopted a perceptual fluency choice rule in which the choice word achieving its peak value more quickly was chosen. With this "time to peak response" rule, lingering activation from a near threshold presentation provides a head start to a target word, thus supporting accurate responding even if the target is not explicitly identified. However, this fluency rule does not work as well for the familiarity layer, which runs more slowly (lexical semantic activation achieves peak activation in 100 to 200 ms, whereas familiarity takes 400 to 1,000 ms). Furthermore, there is evidence that episodic familiarity is a strength measure that can be dissociated from latency (Nobel & Shiffrin, 2001). In this model, a perceptual fluency head start from the perceptual layers results in greater peak familiarity because a pre-activated word can more readily inhibit the alternative choice. Therefore, rather than using a fluency choice rule, which was appropriate to perceptual identification, the choice rule is modified for recognition testing, resulting in Equation A4, in which O_T is the peak familiarity output achieved by the target and O_F is the peak familiarity output achieved by the foil, and N is the gain of the logistic, which is inversely related to the "noisiness" of the familiarity decision. This is the performance gain seen in Table 1.

$$p(c) = \frac{e^{N(O_T - O_F)}}{1 + e^{N(O_T - O_F)}}. \quad \text{(A4)}$$

All of the model parameters were set to previously published default values except for the connection strength between the

(*Appendix continues*)

lexical–semantic and familiarity layers for targets as well as *N*. These two parameters were optimized for each experiment, as seen in Table 1. In addition, the speed of integration for the familiarity layer (S_F) was set to .0046, and the connection strength between lexical–semantic and familiarity for foils was set to .5 for all five experiments (setting these parameters to the same values allowed comparison of the optimized parameters). The model contains "structural" parameters that represent settings common to any implementation of the model. These structural parameters are I = .30 (inhibition), F = .25 (strength of feedback), θ = .15 (activation threshold), and L = .15 (leak current). However, the rates of processing for each layer of the model as well as the rates of depletion and recovery are expected to differ with different stimuli and different modalities, and so Huber and O'Reilly (2003) allowed these parameters to vary in order to quantitatively capture data from various perceptual identification experiments. In particular, one of the previously modeled perceptual identification studies used the same words as the current recognition experiments. Therefore, this extension of the model to episodic familiarity used these same parameters, fixing them to the previously published values that best fit the perceptual priming data. These parameters are S_V = .054 (speed of visual layer), S_O = .046 (speed of orthographic layer), S_L = .015 (speed of lexical–semantic layer), D = .324 (strength of depletion), and R = .022 (strength of recovery).

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