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Sequential Effects in Lexical Decision: Tests of Compound-Cue Retrieval Theory

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According to compound-cue retrieval theories, responses in lexical decision are determined by a passive process that matches a compound of the items in short-term memory against all of the information in long-term memory. Because responses depend on other items in short-term memory in addition to the target item about which a lexical decision is required, compound-cue theories must predict sequential effects and priming effects. For example, a nonword preceding a target should slow responses to the target, and a prime word related to a target word can affect responses to the target even when another item intervenes between them. In this article, the results of 4 experiments are presented and sequential effects are shown to be in accord with compound-cue theory.

For the past 20 years, spreading activation has dominated cognitive psychology as the metaphor by which to understand the processes of retrieving information from memory. Spreading activation has enjoyed such overwhelming dominance that it is only recently that an alternative mechanism for retrieval processes, compound-cue theory, has been proposed. In this article, we review compound-cue theory and add the results of four experiments to the set of data that are consistent with the compound-cue view.

The general assumptions of spreading-activation theories (Anderson, 1983; Collins & Loftus, 1975) are widely known and often thought to be intuitively clear. In contrast, compound-cue theories are new (Dosher & Rosedale, 1989; McKoon & Ratcliff, 1992; Ratcliff & McKoon, 1988), and the alternatives they present to spreading activation are less fully appreciated. An important difference between the two kinds of theories lies in their assumptions about how information presented to the retrieval system focuses on some subset of information in long-term memory. Both kinds of models have been applied to explain data from a number of retrieval tasks, but in this article we are especially concerned with data from lexical decision, a task that requires a binary decision. For this task, spreading-activation theories propose that when an item is presented to the memory system, activation spreads from the representation of that item in long-term memory to other nearby concepts in long-term memory, increasing their activation and making them potentially available to subsequent processes. In contrast, in compound-cue theories, items presented to the retrieval system are assumed to join together in short-term memory to form compounds. A compound is matched against information in long-term memory by a global passive matching process, and the result of the matching process is a value of familiarity for the compound. In compound-cue theory, focusing is a consequence of the combination of items in short-term memory; whereas in spreading-activation theories, focusing is a consequence of activation spreading among items in long-term memory.

Both theories find supporting data in priming effects—the facilitation effects observed when presentation of one item, a prime, speeds up responses to a subsequent item, a target (cf. McKoon & Ratcliff, 1992; McNamara, 1992a, 1992b, 1994a, 1994b; McNamara & Altarriba, 1988; Ratcliff & McKoon, 1988, 1994). For spreading-activation theories, presentation of the prime increases the activation of a related concept, giving that concept an advantage if it is subsequently presented as a target. For compound-cue theories, the prime and target join together into a compound. The familiarity of the compound is high if the joint strengths of the matches of the prime and target against memory are high. For example, when compound-cue theory is implemented in the search of associated memory model (SAM; Gillund & Shiffrin, 1984), priming occurs when the strength value of the prime matched against some concept(s) in memory is high and the strength value of the target matched against the same concept(s) is also high. A simplified example of a memory structure for SAM is shown in Table 1. Each "cue" represents an item that could be presented to the system, and each "concept" is the representation of an item in long-term memory. The entries in the table show the strength of each cue to each concept. The strength of a cue to itself in memory is high (1.0), the strength of a cue to a strongly related concept in memory is also high (1.0), the strength of a cue to some unrelated concept (residual strength) is low (0.2), and the strength of a nonword to memory is lower (0.1). The overall familiarity of a compound is computed by multiplying together the strengths of each item in the compound to a concept in memory and summing over all concepts in memory. In the multiplication, the items in a compound are not weighted equally: In typical lexical decision experiments, the

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Table 1
The Retrieval Structure for the Search of Associative Memory (SAM) Model Used in Modeling Priming Effects

	Concept in memory									
Cue	1	2	3	4	5	6	7	8	9	10
1	1	1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
2	1	1	1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
3	0.2	1	1	1	0.2	0.2	0.2	0.2	0.2	0.2
4	0.2	0.2	1	1	1	0.2	0.2	0.2	0.2	0.2
5	0.2	0.2	0.2	1	1	1	0.2	0.2	0.2	0.2
6	0.2	0.2	0.2	0.2	1	1	1	0.2	0.2	0.2
7	0.2	0.2	0.2	0.2	0.2	1	1	1	0.2	0.2
8	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1	0.2
9	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1
10	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1
11	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
12	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Note. The strength of a cue to a related concept is assumed to be 1.0, residual strength is assumed to be 0.2, and the strength of a nonword is assumed to be 0.1. Cues 11 and 12 are nonwords. Familiarity for a compound of three cues is computed from F(Cue i, Cue j, Cue k) = $\Sigma_l S_{il}^{w1} S_{jl}^{w2} S_{kl}^{w3}$, where S_{il}^{w1} is the strength of Cue i to Concept l with Weight w1.

target is the item about which participants are making a decision and so it is weighted more heavily than the prime. For the pair *dog–cat,* the strength of the prime *dog* to *cat* in memory would be high, and the strength of the target *cat* to *cat* in memory would also be high; likewise, the strength of the prime *dog* to *dog* in memory would be high, and the strength of the target *cat* to *dog* in memory would be high; these strengths (plus many other strengths) would combine, with larger weight on the target than the prime, into a high value of familiarity for the pair leading to facilitation of the response to *cat.*

Because both spreading-activation and compound-cue theories claim to be able to account for priming effects for related prime–target pairs, further tests of the two theories are needed. One arena for such tests is provided by studies of the sequential effects of the various items that can precede a target. This arena encompasses all the effects on target response times of all the different kinds of sequences of items that could precede a target: related words, unrelated words, nonwords, neutral primes, and various combinations of all of these. Some examples of three-item sequences are shown in Table 2. Sequences are defined by three letters: R for a word that is related to another word in the triple, U for a word that is not related to any other word in the triple, and X for a nonword. For example, *lonk dog cat* would be represented by XRR.

Table 2
Sequential Priming Effects (in Milliseconds) From McNamara (1992b)

	Sequence					
Condition	URR	RUR	RRU	XUU	XRR	UUU
Priming	−28	−18	*ns*	31	*ns*	0

Note. U = unrelated word; R = related word; X = nonword; *ns* = nonsignificant effects. The baseline condition is UUU.

The only sequential effect that is predicted by spreading-activation theories is facilitation when a related word precedes a target. With nonword primes there should be no effect of the preceding nonword on response time to a target because there is no spreading-activation mechanism for such an effect. However, in compound-cue theory, the familiarity value that determines response time for a target is a function of the compound of items in short-term memory at the time the target is tested. Therefore, the response time on a target must be affected by the familiarity values of the immediately preceding items. An immediately preceding nonword would have to slow response times to the target because of the nonword's low strength as a cue to memory. Exactly how large different sequential effects should be depends on parameters of the compound-cue model. Compound-cue theory does not specify the number of items in a compound; this must be free to vary across experimental procedures that differ in such variables as the amount of time between the response to a target and presentation of the next item. Compound-cue theory also does not specify the weights given to each item in the compound except that they must decrease from target to farthest preceding item. However, once the number of items in a compound, the weights on each item, and the relative strengths of related, unrelated (residual), and nonword items are specified for a particular set of data, then the theory is completely constrained. All possible sequential effects—from each of the several items preceding the target, from words or nonwords, and from related or unrelated words—must be predicted from the same set of parameters. Thus, sequential effects provide an explicit test of compound-cue theory.

An example of the patterns of sequential effects that are found empirically is given in Table 2, which shows data from lexical-decision experiments by McNamara (1992b, Experiments 2 and 3). For each item in the experiments, participants were asked to decide whether it was a word. A 100-ms pause separated the response to one test item from presentation of the next test item. The baseline condition was a sequence of three unrelated words (UUU). The response time for the target (the third item in the three-item sequence) in the baseline condition was subtracted from response time for the target in each sequential condition to give the priming effects shown in the table (negative effects result from a speedup relative to baseline, and positive effects from a slow down).

In the RUR condition (e.g., *dog table cat*), there is a (significant) 18-ms priming effect. To account for this effect, compound-cue theory must assume that the short-term memory compound that was matched against long-term memory contained three items. Therefore, compound-cue theory would assume that the size of the compounds for all the other sequences in this experiment was also three items. Then, with some combination of weights on the three items in each compound (the same combination of weights for all sequences), compound-cue theory would have to predict the priming effects for all six conditions: both the facilitation effects when related words precede the target and the inhibition effects when nonwords precede the target. Later, in the General Discussion section, we show that compound-cue theory can do this.

In the conditions in which a word target is preceded by a nonword, response times on the target are slowed relative to baseline (e.g., in the XUU condition). To account for this, compound-cue theory simply assumes that exactly the same mechanism operates as with targets preceded by words; that is, total familiarity is calculated in the same way for both kinds of sequences. The only source of nonword inhibition is the low-strength values for nonwords. However, as mentioned above, spreading-activation theories have no mechanism to account for nonword inhibition. Instead, the inhibition must come from a different process than spreading activation. McNamara (1992a, 1992b, 1994a, 1994b) attributes nonword inhibition to some processes other than memory retrieval, processes he labels *sequential effects,* as they have been labeled previously in the literature (Falmagne, 1965; Laming, 1968, 1973; Remington, 1969). McNamara places explanation of these processes outside the domain of spreading-activation theory, leaving them to be explained by whatever response time model is appended to spreading-activation retrieval.

From this account of sequential effects, McNamara (1994a, 1994b) reasoned that if nonword inhibition in lexical decision is due to response processes and not to memory retrieval processes, then the inhibition should only be observed when a response is required to the nonword. If the nonword is presented as a prime to which no response is required—participants are asked only to read it—then the nonword inhibition effect should disappear. This prediction was supported by data from experiments by McNamara (1994a). Primes and targets were presented in pairs: a prime was displayed for 300 ms followed by a blank interval of 50 ms, and then a target was presented for a lexical-decision response. Under these conditions, response times for targets were not significantly slower when the prime was a nonword than when it was a word unrelated to the target. This result is a clear challenge to a compound-cue theory in which nonword effects are ascribed to retrieval processes.

To address this challenge, we conducted the first three experiments presented in this article. We believed that a nonword immediately preceding a word target should slow response times to the target, even when a response is not required to the nonword. The conditions of Experiments 1, 2, and 3 are shown in Table 3. Lexical-decision test items were presented in prime–target pairs; participants were asked only to read the prime item and not to make a response to it. A prime was a word related to the target word, a word unrelated to the target, a nonword, or the neutral word *ready.* In Experiment 1, the stimulus onset asynchrony (SOA) between onset of prime and onset of target was either 150 ms or 300 ms, with the 150-ms SOA used twice as often as the 300-ms SOA. We used the mixture of SOAs to keep participants from adopting a strategy particular to the slow 300-ms SOA. In Experiment 2, all pairs were presented with a 350-ms SOA to replicate the SOA conditions used by McNamara (1994a). In Experiments 1 and 2, the prime and target were presented in different locations on a PC screen; in Experiment 3, they were presented in the same location, again to replicate conditions used by McNamara (1994a). In all three experiments, we found a significant nonword inhibition effect.

For Experiments 1, 2, and 3, we were concerned with sequences of only two items: the prime and target. The procedure used in the experiments paired the prime and target by presenting a warning signal in advance of the prime and requiring a response only to the target. It is reasonable to think that the compounds formed in short-term memory would mirror the presentation procedure so that each compound would typically contain just two items. However, it might also be the case that the target of the previous pair sometimes entered the compound. For Experiments 1, 2, and 3, we held constant the relation between the preceding target and the prime–target pairs in which we were interested; the preceding target was always an unrelated word. In Experiment 4, we varied the relations between succeeding prime–target pairs to provide further tests of compound-cue theory.

Experiments 1, 2, and 3

Method

Participants. In Experiment 1, there were 48 participants that took part in the experiment for credit in an introductory psychology course.

Table 3
Reaction Times (RTs; in Milliseconds) and Error Rates (ERs; in %) From Experiments 1, 2, and 3

	Experiment 1				Experiment 2 (350-ms SOA)		Experiment 3 (350-ms SOA)	
	150-ms SOA		300-ms SOA					
Condition	RT	ER	RT	ER	RT	ER	RT	ER
Prime								
Related word	608	2	593	2	486	6	536	1
Neutral	632	3	599	3	533	7	574	3
Unrelated word	639	2	616	3	515	6	564	1
Nonword	649	4	647	6	551	8	616	3
Filler								
Word–word	609	3	592	2	556	6	590	2
Nonword–word	621	4	606	5	583	8	618	3
Neutral–word	609	3	590	2	552	6	598	2
Word–nonword	644	3	648	4	617	6	672	3
Neutral–nonword	631	2	631	4	611	6	663	4
Nonword–nonword	635	3	624	3	629	7	672	2

Note. SOA = stimulus onset asynchrony.

There were 12 participants from the same population in Experiment 2, and there were 12 participants who were paid for their participation in Experiment 3.

Materials. The materials for the experimental design consisted of 120 target words, a related word prime for each target word, and a nonword prime for each target word. For example, one target was *pepper;* its related prime was *salt,* and its nonword prime was *ment.* Some of the related prime–target pairs were those used by McNamara (1994a), and some were from McKoon and Ratcliff (1979). The nonword prime for a target always had the same number of letters and syllables as the word prime. There were also pools of 630 words and 540 pronounceable nonwords used as filler primes and targets.

Procedure. All stimuli were displayed on the screen of a PC, and responses were collected from the PC's keyboard. In each experiment, each prime–target pair was tested in the same manner.

For Experiment 1, each pair began with a warning signal (a row of dots) displayed on the PC screen for 200 ms. The signal was then erased, and the prime displayed in the same location as the signal had been. The prime remained on the screen for either a 150-ms SOA or a 300-ms SOA, depending on the experimental condition. After that, the prime was erased, and the target displayed on the line below where the prime had been. The target remained on the screen until the participant responded by pressing the *?/* key for a word response and the *Z* key for a nonword response. If the response was correct, then the warning signal for the next item was displayed. If the response was not correct, then an error message was displayed for 3.6 s before the next warning signal. A message to "press the space bar" to begin the next set of test items was displayed about every 30 test items to give participants short breaks.

Because we obtained a nonword inhibition effect in Experiment 1, we decided to repeat the experiment with the timing used by McNamara (1994a, Experiments 1 and 2) when he failed to find nonword inhibition to see if we could obtain inhibition by using his procedure. In Experiment 2, each prime–target pair began with a warning signal displayed for 350 ms, followed by a 500-ms blank interval. Then the prime was displayed for 300 ms, followed by a 50-ms blank interval, and then the target. If the response to the target was correct, the warning signal for the next pair was displayed after a blank interval of 2 s. If the response was incorrect, an error message was displayed for 1 s, followed by the 2-s blank interval. This is a much slower procedure than we used in Experiment 1, and we thought it might have contributed to McNamara's failure to obtain nonword inhibition. For Experiment 3, we repeated the experiment again with the prime and target displayed in the same location, the procedure that was used by McNamara (1994a).

Design. For Experiment 1, the four conditions in the experimental design, related word prime, neutral word prime, unrelated word prime, and nonword prime were each tested with 30 items: 20 with the 150-ms SOA and 10 with the 300-ms SOA. We used the 150 ms twice as often because we worried that participants might otherwise tend to ignore it. The neutral word was the word *ready.* The unrelated word prime for a target was randomly chosen from the related primes for other targets. The 120 targets were assigned to experimental condition by a Latin square design with sets of items crossed with sets of participants. There were also 270 filler words used as targets and 390 filler nonwords used as targets. For 150 of the word target fillers, the prime was an unrelated word; for 60 of them, it was a nonword; and for 60, it was the neutral prime. For 210 of the nonword targets, the prime was a word; for 90 it was a nonword; and for 90 it was the neutral prime. For all of the filler conditions, two thirds of the SOAs were 150 ms, and one third were 300 ms. The 120 items in the experimental design were always preceded by a test for which the target was a word; for approximately two thirds of the cases, the preceding target had a word prime, and the remaining cases were split about equally between nonword and neutral primes. Otherwise, the order of presentation of test items was random, with the randomization changed after every second participant. No word or nonword was displayed more than once in the experiment (except for the neutral prime *ready*).

The design of Experiment 2 was almost the same. The only differences were that all pairs were tested with the same SOA; to shorten the experiment, about one quarter of the total number of test pairs was randomly deleted; and the randomization of order of presentation of test items was changed after every participant instead of after every second participant. Experiment 3 was the same as Experiment 2, except for the change in display location of the target.

Results

For all the experiments, means for response times and error rates were calculated for each participant in each condition (with the slowest approximately 1% of the data excluded), and means of these means are displayed in the tables. Table 3 shows the data from Experiments 1, 2, and 3. For analyses of variance (ANOVAs), the significance level was set at .05 throughout this article, unless otherwise indicated. For each experiment, standard errors calculated from the ANOVA MSE term are reported as measures of variance.

For Experiment 1, the first result to note is that, as would be expected, a related prime facilitated response times to target words relative to an unrelated prime at both SOAs. Second, a nonword prime slowed responses to target words, as predicted by compound-cue theory. An ANOVA showed the main effects of priming condition and SOA significant, $F(3, 141) = 11.2$ and $F(1, 47) = 9.3$, respectively. The interaction of the two variables was not significant, $F(3, 141) = 1.5$. Planned tests showed target responses faster with the related prime than the unrelated prime, $F(1, 141) = 6.7$, and slower with the nonword prime than the unrelated word prime, $F(1, 141) = 3.9$, $p = .052$. The standard error of the means was 7 ms. The error data followed the response time data, with main effects of priming condition, $F(3, 141) = 4.6$, and SOA, $F(1, 47) = 14.1$. The standard error of the means for errors was 0.5%.

In Experiment 2, there was both a facilitation effect from related primes to their targets and a nonword inhibition effect (Table 3). Response times in the four priming conditions were significantly different, $F(3, 33) = 11.5$. Planned tests showed significant facilitation for related pairs, $F(1, 33) = 6.4$, and significant inhibition from nonword primes, $F(1, 33) = 9.9$ (in each case, a comparison was made against the unrelated word prime condition). The standard error of the response time means was 8 ms. There were no significant effects on error rates ($F < 1.0$).

Experiment 3 essentially replicated Experiment 2. Response times in the four conditions of the experimental design were significantly different, $F(3, 33) = 9.4$. Planned tests showed that facilitation for related pairs approached significance, $F(1, 11) = 4.5$, and significant nonword inhibition, $F(1, 11) = 16.6$. The standard error of the response time means was 9 ms. There were no significant effects on error rates ($F < 2.0$).

All three experiments showed the nonword inhibition effect in the experimental conditions. They also showed the effect in the filler conditions: Responses to a word were slower when it was preceded by a word than when it was preceded by a nonword. Across the three experiments, the nonword inhibition effect for the filler items was larger than the average standard error in the response times for those items, which was 6.1 ms. Nonword inhibition was also found in the filler conditions of experiments reported by McKoon and Ratcliff (1992).

Experiment 4

For Experiments 1, 2, and 3, our goal was to show a nonword inhibition effect for a single prime on a target. We designed Experiment 4 to examine longer sequences of related and unrelated words and the neutral prime *ready.* Items were presented in prime–target pairs, with a lexical-decision response required only for the target; in the experimental conditions, we manipulated sequences of one prime–target pair preceding another. There were five experimental conditions, shown in Table 4. Each condition is shown as two prime–target pairs, one preceding the other. The neutral prime *ready* is abbreviated by N, a word unrelated to the target of the second pair is abbreviated by U, and a word related to the target of the second pair is abbreviated by R. The prime for the first pair was always the neutral word. The pairs vary in whether the target of the first pair is related to the target of the second pair (as it is in the conditions NR–NR and NR–UR) and whether the prime of the second pair is related to its target (as it is in NU–RR).

The conditions of Experiment 4 were chosen to match the conditions of an earlier experiment for which the task was recognition instead of lexical decision (Ratcliff & McKoon, 1988, Experiment 2). We designed both the earlier experiment and this one to test compound-cue theory by examining its predictions about how items will join together to form compounds in short-term memory. The main prediction was that one word could "bump" another out of the compound. We assume that the neutral prime, because it was presented so frequently in the experiment and known to carry no information, is not included in the compound matched against long-term memory. So in any sequence for which the second prime is the neutral word, the first target can join with the second target in its compound. As a consequence, response time on the second target in the NR–NR sequence should be facilitated over response time on the second target in the NU–NR sequence. For example, response time for the target *cat* should be facilitated in the sequence *ready–dog ready–cat* relative to the sequence *ready–table ready–cat.* Given this facilitation, then we can go on to predict the bump-out effect: Replacing the neutral prime for the second target with a word unrelated to the target should bump the preceding target out of the compound. Response time on the second target should be no faster in the NR–UR condition than in the NU–UR condition. In other words, response time for the second target in the sequence *ready–dog table–cat* should be no faster than in the sequence *ready–lake table–cat* because in the first sequence *table* bumps *dog* out of the compound for *cat.* For these predictions, we have assumed that items farther back than one pair have weights so small that they do not affect the total familiarity so that only the one preceding pair can affect response times on a target.

The predictions just outlined hold for prime–target SOAs that are sufficiently long for a prime to be perceived and processed into a compound. However, a 50-ms SOA is too short for a prime to be processed sufficiently to enter the compound. This means that in all conditions with a 50-ms SOA, response time on a target should be determined not by its prime but by the preceding target. In other words, the bump-out effect should not be obtained at a 50-ms SOA. Unlike with longer SOAs, responses on the second target should be faster with the sequence NR–UR than with the sequence NU–UR.

All of these predictions were confirmed with recognition in the experiment reported by Ratcliff and McKoon (1988). In that experiment, participants studied lists of sentences. Test items were presented in prime–target pairs, and participants were asked to decide for each target whether it had appeared in the studied sentences. Two words were considered related if they came from the same sentence and unrelated if they came from different sentences. A target facilitated response time for a following related target at the 50-ms SOA no matter what the intervening prime was. However, at a 350-ms SOA, an unrelated prime bumped the preceding related target out of the compound so that it did not facilitate response times.

For lexical decision, McNamara (1994a) failed to confirm these predictions. However, given our success in finding the nonword inhibition effect in Experiments 1, 2, and 3, we designed Experiment 4 to look for the bump-out effect.

Table 4
Reaction Times (RTs; in Milliseconds) and Error Rates (ERs; in %) From Experiment 4

	50-ms SOA		150-ms SOA		350-ms SOA	
Condition	RT	ER	RT	ER	RT	ER
NU–RR	565	0.4	546	0.3	520	0.7
Ready–bond						
Salt–pepper						
NU–NR	563	0.0	554	1.1	530	0.4
Ready–bond						
Ready–pepper						
NU–UR	579	0.4	567	0.4	542	1.1
Ready–bond						
Loan–pepper						
NR–NR	552	0.4	537	0.7	503	1.4
Ready–salt						
Ready–pepper						
NR–UR	557	0.4	544	1.4	541	1.1
Ready–salt						
Loan–pepper						

Note. SOA = stimulus onset asynchrony; N = neutral word; U = unrelated word; R = related word.

Method

Participants. There were 48 participants who took part in the experiment for credit in an introductory psychology course.

Materials. The materials for the experimental design consisted of 144 sets of words. Each set contained a target word, a related word prime, and two other unrelated words. The unrelated words were selected to have the same number of letters, the same number of syllables, and the same frequency in English as the related word prime. For example, one set consisted of the target *pepper,* its related prime *salt,* and the two unrelated words *loan* and *bond.* There were also a pool of 580 nonwords, a pool of 600 words to be used as fillers, and a pool of 106 pairs of weakly related words to be used as fillers. For half of the participants there was also a pool of 1,000 low-frequency words used as fillers.

Procedure. All stimuli were displayed on a PC screen, and responses were collected from the PC's keyboard. Each prime–target pair was tested in the same manner. First, a warning signal (a row of dots) was displayed on the PC screen for 200 ms. The signal was then erased, and the prime displayed in the same location as the signal had been. The prime remained on the screen for a 50-ms SOA, a 150-ms SOA, or a 350-ms SOA, depending on the experimental condition. After that, the prime was erased, and the target displayed on the line below where the prime had been. The target remained on the screen until the participant responded by pressing the ?/ key for a word response and the *Z* key for a nonword response. If the response was correct, then the warning signal for the next item was displayed after a 50-ms pause. If the response was not correct, then an error message was displayed for 3.6 s before the next warning signal. A message to "press the space bar" to begin the next set of test items was displayed about every 30 test items to give participants short breaks. Participants were instructed to respond as quickly and as accurately as possible.

Design. The five conditions of the experimental design are presented in Table 4. Each condition was defined by two prime–target pairs that were sequentially presented. In the first condition, a related prime–target pair (RR) was preceded in the test list by a pair for which the prime was neutral (the word *ready*) and the target was one of the unrelated control words for the related target (NU). In the second condition, the related prime was replaced by the neutral prime (NU–NR); in the third condition, it was replaced by one of the unrelated control words (NU–UR). In the fourth condition, the targets of the two pairs were related, both with neutral primes (NR–NR); in the fifth condition, the second prime was one of the unrelated control words (NR–UR). The 144 sets of items were divided into six groups and assigned to the experimental conditions by a Latin square design (with six groups of participants) in which the first condition was represented twice to give it double the number of observations per participant. Half of the items in each condition were tested with the 150-ms SOA, one fourth with the 50-ms SOA, and one fourth with the 350-ms SOA.

For half of the participants, in addition to the 288 prime–target pairs of the experimental design, there were 336 filler pairs. For 48 of the fillers, the prime and target were unrelated words; for another 48, the prime and target were weakly related words (e.g., *savage–barbaric*). For 240 of the fillers, the target was a nonword: 120 had word primes and 120 had the neutral prime.

For the other half of the participants, the filler conditions were changed. We had thought that including low-frequency words in the experiment might lead participants to perform differently, although this turned out not to be the case. For 320 filler pairs, the prime and target were unrelated, and both were low-frequency words. For 106 filler pairs, the prime and target were weakly related. There were also 580 nonword targets, half primed with the neutral word and half primed with a low-frequency word.

For all of the fillers, the 150-ms SOA was chosen with probability 0.5, the 50 ms-SOA with probability 0.25, and the 350-ms SOA with probability 0.25. The order of presentation of test items was random, a new randomization for every second participant. No word or nonword was displayed more than once in the experiment (except for the neutral prime *ready*).

Results

Means of response times and error rates are displayed in Table 4. Means for the filler targets are shown in Tables 5 and 6. There was no significant difference between the two groups of participants, and there was no significant interaction between the groups and any experimental condition (all $Fs < 1$).

There are three main points to note about the data. First, at the 150- and 350-ms SOAs, a related prime facilitated response times to its target (comparing the NU–RR and NU–UR conditions); the amount of facilitation was 21 ms at the 150-ms SOA and 22-ms at the 350-ms SOA. Second, there was a large bump-out effect at the 350-ms SOA. When two related targets were separated by an unrelated word (NR–UR), response times were slower (541 ms) than when the two targets were separated only by the neutral prime (NR–NR, 503 ms). Third, at the shorter SOAs, it appears that response times to a target related to the previous target were facilitated no matter what the intervening prime was. In both the NR–UR and the NR–NR conditions, response times were shorter than in the control conditions, NU–UR and NU–NR.

An ANOVA confirmed these conclusions. Overall, the effects of the three SOA conditions and the five priming conditions on response times were significant, $F(2, 94) = 23.2$ and $F(4, 188) = 11.9$, respectively. Planned tests showed significant facilitation for a related prime to its target at both the 150-ms SOA and the 350-ms SOA conditions, $F(1, 376) = 6.0$ and $F(1, 376) = 6.6$, respectively. The bump-out effect at the 350-ms SOA was significant when comparing the NR–NR condition to the NR–UR condition, $F(1, 376) = 24.1$. It was also significant when the difference between NR–NR and NR–UR was compared with the difference between NU–NR and NU–UR, $F(1, 376) = 9.3$. Target-to-target facilitation was significant (averaging the NR–NR and NR–UR conditions against the NU–NR and NU–UR conditions at the 50-ms and 150-ms SOAs), $F(1, 376) = 4.4$. The standard error of the

Table 5
Reaction Times (RTs; in Milliseconds) and Error Rates (ERs; in %) for Participants With Low-Frequency Fillers

	50-ms SOA		150-ms SOA		350-ms SOA	
Condition	RT	ER	RT	ER	RT	ER
NU	651	2.4	633	2.0	607	1.4
UU	886	34.7	871	31.4	865	30.2
WR	649	2.5	610	1.4	574	0.5
NX	844	10.3	849	11.6	835	12.4
UX	840	10.3	859	10.5	893	13.9

Note. SOA = stimulus onset asynchrony; N = neutral word; U = unrelated word; WR = weakly related word; X = nonword.

Table 6
Reaction Times (RTs; in Milliseconds) and Error Rates (ERs; in %) for Participants With No Low-Frequency Fillers

	50-ms SOA		150-ms SOA		350-ms SOA	
Condition	RT	ER	RT	ER	RT	SOA
NU	642	4.1	612	3.7	589	1.8
UU	621	4.0	621	0.7	571	0.7
WR	642	3.5	607	2.7	580	1.5
NX	702	3.0	691	4.0	689	7.9
UX	726	4.7	708	4.9	699	6.6

Note. SOA = stimulus onset asynchrony; N = neutral word; U = unrelated word; WR = weakly related word; X = nonword.

mean for the response times was 6.0 ms. There were no significant effects on error rates (all $Fs < 1.9$).

General Discussion

In compound-cue theory, the familiarity that determines the response time for a target is a joint function of all the items in the compound in short-term memory at the time the target is tested. Compound-cue theory must, therefore, predict sequential effects on target response times. The goal of the experiments in this article was to match predictions of compound-cue theory against two simple sequential effects.

First, Experiments 1, 2, and 3 showed a nonword inhibition effect: The lexical-decision response time to a word was slowed if it was immediately preceded by a nonword relative to when it was immediately preceded by a word. This is consistent with compound-cue theory because the overall familiarity of a nonword–word combination should be less than the overall familiarity of a word–word combination. The familiarity should be less because the strength of any nonword is less than the strength of any word (as in Table 1).

Second, Experiment 4 showed a bump-out effect in lexical decision. When one prime–target pair immediately followed another prime–target pair and the two targets were related to each other, then one target primed the next if the intervening prime was the neutral prime, but not if the intervening prime was some unrelated word (if the SOA was long enough for the prime to be integrated into the compound). The assumption is that when the prime is neutral, it does not enter the compound formed in short-term memory, and the previous target can remain in the compound. However, when the prime is an unrelated word, it does enter the compound, bumping the previous target out of the compound. The bump-out effect in Experiment 4 conceptually replicates the bump-out effect obtained previously with recognition (Ratcliff & McKoon, 1988), as would be expected by compound theory's assumption that both tasks involve binary decisions that are based on the familiarity of compounds in short-term memory. Although compound-cue theory has not been applied to the task in which participants are asked simply to name a target word, Masson (1995) obtained a bump-out effect in that task, again replicating the effect obtained by Ratcliff and McKoon (1988).

McNamara (1994a) failed to find either of the two effects, nonword inhibition or bump out, and used the failures as the basis of claims that compound-cue theory failed to account for significant aspects of the data on sequential effects (1994a, 1994b). We cannot point to any single factor as responsible for the differences between our results and McNamara's. The probabilities with which various sequences of different kinds of test items appeared in our experiments are about the same as in his experiments. The variance in response times is about the same. The only differences that we can see are that our experiments collected more data per condition than McNamara's, and, possibly, that there are differences in the participant populations. In Experiments 2 and 3, we duplicated conditions in which McNamara failed to find nonword inhibition (a single slow SOA between prime and target and the same location on the display screen for both prime and target), but in neither case was the inhibition eliminated. Borowsky and Besner (1993) also failed to find nonword inhibition; one difference between their results and ours is that response times in their experiments were considerably slower than in our experiments.

The results of Experiments 1, 2, and 3 (as well as those of previously published experiments; see McKoon & Ratcliff, 1992; Ratcliff & McKoon, 1981, 1994) show that individual sequential effects are predicted by compound-cue theory. However, the question remains of whether compound-cue theory can account for all of the observed sequential effects simultaneously. Table 7 shows a number of effects from several different experiments. The priming effects in the first five columns come from data from experiments by McNamara (1992b), as discussed in the introduction. To these effects, we have added the nonword inhibition effect in the column headed UXU. In Experiment 1, the effect averaged 21 ms; in Experiment 2, the effect was 36 ms; and in Experiment 3, it was 52 ms. The average of these three numbers is 36 ms, the number entered in the table. Of course, averaging across these experiments and comparing across the different experiments in the different columns of Table 7 can only provide rough estimates of the sizes of the different effects. Yet McNamara (1992b) has used these estimates to argue that compound-cue theory cannot account for patterns of sequential effects. So, in response, as a demonstration that compound-cue theory can do this, we fit the compound-cue model as implemented in SAM (Gillund & Shiffrin, 1984) to the numbers in Table 7.

The model we used was the deterministic variant of the Gillund and Shiffrin (1984) model that has been used before to make predictions about priming effects (e.g., McNamara, 1992a; Ratcliff & McKoon, 1988). We implemented the model to search for the parameters that best fit the numbers in Table 7. There were three strength parameters: the strength of a word cue to a related concept in memory, the residual strength of a word cue to an unrelated concept in memory, and the residual strength of a nonword cue to a concept in memory (these values were set to 1.0, 0.2, and 0.1, respectively, in Table 1). Allowing these three parameters to vary freely, we found

Table 7
Sequential Priming Effects and the Search of Associative Memory Model

Condition	Sequence						
	URR	RUR	RRU	XUU	XRR	UUU	UXU
Priming in data (in ms)	−28	−18	*ns*	31	*ns*	0	36
Familiarity	5.45	5.27	4.91	4.28	4.83	4.86	4.08
Predicted priming (in ms)	−28	−20	−2	27	2	0	37

Note. U = unrelated word; R = related word; X = nonword; ms = milliseconds; *ns* = nonsignificant effects.

the best fitting solution with the parameter values of 1.72, 0.22, and 0.11, respectively. There were two parameters to specify the weights on the three cues in a compound (the three weights sum to 1, hence there were only two free parameters). These parameters were also allowed to vary freely, except that they must be ordered with most weight given to the target and least to the cue farthest from the target, and the obtained weights were 0.72 for the target, 0.16 for the cue immediately preceding the target, and 0.12 for the cue preceding that. The parameter to translate familiarity to reaction time, also allowed to vary freely, was 48 ms per unit of familiarity. Table 7 shows the familiarity values and the predicted priming effects that were obtained with the six parameters. The model fits the data with maximum discrepancy of only 4 ms between fit and data. The predictions are sufficiently good that we can reject McNamara's claim (1992b) that compound-cue theory is falsified because it cannot simultaneously account for all of these sequential effects.

In fitting SAM to the data in Table 7, the number of parameters is about the same as the number of data points. There are several points to make about this observation. First, there are constraints on the model beyond those of the individual data points. For example, if the weight on the prime is greater than the weight on the cue preceding the prime, then all conditions with a prime manipulation must have a larger effect than conditions with a manipulation of the cue preceding the prime. For example, URR must have a larger effect than RUR, and UXU must have a larger effect than XUU. The model would not be able to account for deviations from this pattern. Similarly, the XRR and URR conditions must be about the same amount faster than their respective baselines (XUU and UUU). To illustrate the constraints, we changed each one of the data points by 35 ms (one point at a time) and then tried to fit the model to the old data plus the one modified data point. In each case, the model missed the data in at least two conditions by over 10 ms, with only one exception (when the RRU condition was perturbed by 35 ms, that condition missed by 19 ms, and four other conditions missed by 5 ms or more). These simulations show that the model cannot fit arbitrary patterns of data. The model places constraints on the patterns of data that essentially reduce the number of degrees of freedom from what would be expected from the number of free parameters in the model. To fully constrain the model, systematic data need to be collected for all possible combinations of three cue sequences. In addition, the model could be further constrained by data for sequences in which the target was a nonword, and if variability were introduced into the strength matrix, then the model could be constrained by error data (at the expense of adding a mechanism that predicts both accuracy and reaction time).

As data and theory currently stand, we conclude that compound-cue theory is consistent with sequential effects in lexical decision. For the spreading-activation theory adaptive control of thought (ACT*), as well as earlier spreading-activation theories, there is no mechanism for differentiating nonword, neutral, and unrelated word primes—none of these can produce facilitation or inhibition on a target. Nonword inhibition would have to be modeled by assumptions about reaction time processes that occur subsequently to retrieval processes, that is, processes that are affected by switching from positive to negative responses. The bump-out effect causes serious problems for early spreading-activation models (Anderson, 1976; Collins & Loftus, 1975; Collins & Quillian, 1969) because it requires some mechanism to allow an intervening item to suppress activation spreading from one word to another related word. ACT* (Anderson, 1983), on the other hand, could be modified to accommodate the bump-out effect because it has a mechanism by which an intervening item can stop the spread of activation from one word, allowing activation on words related to it to decay. The bump-out effect was originally introduced as a test of compound-cue theory, and discussion of its implications for spreading-activation theories was elaborated in that context (Ratcliff & McKoon, 1988, p. 400).

Sequential effects provided one strong challenge to compound-cue theory. It has been argued that so-called "mediated" priming effects provide another. Spreading-activation theories postulate pathways in long-term memory that allow activation to spread from a prime through chains of mediators to a target, allowing the prime to facilitate the response to the target even though there is no direct connection between them. For compound-cue theories, the concept of distance along pathways is not meaningful. Priming effects occur because of strengths from cues in short-term memory to concepts in long-term memory. There are only direct strengths between an item in the short-term memory compound and itself in long-term memory and, in the Gillund and Shiffrin (1984) model, between an item in short-term memory and a directly related concept in long-term memory (see Table 1). A finding of facilitation effects for primes and targets connected only through longer pathways would be inconsistent with compound-cue theory.

The problem in testing for this inconsistency empirically is how to know for sure that there is no direct connection between a prime and target. McNamara (1992a, 1992b, 1994a, 1994b) has suggested the use of free association probabilities to represent network link strengths. Ratcliff and McKoon (1994) showed that this would not work because, for several sets of stimuli, the probabilities with which first associations are given to the stimuli vary widely while the amount of priming remains constant (see McKoon & Ratcliff, in press). Even if all of the associations to a given stimulus are used, not just the first, the probabilities do not predict amounts of priming correctly (so long as the probabilities of producing mediating chains for individual stimuli are computed before rather than after averaging across stimuli). Ratcliff and McKoon (1994) also formalized the use of free association probabilities by implementing them in a version of ACT* as measures of link strengths, but with this implementation ACT* could not correctly predict priming effects. McNamara (1994b) criticized the implementation because it did not incorporate a restriction from the original ACT* that relates link strengths to node strengths. The restriction would require that for any two items, A and B, there could never be one mediator X that was strongly linked to A and weakly linked to B and another mediator Y that was weakly linked to A and strongly linked to B. This restriction is implausible, and it is also violated by free association data. With the restriction relaxed, ACT* predicts large differences in priming where none exist.

Because free association production probabilities cannot be used to predict priming effects in ACT* (or in any simple spreading-activation model), they cannot be used to decide whether prime–target pairs are or are not directly connected, and, therefore, they cannot be used to test compound-cue theories. For compound-cue theories, priming effects might be predicted from other measures such as similarity, relatedness, or probability of cooccurrence (see McKoon & Ratcliff, 1992). Of course, free association production probabilities are useful in other ways (contrary to McNamara's, 1994b, p. 186, implication), certainly in developing experimental materials and also as interesting phenomena in their own right with a long and distinguished history of study.

In summary, compound-cue theory and spreading-activation theories are still both viable contenders to model the retrieval of information from long-term memory. Compound-cue theory provides global memory models (Gillund & Shiffrin, 1984; Hintzman, 1988; Murdock, 1982) with a mechanism with which to account for priming effects. Compound cues can be implemented either with localist models in which each item in memory is represented by a single node (Gillund & Shiffrin, 1984) or with distributed models in which an item is represented across nodes (Hintzman, 1988; Murdock, 1982). Moreover, the compound-cue mechanism is not in principle contradictory to the concept of "activation" in long-term memory. So long as the amount of match between the items in short-term memory and long-term memory is determined by the combination of the short-term memory items, a variety of different means of calculating the match could be implemented. For example, a compound-cue mechanism could be implemented with Dell's (1986) model for speech production, which is a localist connectionist model with each concept represented by a single node connected to other nodes with reverberating activation as its main processing mechanism (contrary to a statement by McNamara, 1994b). On the other hand, spreading-activation theories of retrieval are more limited: It is not possible to see how spreading activation's explanatory process of one concept activating another could be implemented in anything but a localist network representation of long-term memory; there is no obvious way to implement it in distributed models (in which each word is represented as a pattern of activation across common nodes) such as Seidenberg and McClelland's (1989) or Masson's (1995) or in feature models such as Smith, Shoben, and Rips (1974). However, despite the differences that separate compound-cue and spreading-activation theories, both accommodate the empirical data that are currently available. Recent debate has centered on the falsifiability of compound-cue theory; perhaps the next challenge is to find critical tests of spreading-activation theory.

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