Conditions of error priming in number-fact retrieval

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Analysis of errors in simple multiplication has shown that answers retrieved on previous trials are initially inhibited (*negative error priming*) but later are promoted as errors to subsequent problems (*positive error priming*). Two experiments investigated whether error priming is associated either with problem-specific retrieval processes or with representations of answers that can be manipulated independently of problems. In Experiment 1, answers were primed by visually presenting products for 200 msec prior to problems. Correct-answer primes facilitated retrieval, related-incorrect primes interfered with retrieval more than unrelated primes, and both effects were greater for more difficult problems. Primes affected only the trial on which they were presented, however, whereas both negative and positive error priming from previous problems were observed across trials. In Experiment 2, subjects named and retrieved multiplication products on alternating trials. Just-named products were inhibited as errors to the following multiplication problem (i.e., *negative error priming*), but, compared to positive priming from previous retrieved products, positive error priming from previously named numbers was weak. The results indicate that positive error priming is due mainly to an encoding or retrieval bias produced by previous problems, whereas negative error priming entails suppression, or de-selection, of answer representations.

This paper concerns error priming, the phenomenon whereby retrieval errors on simple multiplication problems (e.g., $3 \times 9 = 18$) are influenced by the events on preceding trials. Campbell and Clark (1989) showed that, relative to chance probabilities, the answer given one trial back has a low probability of matching an error response (*negative error priming*), whereas answers given 3 to 10 trials back show an increased probability of matching an error (*positive error priming*). Overall, 10% to 20% more errors were matched than would be expected by chance, and positive error priming had a measurable range of about 60 to 90 sec. Although Campbell and Clark were able to estimate the time course of the negative and positive components of error priming, little is known about the specific processes or factors that produce the effects. In this article, I report two experiments that were designed to delineate further the necessary conditions for error priming.

The *network-interference model* of simple multiplication (Campbell, 1987a, 1987b, 1990; Campbell & Clark, 1989; Campbell & Graham, 1985; Graham, 1987; Graham & Campbell, 1990) provides a theoretical framework for understanding error priming. The model assumes that peo-

ple acquire a densely interconnected network of visual and verbal associations among numerical operands, operations, and answers. When a familiar problem (e.g., 4×7) is initially presented, a set of potential responses is activated that includes both the correct answer and incorrect answers that are associated with features of the problem. In multiplication, for example, analyses of both children's and adults' errors suggest that the most strongly activated candidates are those related to the problem or correct product with respect to multiplicative associations (i.e., correct answers to other problems in the same times table), numerical magnitude, and perceptual or lexical features (Campbell & Graham, 1985; Graham, 1987; Miller, Perlmuter, & Keating, 1984; Siegler, 1988).

According to the model, retrieval of the correct answer is more difficult for problems that strongly activate multiple candidates than it is for problems that concentrate activation primarily in a single correct candidate. The finer associative discriminations required in the former case yield more errors and longer processing times (see Ashcraft, 1982, 1987; Campbell & Graham, 1985; Graham, 1987; Siegler, 1988; Siegler & Shrager, 1984, for discussions of factors influencing the acquisition of the retrieval structure for arithmetic facts). Even skilled adults produce errors under speed pressure, presumably because the discrimination threshold is set so low that the evidence or "resonance" (Zbrodoff & Logan, 1990) accumulated for an incorrect answer can temporarily exceed the evidence for the correct answer.

A fundamental assumption of the network-interference model is that problems that share surface features activate overlapping sets of answers. For example, 4×8 and

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4×6 share “4” and “×,” and, therefore, both problems activate answers from the four-times table. This assumption, that problems can activate intersecting retrieval structures, implies that retrieving (and thereby activating) an answer by way of one problem can temporarily facilitate or interfere with retrieval performance on other problems; several studies have provided evidence in support of this view (Campbell, 1987a, in press; Campbell & Clark, 1989).

Whereas the network-interference model was developed to account specifically for phenomena of mental arithmetic, Graham and Campbell (1990) demonstrated that many of the same retrieval phenomena are observed with nonnumerical stimuli that simulate the combinatorial structure of arithmetic (i.e., stimuli composed of combinations of elements that occur in multiple items). Thus, the model and associated findings are not intrinsically tied to the numerical domain and, indeed, the assumptions of the model are in principle comparable to those presented in more general theories of associative memory (e.g., Anderson, 1983; MacKay, 1987b; Raaijmakers & Shiffrin, 1981). Given this, it is not surprising that several memory phenomena observed with nonarithmetic stimuli, such as retrieval priming effects (Pusen, Erickson, Hue, & Vyas, 1988; Roediger, Neely, & Blaxton, 1983), generation effects (Slamecka & Graf, 1978), and fan effects (Anderson, 1983; Pirolli & Anderson, 1985), have parallels in retrieval of arithmetic facts (e.g., Campbell, 1987b, in press; Crutcher & Healy, 1989; Gardiner & Rowley, 1984). Thus, although error priming has not been studied outside of the arithmetic domain, understanding the effect in the context of multiplication may well have implications for other paradigms of cognitive psychology.

Time Course of Error Priming

The assumptions that related problems activate overlapping regions of a common retrieval structure, and that there are residual effects of each retrieval episode, provide a basis for understanding how processing one problem can directly affect retrieval performance on a subsequent problem. Within the network-interference framework, Campbell and Clark (1989) proposed that positive and negative error priming result from two opposing factors: *excitatory* influences temporarily increase the accessibility of the retrieved answer and promote its subsequent reproduction by way of a related problem (positive error priming). At the same time, however, *inhibitory* influences counteract or suppress the accessibility of just-retrieved answers (negative error priming).

The pattern of error priming over time, with negative priming for just-retrieved answers, followed by positive priming from more remote trials, is assumed to reflect the relative strengths and decay rates of the two factors. The excitatory, positive factor is assumed to be maximal at the moment of retrieval and then to decay. The inhibitory factor is initially stronger than the excitatory factor and produces a net suppression of just-retrieved answers. The inhibitory influence decays more quickly than exci-

tation, however, and positive error priming emerges when the residual excitatory effect exceeds the more quickly decaying inhibitory effect. On the basis of Campbell and Clark's analysis, the two factors are in equilibrium after approximately one to two minutes, at which time the probability that an error matches a previously given answer returns to chance levels.

Greater initial strength and faster decay for the inhibitory effect may represent an optimal balance between the benefits of enhanced access to recently activated processes as opposed to the benefits of inhibiting potential interference from those processes. Strong initial inhibition prevents the most recent response from dominating subsequent processing (e.g., MacKay, 1987a). Rapid decay of inhibition, however, permits the system subsequently to exploit increased accessibility caused by residual excitation, perhaps as “cache memory” in computers exploits the principle that recently accessed information has a relatively high probability of being retrieved again. The cost of this enhanced access is weak interference from previous processing (e.g., positive error priming).

Encoding-Based versus Answer-Based Explanations of Error Priming

Although Campbell and Clark's (1989) analysis supports a role for both excitatory and inhibitory factors in error priming, their experiment did not elucidate the necessary conditions for error priming. The present experiments investigated two possible sources of error-priming phenomena. The effects could originate in problem encoding processes, where encoding refers to the collection of associative connections through which a problem activates potential answers. Campbell and Graham (1985; see also Siegler, 1988) observed that most multiplication errors are products that are multiplicatively related to one of the operands (table-related errors; e.g., $4 \times 9 = 32$); consequently, when an error matches a previously retrieved product (i.e., $4 \times 8 = 32$), the two problems usually have common stimulus components (i.e., 4 and $\times$). With respect to the network-interference model, the two problems overlap in the associative structures they activate. Positive error priming may occur when the encoding structures activated by the current problem overlap with the residual activation of previous encoding operations. This partial reactivation of recent encoding processes may cause the entire previous retrieval operation to be reinstantiated, with the result that a recently generated response is generated again. Although it seems less plausible that negative error priming is associated with an encoding bias, it remains possible that the effect originates in the temporary fatiguing or suppression of problem encoding processes.

Instead of error priming originating in problem-specific encoding or retrieval processes, the effects could be tied to answer representations that can be manipulated independently of problems. Retrieving and stating an answer activate verbal and possibly visual forms of the answer in working memory, and residual activation of these repre-

sentations could explain positive error priming. The positive effect may be caused when the current problem provides additional activation to an answer that is already active in working memory. Similarly, negative error priming would arise if subjects were able to temporarily suppress or otherwise "de-select" recently generated answers. For example, subjects may be able to inhibit an answer by tagging it as "used" and avoid reproducing it on subsequent trials. According to this account, mechanisms that directly affect the accessibility of answer representations determine the time course of error priming.

Overview of Experiments 1 and 2

These two hypotheses lead to different predictions: An account that localizes error-priming effects in encoding processes predicts that error priming should be observed only when previous answers have been retrieved by means of their corresponding problem. In contrast, if error priming requires only recent activation of answers, then error-priming effects may be observed when answers are activated by any means. To test these alternatives, the two experiments investigated whether or not visually presented number primes or numbers that are read aloud produce the same error-priming effects as does the performing of arithmetic problems. Experiment 1 examined numerical primes; Experiment 2 examined numbers read aloud. If error priming can be produced by encoding answers directly, then the error-priming effects observed by Campbell and Clark (1989) should be observed in connection with the primes in Experiment 1 and the named numbers in Experiment 2. If error priming depends upon retrieving previous answers by way of problems, then visual primes and named numbers ought not to produce error priming.

EXPERIMENT 1

In this experiment, multiplication problems were preceded by numerical primes for 200 msec, and the primes provided the means for testing whether direct presentation of answers is sufficient to produce error-priming effects across trials. In a similar study, Campbell (1987b, Experiment 2) showed that correct-answer primes reduced both response time and errors relative to a neutral, non-numerical prime, whereas incorrect primes increased response time and errors. These results confirm that direct presentation of answers has at least a short-term effect on multiplication performance. Thus, it is possible that visual primes may also be sufficient to produce longer lasting error-priming effects.

Priming of Related versus Unrelated Answers

Experiment 1 also constituted a replication of the priming manipulations tested by Campbell (1987b, Experiment 2). A replication is important because of a confounding of factors in the original study. A central hypothesis for that experiment concerned whether or not a false prime that is multiplicatively related to the upcoming problem interferes with retrieval more than an unrelated prime.

Such a finding would be generally consistent with the network-interference model, because the model implies that increasing the accessibility of a strongly related, incorrect answer should reduce the accessibility of the correct answer (Campbell, 1987a, in press; see Pusey et al., 1988, for a comparable explanation of negative effects of priming from category members using verbal materials).

Although Campbell (1987b, Experiment 2) found that RTs were longer and accuracy lower for the "related" than for the "unrelated" condition, subsequent examination of the false primes showed that the related/unrelated distinction was confounded with the odd/even agreement of primes and correct products. In particular, a higher percentage of related primes than unrelated primes were in agreement with the odd/even status of the correct answer. Krueger (1986; see also Krueger & Hallford, 1984) has shown, with the use of a verification task, that subjects are slower to reject false answers with the correct odd/even status, possibly because subjects use odd/even rules to check the plausibility of presented answers (e.g., if either multiplier is even, the correct product must be even). For the present experiment, a new set of false-answer primes was generated to avoid this confound.

Method

Subjects. Sixty-six university undergraduate students from the University of Western Ontario participated as part of a course requirement. The subjects' ages ranged from 18 to 27, and there were approximately equal numbers of males and females. All subjects reported normal or corrected-to-normal vision. One subject's data was lost because of equipment failure; the data for five other subjects were not included for analysis because RTs and error rates ($> 25\%$) indicated poor knowledge of the multiplication facts. Thus, the following analyses were based on a total of 60 subjects.

Apparatus and Stimuli. Stimuli were presented with a Commodore 128 microcomputer connected to a monitor that displayed green characters against a dark background. The characters were about 6 mm high $\times$ 4 mm wide. A lapel microphone connected through a relay switch to the computer controlled a software clock accurate to ± 1 msec.

The stimuli consisted of the multiplication problems and products in the range from $2 \times 2 = 4$ through $9 \times 9 = 81$. Zero-times and one-times multiplication problems were not tested, because these problems probably are solved by retrieval of rules (i.e., $N \times 0 = 0$, $N \times 1 = N$; e.g., Ashcraft, 1982; Baroody, 1985) as opposed to direct retrieval of an answer. When commuted pairs (e.g., 2×7 and 7×2) are treated as distinct combinations, there are 64 different problems in the range from 2×2 through 9×9 . When operand order is ignored, there are 36 problems, and Campbell (1987b) divided these into a set of 18 "easy" problems and 18 "difficult" problems by using the normative production data from adults presented by Campbell and Graham (1985, Appendix B). The 18 problems with the fastest mean RTs were the easy problems. Because of the positive relationship between problem magnitude and difficulty (e.g., Miller et al., 1984; Stazyk, Ashcraft, & Hamann, 1982), the easy set is largely composed of small-number problems, and the difficult set is largely composed of large-number problems. All "tie" problems, except 8×8 , also appear in the easy set.

Two false-answer primes were selected for each problem by using the table of frequencies of multiplication errors presented in Campbell and Graham (1985, Appendix B). About 80% of the errors observed by Campbell and Graham were *table-related* errors; that is, correct answers to a different problem in the same "times table"

(i.e., problems that share a common multiplier). One false answer assigned to each problem was a table-related product that occurred with relatively high frequency as an error to that problem (*related primes*). The other false answer was a table-unrelated product that occurred with low frequency as an error response (*unrelated primes*). The odd/even agreement between primes and a problem's correct answer was balanced across false-prime type and problem difficulty. The easy and difficult problem sets and the false answers assigned to each problem are listed in the Appendix.

Design and Procedure. The design and procedure were the same as Campbell (1987b, Experiment 2), except that (1) the prime duration used in the present study was 200 msec, in contrast with the 300-msec duration used by Campbell (1987b), and (2) prior to priming trials, subjects received two practice blocks of multiplication trials involving the problems from 2×2 through 9×9 as a warm-up.

During priming trials, each subject was tested on all 36 problems in each of four blocks. Each problem was tested under one of four priming conditions in each block. In one condition, the correct product served as the prime. A prime composed of two adjacent number signs (##) constituted the neutral condition. The related and unrelated false primes constituted the other two conditions. There were nine trials involving each prime type in each block. Thirty-six orders of the four prime conditions were constructed, and, for each subject, problems were assigned randomly to an order of conditions across blocks. Thus, the testing of any particular easy or difficult problem in any prime condition was random with respect to block. The 36 orders included the 24 permutations of the four conditions. The remaining 12 orders were selected such that, among them, all pairwise orders of conditions occurred equally often. For each subject, the order of problems in each block was independently randomized. Approximately half of the "nontie" problems (problems in which multipliers are not the same) were randomly assigned so that the numerically smaller multiplier appeared on the left in the first block. Operand order then alternated across blocks.

Instructions to subjects described the range of problems that would be encountered and stressed the importance of both speed and accuracy. Subjects were informed that, before each problem appeared, either a numerical or nonnumerical stimulus would flash briefly on the screen at the fixation point. They were also told that sometimes a numerical stimulus would be the correct answer to the upcoming problem, but that this occurred at random and could not be used to predict the problem. Subjects were told that, although it was important to focus on the fixation dot at the beginning of each trial, their only responsibility was to provide the answer to each problem.

On each trial, a fixation dot appeared at the center of the screen and flashed twice over a 1.5-sec interval. The prime appeared as the third flash, with the rightmost character at fixation. The prime remained on the screen for 200 msec, after which a problem appeared immediately, with the multiplication sign at fixation. Problems were presented horizontally at the center of the screen in a five-character field; the two multipliers were separated by an uppercase "X" with adjacent blank characters. Provided that the experimenter entered the given answer within 3 sec, the interval from the response on one trial to the presentation of the stimulus on the next was 4.5 sec. RTs were measured to ± 1 msec from the onset of the problem until a verbal response triggered the voice key. Testing each subject required about 40 min.

Results

The results are presented in two sections. The first section examines *intratrial* effects of primes on RT and errors, with separate treatment of correct versus neutral primes and related versus unrelated primes. The second section reports analyses of *intertrial* error-priming effects to determine whether or not the primes and previously retrieved products produced comparable error priming.

Intratrial effects of primes. RTs were spoiled by failures of the voice key on 1.4% of trials, and the 2.6% of RTs that were more than 2.5 standard deviations from a subject's mean in each prime $\times$ difficulty condition were discarded as outliers. Problem-wise deletion of missing cases ensured that, across prime conditions, a subject's cell means were based on a common set of problems. Figure 1 presents the mean RTs and error rates (*PE*) for the easy and difficult problems in each of the four prime conditions.

Correct versus neutral primes. A 2×2 repeated-measures analysis of variance (ANOVA) of RTs and errors, which included only the correct and neutral conditions, replicated the results of Campbell (1987b).¹ The effects of difficulty [$F(1,59) = 99.68$, $MS_e = 12,763.8$, for RT; $F(1,59) = 83.18$, $MS_e = 33.9$, for *PE*] and prime type [$F(1,59) = 44.97$, $MS_e = 4,317.0$, for RT; $F(1,59) = 22.91$, $MS_e = 27.51$, for *PE*] were significant, as was their interaction [$F(1,59) = 6.61$, $MS_e = 3,099.4$, $p = .013$, for RT; $F(1,59) = 29.67$, $MS_e = 17.8$, for *PE*]. Specifically, the facilitation caused by a correct prime was greater for more difficult problems (-75 msec, -6.2 *PE*) than it was for easier problems (-38 msec, -0.3 *PE*).

Related versus unrelated primes. A parallel analysis of the related and unrelated conditions showed that table-related primes produced slower RTs [$F(1,59) = 12.96$, $MS_e = 3,325.2$] and more errors [$F(1,59) = 15.45$, $MS_e = 68.9$], relative to the unrelated prime. Thus, the current experiment confirmed Campbell's (1987b, Experiment 2) observations. Relative to unrelated primes, related primes produced more interference for difficult problems than for easier problems [$F(1,59) = 9.58$, $MS_e = 40.6$, $p < .005$, for *PE*; $F(1,59) = 3.73$, $MS_e = 5,088.2$, $p = .058$, for RTs; see Koshmider & Ashcraft, in press, for a comparable effect with the use of a verification task]. The prime type $\times$ difficulty interaction was also obtained in a separate analysis of the related- and neutral-prime conditions [$F(1,59) = 6.07$, $MS_e = 3,605.8$, $p < .025$, for RTs; $F(1,59) = 15.35$, $MS_e = 35.4$, for errors].

The finding that related primes produced greater interference than did unrelated primes implies that the primes affected associative processes intrinsic to the retrieval of multiplication answers. Therefore, it cannot be argued that the answer representations accessed by way of the primes are incapable of influencing the retrieval of multiplication facts. The relatedness effects of primes thus affirm the use of visual primes as a control condition for distinguishing answer-based, as opposed to encoding-based, explanations of error priming. Indeed, analyses of specific errors indicated that the false primes produced at least a short-term (intratrial) form of positive error priming.

Intratrial priming of specific errors. Table 1 presents the frequencies with which the related and unrelated primes assigned to each problem were stated as errors to those problems in each of the four conditions. The neutral-prime condition provided an estimate of base-rate frequencies in the absence of priming: The answer used as the related prime for problems accounted for 26% of errors in the

Figure 1. Mean correct response time (RT) and error rate (PE) as a function of prime type and relative problem difficulty.

Table 1
Frequencies of the Related and Unrelated Primes as Error Responses

Prime Condition	Error Classification		
	Related Prime	Unrelated Prime	Others
Correct	21	1	44
Neutral	35	0	101
Unrelated	36	20	116
Related	160	1	103

Note—Related Prime; Unrelated Prime = the erroneous answer was the related or unrelated prime assigned to each problem (see the Appendix). Others = errors other than the answers used as primes.

neutral condition, whereas the answer used as the unrelated prime never appeared as an error to the corresponding problems on neutral-prime trials. In contrast, in the related-prime condition, 61% of the errors were the presented prime and 0.3% were the unrelated prime. In the unrelated condition, 21% of the errors were the answer used as the related prime and 12% were the unrelated prime.

This pattern shows that the higher frequency of errors in the related- and unrelated-prime conditions, relative to the neutral condition, was largely due to errors made by stating the presented prime. Thus, visual presentation of answers produced an intratrial form of positive error priming. This confirms that the primes were capable of influencing specific multiplication errors. Therefore, an absence of intertrial effects of primes on errors cannot be attributed to the answer representations activated by primes' being independent of multiplication retrieval processes. The following analyses addressed whether or not the primes also produced intertrial error-priming effects comparable to those observed by Campbell and Clark (1989).

Intertrial priming of specific errors. To examine the influence of primes across trials, and to examine the effects of previous problems on specific errors, a lag analysis of errors was performed by using the method developed by Campbell and Clark (1989). A computer program located "tabled" errors (i.e., errors where the stated answer was a correct product to other problems tested; 93%

were tabled in the present experiment) and then searched back through earlier trials. The program attempted to match each error with either the correct answer to previous problems or to the false primes presented on past trials within each block. Matches when the prime was also the correct answer were not counted, because the possible effects of the prime would be confounded with the effects of retrieval of the same answer.

Table 2 presents the observed and expected percentages of tabled errors matched over lag ranges of 1–10 trials, 11–20 trials, 21–30 trials, and at all lags (i.e., 1–35 trials). Estimates of expected matching rates were obtained by randomizing the order of nonerror trials in each block and redoing the lag analyses on the random arrangements of products and primes relative to the positions of errors. The absolute positions of errors were not altered so that the number of matching opportunities at each lag would be the same as in the original data.² Table 2 presents, for each lag range, the expected percentage of errors matched and the standard error based on 50 randomizations for each match type (i.e., previous correct-product and previous false-prime matches).³

For previous correct-product matches, the +4.8% mean deviation above chance was significant ($z = 3.4$, $p < .001$), confirming a positive, intertrial error-priming effect. The effect was concentrated in the lag range from 1 to 10 (+7.2% deviation from chance, $z = 4.5$) but was lower in magnitude than were the +10% to +20% effects reported by Campbell and Clark (1989) for the same 4.5-sec response-stimulus interval. There was no evidence of an effect over larger lags. For 83% (345/415) of the previous correct-product matches, the problem that generated the error and the problem associated with the matched product shared a common operand.

The analysis of previous false-prime matches, however, provided no evidence that the primes exerted a comparable influence on errors across trials: Neither the overall deviation of +1.4% ($z = 1.21$, $p > .10$, one-tailed), nor the +1.0% ($z = .83$, $p > .10$, one-tailed) difference over lags 1–10 was significant.

Table 2
Observed and Expected Percentages of Multiplication Errors Matched in Experiment 1

Match Type	Lag Range in Trials							
	1–10		11–20		21–30		1–35	
	PE	SE	PE	SE	PE	SE	PE	SE
Previous Correct								
Product								
Observed	35.3		16.0		7.1		59.1	
Expected	28.1	1.6	17.5	1.7	7.5	0.9	54.3	1.4
Difference	+7.2		–0.5		–0.4		+4.8	
Previous False								
Prime								
Observed	12.4		7.1		3.3		23.3	
Expected	11.4	1.2	7.0	0.9	3.1	0.6	21.9	1.2
Difference	+1.0		+0.1		+0.2		+1.4	

Note—PE = observed and mean expected percentage of errors matched within the specified lag range. SE = standard error.

Lag-by-lag analysis. Whereas the foregoing type of analysis is sensitive to positive error priming, assessment of negative error priming, which is measurable only over a lag of one or two trials (Campbell, in press; Campbell & Clark, 1989), requires a lag-by-lag analysis. Furthermore, evidence of positive error priming from previous false primes also could emerge in a more fine-grained analysis. Therefore, more detailed analyses of lags 1-10 were performed. For each subject, the error-matching rates for previous correct products and previous false primes at each lag were computed. The matching rates were calculated as the number of correct-product or false-prime matches at a specific lag taken as a percentage of the number of matching opportunities for that lag. Figure 2 presents the mean observed matching rate at each lag for previous correct products and for previous false primes. The random analyses described earlier were used to obtain expected matching rates and standard errors for each lag. The expected error-matching rates are approximately constant across lags. For multiplication trials, the average expected rate was 3.46% across lags, whereas the average expected matching rate was 1.44% for primes. The expected rates are represented in Figure 2 by straight lines corresponding to these values.

One important result illustrated in Figure 2 is the replication of negative error priming observed by Campbell

and Clark (1989): The rate at which errors matched the previous correct product at a lag of one trial was 0.97%, significantly below the expected rate ($z = -3.1$, $SE = .81$, $p = .001$). The low rate of lag-of-one matches is evidence that subjects temporarily inhibit or de-select just-retrieved answers. The frequency of correct-product matches at lag of one was uniformly low across blocks (2, 1, 2, and 2 lag-of-one error matches in Blocks 1 through 4, respectively, as opposed to about 5 per block expected by chance). Thus, negative error priming associated with previous correct products appeared to be present from the outset of testing.

Positive error priming due to previous correct products was numerically largest at a lag of four trials, with a matching rate of +6.25%, about twice the rate expected by chance ($z = +2.50$, $p = .012$). The pattern of correct-product matches across lags was irregular, however, with the point at lag of five appearing at chance and the correct-product matching rate at lags of seven and ten trials apparently above chance ($z = +2.28$ and $+2.17$, respectively). This variability probably reflects the influence of the primes. The false prime presented on the same trial accounted for many of the errors, and the correct prime sharply reduced errors. These strong intratrial priming effects would tend to mask the influence of intertrial effects on errors. Although the variability makes it diffi-

Figure 2. Observed and expected rates (%) of errors matching previous multiplication products and false primes as a function of lag in trials.

cult to assess where the error-priming curve returns to chance, positive priming over 10 trials (about 1 min) is within the range estimated by Campbell and Clark (1989).

Figure 2 also shows that previous false primes exerted no measurable error-priming effect past the trial on which they were presented, with respect neither to positive nor to inhibitory effects on errors (largest z for deviations from expected matching rate at any lag was 1.5, $p > .10$).

Discussion

Visually presented number primes had strong intratrial effects on multiplication but produced no effects that were measurable across trials. Therefore, different mechanisms underlie the short-term effects of visual primes and longer term error priming from previous correct products.

One possible source of intratrial effects is that presentation of primes promotes a recognition strategy in which the familiarity of the prime-problem combination is assessed and the prime stated, if the familiarity is sufficiently high (Roediger et al., 1983; Zbrodoff & Logan, 1990). According to this account, related primes produced longer RTs and more errors than did unrelated primes, because the related primes were correctly associated with one of the problem's multipliers in the context of another problem. This partial match would produce relatively high familiarity and make the related primes more difficult to reject as irrelevant. Retrieval for some of the easier problems may be relatively automatic, however (Koshmider & Ashcraft, in press; Lefevre, Bisanz, & Mrkonjic, 1988; Zbrodoff & Logan, 1986), and generation of the correct answer for easier problems would be at least as quick and accurate as judging the familiarity of the prime-problem combination. In this case, prime-problem familiarity would play a smaller role for the set of easy problems, resulting in the observed interactions with problem difficulty.

Numerical primes could also involve more automatic processes. According to the network-interference model, if the answer representations (e.g., lexical codes) activated by primes are the same representations assumed to compete in the multiplication retrieval process, then the primes directly affect retrieval by temporarily altering the distribution of activation among candidate answers. Preactivation of an answer facilitates performance when that answer is correct but interferes with correct retrieval when it is false. The greater interference from priming tabled-related answers would occur because those answers are also directly primed by the following problem. The combined prime-based and problem-based activation could amplify interference, possibly because such effects combine multiplicatively (Campbell, 1987a). The finding that performance on difficult problems was more disrupted by related primes than was performance on easier problems supports the assumption (Campbell & Graham, 1985; Graham & Campbell, 1990; Siegler, 1988) that retrieval difficulty in mental arithmetic is associated with susceptibility to interference from related answers.

Despite the strong intratrial effects of visual primes, error-priming effects across trials were associated only with previous correct products. Specifically, the correct product to the immediately preceding multiplication problem was inhibited as an error response (negative error priming), but the correct answers to more remote problems, out to a range of approximately 10 trials (about 1 min), were promoted as errors (positive error priming). The results of Experiment 1 confirm that these effects do not occur when answers are activated by any means. Given that visual presentation of numbers produced no measurable effects across trials, intertrial priming evidently originates either in residual effects associated with problem encoding or with processes required when numbers are named, as opposed to only viewed and not named. Experiment 2 introduced a number-naming condition to distinguish these possibilities.

EXPERIMENT 2

Although negative error priming was observed only as a function of previous correct products in Experiment 1, it remains possible that this effect is tied to inhibition of answer representations and does not depend on problem encoding per se. Negative priming could be caused by inhibition of answers but not be observed in association with the primes in Experiment 1, because the 200-msec prime duration was too fast for inhibitory processes to operate (see Neely, 1977). Indeed, it follows from the strong interference effects of primes that responses to the primes were not inhibited prior to problem presentation. In Experiment 2, subjects received multiplication problems, alternated with naming trials, on which they were required to read multiplication products aloud. The interval between naming and multiplication trials was about 5 sec; thus, the lag between naming and multiplication was comparable to that at which negative error priming was observed as a function of previous correct products in Experiment 1.

The naming trials in Experiment 2 also permitted a further test of whether positive error priming is associated with problem-specific retrieval processes, or with representations of answers that can be manipulated independently of problems. Although it is probable that the visual primes in Experiment 1 activated verbal or lexical representations of answers, there was no way to directly determine this from the data. It remains possible, therefore, that longer range, positive priming effects may be induced when subjects read products aloud and that previous problem-based retrieval is not necessary.

Method

Subjects and Apparatus. Sixty-four subjects were tested. Most of the subjects were also tested in one or two other experiments during a session, but the multiplication task discussed here was usually performed first. All participants were recruited from the subject pool organized by the Department of Psychology, received a course credit for their participation, and reported normal or

corrected-to-normal vision. The subjects were in their late teens and twenties and there were approximately equal numbers of males and females. The apparatus was identical to that used for Experiment 1.

Stimuli and Design. Multiplication products and problems in the range from $2 \times 2 = 4$ through $9 \times 9 = 81$ were presented in blocks of 62 trials. Subjects named products aloud on odd-numbered trials and generated the answers to problems on even-numbered trials. The multiplication problems in the range from 2×2 through 9×9 involve 31 different products. Each block of trials included all 31 products for naming and 31 problems with different products. Five products are correct answers to more than one problem (i.e., 12, 16, 18, 24, and 36), and the five shared-product problems excluded in one block of trials were exchanged for their same-product counterparts in the subsequent block. Each subject received four blocks, with the problems tested in Blocks 1 and 2 repeated in Blocks 3 and 4. The order of problems and products was randomized for each block for each subject, with the constraint that a to-be-named product and its corresponding problem were separated by at least 20 trials. The order of operands for nontie problems was determined as in Experiment 1.

Procedure. The subjects, tested individually in a dimly lit room with the experimenter present, sat facing the monitor at a distance of about 60 cm. The subjects were told that they were being tested on speed of number naming and simple multiplication and were instructed to state the answer for each trial as quickly and accurately as possible. The subjects were warned that responding quickly would result in occasional errors and were encouraged not to feel upset by errors, because errors simply confirmed that they were responding as quickly as possible.

Blocks of trials were separated by a minimum of 10 sec. On each trial, a fixation dot appeared briefly at the center of the screen and flashed twice over a 1.5-sec interval. On naming trials, the to-be-named number appeared on what would have been the third flash, with the rightmost character at fixation, and remained on the screen until the subject responded. Similarly, for multiplication trials, the problem appeared on the third flash, with the " $\times$ " appearing at the fixation point, and remained on the screen until the subject responded. The display configuration for problems was the same as in Experiment 1. After each trial, the experimenter immediately entered the stated answer at the computer keyboard, after which the fixation dot for the next trial appeared. To prepare the subject for the upcoming trial, the prompt "NAME" or "MULTIPLY" appeared at the center of the screen while the experimenter was entering the response. As in Experiment 1, the response-stimulus interval was 4.5 sec.

Results

The observed and expected percentages of multiplication errors matched over lags of 1-10, 11-20, 20-30, and 1-30, for previous correct-product matches and previous named-number matches, are presented in Table 3. Standard errors were based on variance in the observed matching rates, and the expected values were derived from a binomial model. Specifically, the binomial probability of a tabled error being matched at any given trial position is given by 1 divided by the number of possible positions (31 for naming-trial matches, and 30 for multiplication matches; i.e., one multiplication position is occupied by the error trial). The expected proportion of errors matched for a subject over a given lag range is computed by summing the probabilities that each error is matched within that range and dividing by the number of errors that are matchable over that range (e.g., an error that occurs on Trial 10 cannot be matched at lags greater than 9).

Previous correct products matched multiplication errors at a rate higher than in Experiment 1 and more similar to previous results (i.e., Campbell & Clark, 1989): The mean percentage of correct-product matches was 13.9% higher than was expected by chance ($z = 6.9, p < .001$). The effect was concentrated over lags of 1-10, where the deviation was +16.1%. The slight deviation below the chance rate over lags of 21-30 (-1.9%, $z = -2.7, p < .01$) is probably an artifact of the strong error priming over shorter lags, which reduced the opportunity for distant primes to have an effect. In 84% of correct-product matches (406 of 485), the problem on the matching trial and the problem that generated the error shared a common multiplier.

In the analysis of previous named-number matches, there was no evidence of error priming at this grain of analysis, with the overall error-matching rate falling 2.6% below the expected rate ($z = -1.30, p > .10$).

Lag-by-lag analysis. A finer grain of analysis showed, however, that previously named numbers did have an effect on multiplication errors. Figure 3 presents the mean error-matching rate for each of lags 1 through 10 for

Table 3
Observed and Expected Percentages of Multiplication Errors Matched in Experiment 2

Match Type	Lag Range in Trials							
	1-10		11-20		21-30		1-30	
	PE	SE	PE	SE	PE	SE	PE	SE
Previous Correct								
Product								
Observed	43.9		16.2		3.8		63.9	
Expected	27.8	2.0	16.5	1.4	5.7	0.7	50.0	2.0
Difference	+16.1		-0.3		-1.9		+13.9	
Previous Named								
Number								
Observed	25.4		16.2		7.3		48.9	
Expected	27.9	1.7	17.1	1.6	6.5	1.0	51.5	2.0
Difference	-2.5		-0.9		+0.8		-2.6	

Note—PE = mean observed or expected percentage of errors matched within the specified lag range. SE = standard error.

previous correct-product matches (P-1, P-2, ..., P-10) and previous named-number matches (N-1, N-2, ..., N-10). The expected rate for named-number matches at each lag was 3.23% (1/31); for correct-product matches, the expected rate was 3.33% (1/30; the trial position containing the error must be excluded).

As illustrated in Figure 3, the error-matching rate for the number named immediately preceding the error (N-1) was significantly below chance (matching rate = 1.79%, $SE = .56$, $z = -2.58$, $p < .01$). The highest matching rate for named numbers, which was 4.90% at N-2, did not exceed the rate expected by chance ($SE = .97$, $z = 1.72$, $p < .05$, one-tailed), but this effect was weak compared with the magnitude of positive error priming from previous correct products (see below). Thus, whereas naming numbers produced, at most, only a weak effect of positive error priming, naming was associated with a negative error-priming effect comparable to that associated with correct products (see Campbell & Clark, 1989).

The lag-by-lag analysis of priming from previous correct products showed that both the magnitude and lag associated with the peak positive effect were similar to those observed by Campbell and Clark (1989). Positive error priming from correct products was strongest at a lag of P-3 (i.e., a lag of 6 responses, due to the interleaved naming trials; about 30 sec), with an observed matching rate

about three times greater than expected by chance (9.23%). The matching rate was slightly above chance for P-1 and increased over P-2 and P-3 before returning to chance after P-6 or P-7 (about 60 sec). Although there was no direct evidence of inhibition in the analysis of correct-product matches, the curvilinear shape of the error-priming function suggests the same counteracting inhibitory and excitatory factors proposed by Campbell and Clark.

GENERAL DISCUSSION

The results indicate that the positive and negative components of error priming involve different mechanisms: Retrieving a number by means of a multiplication problem can strongly prime specific errors on subsequent trials, whereas simply naming that number produces a much weaker positive error-priming effect. In contrast, processes engaged during or following both the multiplication and naming operations lead to a comparable short-term reduction in the probabilities of specific errors (i.e., negative error priming).

Positive Error Priming

Stronger positive error priming from previous correct products, relative to named numbers, suggests that the

Figure 3. Observed and expected rates (%) of errors matching previous multiplication products and named products as a function of lag.

positive effect is substantially due to an encoding or retrieval bias. This is consistent with the observation in both experiments that, for most error matches with previous correct products (about 83%), there also were matching problem components (i.e., the problem producing the error usually shared a multiplier with the problem on the matching trial). According to the encoding-bias account, positive error priming occurs when residual activation or strengthening of previous encoding operations interacts with encoding processes instantiated on a later trial. This occurs when two problems share stimulus features (e.g., a common multiplier) or when there is substantial overlap in the retrieval structures activated. The structural overlap causes processing on the later trial to retrace to completion the earlier sequence of retrieval operations.

Whereas the present experiments implicate problem-encoding or retrieval processes in positive error priming, there was evidence of a weak positive error-priming effect from previously named numbers in Experiment 2. Simply reading a product aloud does promote specific multiplication errors across trials, but this effect is much weaker and shorter lived than that produced when the product is retrieved from its corresponding problem. As there was no evidence that visual presentation without naming (i.e., the primes used in Experiment 1) produced intertrial priming effects, the finding of positive error priming from naming trials implies that actual production of the name is important for intertrial error priming. Visual presentation without naming is sufficient to induce positive error priming, however, when the interstimulus interval is very brief (e.g., 200 msec), as in Experiment 1. When skilled readers of Arabic numbers attend to one- or two-digit numbers, the name for the number is accessed easily. Thus, it is likely that the primes in Experiment 1 and the named products in Experiment 2 had similar consequences with respect to the internal representations that were activated. The different intertrial consequences of visual presentation and the naming of products, therefore, suggests that spoken production of the number name results in stronger, more enduring activation of answer representations.

The present findings strengthen the link suggested by Campbell and Clark (1989) between positive error priming and the *generation effect* observed in recall tasks. The generation effect occurs when producing to-be-remembered items from a cue or from partial information leads to superior recall performance compared with stimuli that are only read. The phenomenon is most often studied with word-based stimuli, but it is also obtained with multiplication problems and products (Crutcher & Healy, 1989; Gardiner & Rowley, 1984). Although positive error priming is an interference effect, it presumably arises from residual excitation that later promotes retrieval of specific items. As with generation effects, positive error priming is stronger when products are generated than when they are simply read.

Negative Error Priming

Experiment 1 confirmed negative priming between successive multiplication trials, but the results of Experiment 2, which showed that negative error priming also occurs following the simple naming of a number, indicates that the effect does not depend on previous encoding of problem operands. Because it is number-word production processes that number naming and multiplication share, the results imply that negative error priming occurs when subjects suppress or de-select answer representations or answer-production processes. Negative priming of answers may function to control intertrial interference when problems are tested one after the other. Consistent with this possibility, Campbell (1990) found that when related multiplication problems ("neighbors" in the same times table) were tested in succession (i.e., within the range of negative error priming), second-problem performance was facilitated compared with unrelated problems that occurred in succession. Thus, negative priming potentially reduces interference when related answers from recent trials may still be highly activated.

Negative error priming could be caused by several different types of inhibitory mechanisms (see Bjork, 1989, for a discussion of functions of inhibitory processes in retrieval). One possibility is that subjects can tag answers as "used" and avoid repeating recent responses (cf. Geiselman & Bagheri, 1985). This would be a good strategy in the present experiments, because the same correct answer usually did not repeat on successive trials. In Experiment 1, however, some correct answers did recur within each block of trials (e.g., 2×6 could follow 3×4), and there was frequent repetition of correct answers as primes. Thus, to explain the negative priming in Experiment 1, the tagging hypothesis must assume a rather sophisticated control process that can distinguish between traces of retrieved answers and primes, and that operates even when there is some probability that a just-used answer will be immediately required. Furthermore, negative priming appeared to be operating even in the first block of trials in Experiment 1, suggesting that the effect was present before subjects were sensitized to repetition frequencies. These considerations reduce the plausibility of an account that emphasizes intentional strategies.

Instead of intentional de-selection of recent answers, negative priming in arithmetic could also involve involuntary processes. For example, there is evidence of inhibition of distractor stimuli in selective-attention tasks (e.g., Tipper, MacQueen, & Brehaut, 1988), and automatic mechanisms for dampening activation have been proposed in models of associative memory (e.g., Anderson, 1983) and in general theories of cognitive skills (e.g., MacKay, 1987a). MacKay, for example, proposed that once the components of a skilled behavior have been activated, they automatically undergo a period of inhibition that prevents them from being reactivated and from interfering with ongoing performance. Such a mechanism would have clear

functional value in number-fact retrieval, where interference caused by the numerous associative interconnections among related problems and operations potentially could dominate retrieval performance.

CONCLUDING COMMENTS

The network-interference model has provided a useful general framework for understanding memory for multiplication facts, both with respect to the course of acquisition (Campbell, 1987c; Campbell & Graham, 1985; Graham, 1987) and with respect to effects of priming, repetition, and other experimental manipulations. Like other recent attempts to characterize number-fact representation, however (e.g., Ashcraft, 1987; Siegler & Shrager, 1984; Widaman, Geary, Cormier, & Little, 1989), the research has been focused on studying the organization of the memory structures (e.g., as "networks of answers" or "distributions of associations") and has largely ignored the nature of the representations the structures contain. This is not particularly surprising, because it has been possible to accommodate a large number of empirical findings without making any explicit assumptions about whether the underlying representations are visual, verbal, or more abstract in form. In contrast, parallel issues of representation have been central in other areas of cognitive psychology, notably in the areas of language and reading skills, where research has implicated a large number of specific codes (e.g., visuospatial, phonological, lexical, semantic, etc.). Pursuing the representational basis of cognitive arithmetic, and the excitatory and inhibitory mechanisms that mediate retrieval, may open the way for fruitful crosstalk between research areas that have been largely independent (Campbell & Clark, 1988; Clark & Campbell, 1990).

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NOTES

1. Type I error probabilities for *F* tests are less than .001, unless otherwise indicated.
2. The number of matching opportunities for a given lag is equal to subjects' total number of tabled errors, minus the number of errors that occurred on trials numbered less than or equal to the lag (e.g., an error that occurs on Trial 5 cannot be matched at a lag greater than 4). Note

that the expected percentage of errors matched will decrease for larger lags because of the corresponding decrease in matching opportunities as lag increases.

3. Campbell and Clark (1989) determined chance matching rates from a binomial model that assumed a single occurrence of each product as a correct answer in each block. In the present experiment, products and primes occurred with unequal frequency, and a simple binomial model does not apply.

APPENDIX

Easy and Difficult Problem Sets and the False Answers Assigned to Each Problem for Experiment 1

Easy Problem Set				Difficult Problem Set			
Problem	Cor	Rel	Unr	Problem	Cor	Rel	Unr
2×2	4	8	9	2×8	16	18	15
2×3	6	12	13	3×6	18	24	35
2×4	8	16	15	3×8	24	18	14
2×5	10	25	21	3×9	27	18	32
2×6	12	16	15	4×6	24	28	25
2×7	14	21	25	4×7	28	21	27
2×9	18	27	25	4×8	32	24	27
3×3	9	6	8	4×9	36	45	42
3×4	12	24	30	5×7	35	45	27
3×5	15	25	28	5×8	40	45	42
3×7	21	27	25	5×9	45	40	49
4×4	16	8	6	6×7	42	63	64
4×5	20	15	14	6×8	48	72	63
5×5	25	20	21	6×9	54	63	64
5×6	30	35	32	7×8	56	42	36
6×6	36	12	16	7×9	63	56	48
7×7	49	42	45	8×8	64	72	54
9×9	81	54	49	8×9	72	63	49

Note—Cor = correct answer; Rel = related false answer; Unr = unrelated false answer.

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