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Time Course of Error Priming in Number-Fact Retrieval: Evidence for Excitatory and Inhibitory Mechanisms

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Error priming in simple multiplication refers to the finding that retrieval of a product via one problem can increase the probability that the product is stated on a later trial as an error response to another problem. To analyze the magnitude and time course of the error-priming effect, the observed frequencies with which errors matched previously generated answers at different lags were compared with chance frequencies based on the binomial distribution. The time interval between successive problems (4.5 s vs. 7.5 s) and the intertrial activity (filled vs. unfilled) were varied. Surprisingly, the probability that an error matched the answer from the immediately preceding trial (lag of one) was significantly below chance in three of the four experimental conditions and at chance in the filled 7.5-s condition. Error matching probabilities two to three times greater than chance were obtained at an interval of about 30 s, and matches declined to chance thereafter. The results suggest that counteracting inhibitory and excitatory processes determine the magnitude of the error-priming effect over time.

In recent years there has been increasing interest in the cognitive processes underlying basic arithmetic skills (e.g., Ashcraft, 1982, 1987; Campbell & Graham, 1985; Miller & Gelman, 1983; Siegler, 1988; Siegler & Shrager, 1984), and these processes are also relevant to more general theoretical issues in cognition (e.g., Campbell & Clark, 1988; Gonzalez & Kolers, 1987; Zbrodoff & Logan, 1986). Although some theorists have argued that adults' performance on basic arithmetic problems relies extensively on the use of rule-based procedures (e.g., Baroody, 1985), others claim that the procedural methods used during initial acquisition are largely replaced by direct retrieval from semantic memory (Ashcraft, 1987; Campbell & Graham, 1985). In the present article we examine processes that underlie retrieval of answers to arithmetic problems.

The role of retrieval processes in elementary mathematics is demonstrated clearly by evidence that performance on the basic combinations shows a substantial influence of associative interference (Campbell, 1987a, 1987b; Campbell & Graham, 1985; Kreuger, 1986; Siegler, 1988; Siegler & Shrager, 1984; Stazyk, Ashcraft & Hamann, 1982; Winkelman & Schmidt, 1974). For example, Campbell and Graham (1985) found that most errors in simple multiplication made by children and adults (89% in adults) involved *tabled answers*, that is, correct products to other simple multiplication problems, usually from within the same times-table as the correct answer (e.g., $3 \times 7 = 24$ or $3 \times 7 = 28$). Campbell (1985) found a comparable pattern in the errors made by adults on simple division problems. The systematic patterns suggest that simple arithmetic errors often result from incorrect retrieval of associatively related answers. Campbell and Graham proposed that the error patterns reflect an associative-network structure in which each problem is linked to a number of candidate answers and each answer is linked to a number of different problems. Encoding a problem activates a set of response candidates, and the speed and accuracy of retrieval depend on the activation level of the correct answer relative to the activation levels of competing candidates. Similar retrieval interference models have been proposed to account for a variety of memory phenomena (cf. Anderson, 1981, 1983; Gillund & Shiffrin, 1984; Rundus, 1973; Siegler, 1988).

Error–Priming Effect

Perhaps the clearest evidence for associative interference in retrieval of arithmetic facts is the error-priming effect (Campbell, 1987a; Fraser, 1987). Testing adults over several sessions on simple multiplication problems, Campbell found that response times and errors could be influenced by manipulating the specific problems that preceded target problems within a session. The effect on errors was especially potent: Particular products were strongly promoted or virtually eliminated as error responses, depending on the presence or absence of earlier retrievals of those products. Error priming was selective, however, in that the target problems most affected were multiplicatively related to problems and products primed earlier. Campbell proposed that error priming occurs because residual activation from recent retrievals combines with activation delivered by subsequent problems that also access the retrieved answer (e.g., the probability that 6×8 accesses the incorrect answer 42 depends on an existing association between 6 and 42 via $6 \times 7 = 42$, and on residual activation of

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the association and answer from earlier presentation of the problem 6 × 7). The combined activation from the previous and ongoing retrieval episodes increases the probability of retrieving that answer in error relative to trials where that answer has not been recently retrieved.

Although the results of Campbell (1987a) clearly demonstrated error priming in multiplication, the method employed, which involved withdrawing and inserting subsets of problems across multiple sessions, afforded only a coarse-grained analysis of the effect. One purpose of the present study was to measure more accurately the magnitude and duration of error priming: When a problem is presented and an answer retrieved, over what period of time does that retrieval event exert a measurable effect on subsequent retrieval errors? Is the magnitude of the effect mainly dependent on the time between retrievals, or is it more sensitive to the number of intervening retrieval events? The present study also provided an opportunity to test Campbell's assumption that generation of an answer would contribute maximally to its activation in memory at the moment of retrieval. The activation would then decay toward a base rate. These assumptions lead to the prediction that error priming should be maximum on the immediately following trial, with the effect decaying monotonically over subsequent trials. To address these issues, the influence of earlier retrievals on later retrieval errors was measured on a trial-by-trial basis.

Lag Analysis of Error Priming

In the following study, we analyzed error responses in terms of their position within a block of trials, relative to the position of an earlier retrieval of that answer. The answer–error lag is the difference between the trial number of an error response and the trial number of an earlier occurrence of the same answer. The error–priming effect emerges as differences between the frequencies of answer–error matches produced by subjects at different lags and the frequencies expected by chance. The following paragraphs outline the logic of the lag analysis.

Subjects received trial blocks of 31 randomly ordered multiplication problems in the range from 2 × 2 to 9 × 9. Thirty-one different products are associated with this set of problems, and all 31 products were tested in a block. Approximately 90% of adults' errors on the problems from 2 × 2 to 9 × 9 are correct products to other problems in this range (tabled errors; Campbell & Graham, 1985). Even under instructions for speed, however, absolute error rates are quite low (5%–10%), and it has been observed informally in previous studies (e.g., Campbell, 1987a, 1987b; Campbell & Graham, 1985) that subjects usually detect when they have stated an incorrect answer. This implies that even on error trials, subjects eventually retrieve the correct product and that in the present study all 31 products were retrieved in each trial block. Consequently, when a tabled error occurred, the same answer was always retrieved somewhere else in the trial block.

To analyze answer–error lags a computer program located tabled errors and then searched back through the correct answers to earlier problems to determine whether the same answer had been generated on an earlier trial within the block. For each subject at each lag, the program computed a match probability as the number of answer–error matches divided by the number of matching opportunities at that lag. The number of matching opportunities per lag is determined jointly by the number of errors a subject makes and by how those errors are distributed across trials within a block. For example, errors that occur on Trial 2 *or later* provide opportunities for a match at a lag of 1, whereas errors that occur only on Trial 31 provide opportunities for matches at the maximum lag of 30 trials. In general, the number of answer–error matching opportunities per lag decreases for larger lags.

The pattern of observed answer–error match probabilities across lags can be compared with the baseline distribution expected by chance. When errors that involve only correct products to other problems (tabled errors) are analyzed, a search of the other 30 trial positions within a block will always reveal a match somewhere. Given that problems were tested in a random order, there is exactly a 1 in 30 probability by chance that the same answer will be found at any one of the other 30 positions. Therefore, the number of matches expected by chance at each lag is a binomial random variable with a match probability of $p = 1/30$ (about .0333) and an expected value of np, where n is the number of match opportunities. Thus, for any lag, if the mean observed match probability deviates significantly from .0333, it is evidence that error priming exerts an influence over the number of trials corresponding to that lag.

In the following study, the lag analysis was used to evaluate error priming in simple multiplication, and two between-subjects variables were manipulated. For two groups the response–stimulus interval (RSI) was 4.5 s (*short RSI*), and for another two groups the RSI was 7.5 s (*long RSI*). If the range of the error–priming effect depends primarily on the number of intervening trials, manipulating RSI should have little effect on the pattern of match probabilities across lags. If the effect is sensitive primarily to the time between retrieval events, then the error-priming effect should be maximum at longer lags in the short RSI condition than in the long RSI condition. In addition to the RSI manipulation, one group of short RSI subjects and one group of long RSI subjects were given a distractor task to perform between trials (*filled RSI*), whereas the other two groups were given no special instructions regarding the intertrial interval (*unfilled RSI*). The purpose of the filler task was to distract subjects from active processing of the events on the preceding multiplication trial.

General Method

Subjects

Sixty-four subjects were tested in each of the filled and unfilled short-RSI conditions. There were two blocks of trials, and initial analyses indicated no systematic effect of trial block on the phenomena of interest. Therefore, for the two long RSI conditions the number of trial blocks was doubled, and 32 subjects were tested in each. 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.

Apparatus

Stimuli were presented on a Commodore 128 microcomputer connected to a monitor that displayed green characters against a dark background. The characters were about 6 mm high by 4 mm wide. A lapel microphone connected through a relay switch to the computer's parallel port controlled a software clock accurate to ±1 ms.

Stimuli and Design

Multiplication problems in the range from 2 × 2 through 9 × 9 were tested in blocks of 31 trials. Zero-times and one-times 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 operand order is ignored (i.e., when, for example, 3 × 4 and 4 × 3 are treated as the same problem), there are 36 multiplication problems in the range from 2 × 2 to 9 × 9. The 36 problems involve 31 different products, with five products being correct answers to more than one problem (i.e., 12, 16, 18, 24, and 36). Each block of trials contained 31 problems with different products. The five shared-product problems excluded in one block of trials were exchanged for their same-product counterparts in the subsequent block.

Each of the 64 subjects in the short-unfilled and short-filled RSI conditions received two blocks of trials. Each of the 32 subjects tested in long-unfilled and long-filled RSI conditions received four blocks, with problems tested in Blocks 1 and 2 being repeated in Blocks 3 and 4. The order of problems was independently randomized for each block for each subject. Approximately half of the nontie problems (problems in which multipliers are not the same) were randomly assigned to have the numerically smaller multiplier appear on the left in the first block. Operand order then alternated across blocks.

Procedure

Subjects were tested individually in a slightly darkened room with the experimenter present and sat facing the monitor at a distance of about 60 cm. Subjects were told that they were being tested on speed of simple multiplication and were instructed to state the answer to each problem as quickly and accurately as possible. The subjects were warned that responding quickly would result in occasional errors and were encouraged not to be upset by errors because errors simply confirmed that they were responding as quickly as possible.

The experimenter initiated each block of trials, and blocks were separated by a minimum of 10 s. 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. On each trial a fixation dot appeared briefly at the center of the screen and flashed twice over a 1.5-s interval. The multiplication problem appeared on what would have been the third flash, with the *X* appearing at the fixation point and the problem remaining on the screen until the subject responded. The experimenter immediately entered the stated answer at the computer keyboard, after which the fixation dot for the next trial appeared. The interval before the fixation dot flashed was varied between experimental conditions as described below.

Adult subjects almost always detect their errors on simple multiplication problems, and correct feedback was not given to subjects when errors occurred. Subjects who appeared bothered by errors were reminded that an occasional error was unavoidable, given rapid responding.

Procedural Differences Among the Experimental Conditions

The RSI duration (short vs. long) and the activity during the response–stimulus interval (filled vs. unfilled) were manipulated in a 2 × 2 factorial design. In the short RSI condition, the interval from the response on trial *n* to the presentation of the problem on trial *n* + 1 was 4.5 s. In the long RSI condition, the interval was 7.5 s. In all cases, subjects saw the fixation dot flash twice during a 1.5-s interval before the problem appeared. Subjects in the unfilled RSI condition were given no special instructions regarding the period between trials. In the filled RSI condition the interval was filled with an alphabet-generation task. For the alphabet task, a randomly selected uppercase letter from *A* to *Z* appeared at the center of the screen immediately after the response to the multiplication problem. Subjects were instructed to recite the alphabet as quickly as possible, starting with the presented letter (looping back to *A* after *Z* if necessary) and to stop when the fixation dot flashed.

Results and Discussion

Table 1 presents summary statistics for each condition, including mean correct response time (RT), the overall error rate, and the percentage of errors that involved tabled answers. Error rates ranged from 7.9% to 11.5% across conditions. The differences in error rates are probably due mainly to modest differences in speed–accuracy criteria among the groups (e.g., Wickelgren, 1977). The relatively low error rate observed in the short-unfilled RSI condition was associated with the longest mean RT (1,049 ms), whereas the highest rate was observed in the long-filled RSI condition and occurred in the context of RTs that were 22% faster (818 ms). The other two conditions were intermediate with respect to both errors (10.5% and 9.3%, respectively) and RT (895 ms and 845 ms). In all conditions the percentage of errors that involved tabled answers (i.e., correct products to other problems tested) was very high, ranging from 90% to 94%. The mean number of tabled errors per block of 31 trials ranged from 2.3 to 3.2. The answer–error lag analyses involved only tabled-answer errors within blocks (the time between blocks was not strictly controlled, and consequently any systematic error–priming effects between blocks could not be accurately evaluated). Two subjects in the short-unfilled RSI condition and 1 subject in the short-filled condition made no errors; therefore, their results do not figure in the following analyses.

Table 2 shows for each condition the mean percentage of errors that were matched (i.e., preceded by a previous retrieval of the same answer) over all lags, and the mean percentages

Table 1
Overview of Error and Response Time Results

		Errors			
RSI	Interval	Total	*ER*	Tabled	*RT*
4.5	Unfilled	312	7.9	94	1,049
4.5	Filled	416	10.5	90	895
7.5	Unfilled	370	9.3	92	845
7.5	Filled	440	11.5	91	818

Note. RSI = response–stimulus interval in seconds; ER = percent of errors in each experiment; Tabled = percent of errors that involved correct answers to other problems tested; RT = mean correct response time in milliseconds.

Table 2
Observed and Expected Percentage of Errors Matched

	Lag range in trials							
	1–10		11–20		21–30		1–30	
Condition	*PE*	*SE*	*PE*	*SE*	*PE*	*SE*	*PE*	*SE*
Short-unfilled RSI								
Observed	37.8	4.0	13.9	2.1	6.7	2.0	58.4	4.0
Expected (binomial)	27.9		16.4		5.0		49.3	
Expected (random)	26.5		16.1		5.2		47.8	
Short-filled RSI								
Observed	38.8	3.1	17.6	2.1	9.0	2.1	65.4	3.0
Expected (binomial)	28.7		18.4		6.7		53.8	
Expected (random)	27.5		17.3		6.0		50.8	
Long-unfilled RSI								
Observed	44.1	3.3	18.6	2.8	5.7	1.5	68.4	2.4
Expected (binomial)	28.5		18.6		7.1		54.2	
Expected (random)	28.1		17.7		7.0		52.8	
Long-filled RSI								
Observed	49.7	3.7	16.2	2.2	5.3	1.2	71.2	2.8
Expected (binomial)	28.9		17.3		5.7		51.9	
Expected (random)	28.5		17.5		6.0		52.0	

Note. PE = mean observed or expected percentage of errors matched within the specified lag range; SE = standard error; RSI = response–stimulus interval.

matched over trial lags of 1–10, 11–20, and 21–30. Table 2 also includes two estimates of the percentages expected by chance. The first method for estimating chance performance was based on the binomial model with $p = .0333$. To confirm the binomial model, estimates of chance matches were also generated by randomizing nonerror trials and redoing the lag analyses on random arrangements of answers relative to errors. The absolute positions of errors within a block were preserved in the randomization so that the number of answer–error matching opportunities at each lag was the same as in the original data. The expected percentages from the random model reported in Table 2 represent means based on 50 block-by-block randomizations of the data from each condition. As can be seen in Table 2, the results from the binomial model and random analyses were in excellent agreement.

The rightmost column of Table 2 shows the observed and expected percentages of errors matched at all lags. The expected values hover around 50% (by chance an answer should precede or follow the corresponding error with equal probability). The expected values are not exactly 50% because of nonuniform distributions of errors across trials. An expected value greater than 50%, for example, indicates that errors were somewhat more likely on later trials within a block (i.e., if a tabled error occurs toward the end of a block, the chance probability is greater than .5 that the same answer has already been generated). All four conditions produced overall matching percentages significantly greater than expected under the binomial model (smallest $z = 2.28$, $p < .015$), ranging from a deviation of +9.1% in the short-unfilled RSI condition up to +19.3% in the long-filled RSI condition.

A 2 × 2 (Short vs. Long RSI × Filled vs. Unfilled Interval) analysis of variance (ANOVA) was performed on subjects' deviations from chance. The main effect of RSI was significant, $F(1, 185) = 4.565$, $MS_E = 380.455$, $p = .034$, indicating that a higher percentage of errors was matched in the long RSI conditions. Although there was a trend toward a higher percentage of answer–error matches when the intertrial interval was filled, neither the main effect of intertrial activity, $F(1, 185) = 1.572$, $p > .10$, nor the interaction with RSI, $F(1, 185) < 1$, was significant.[1]

It can be seen in Table 2 that the deviations above chance originate mainly in the 10 trials preceding an error; there is little evidence over lag ranges of 11–20 or 21–30 that the observed percentage of matches differed from chance.[2] Over the 1–10 lag range, the increases in answer–error match percentages relative to chance were 35.4%, 35.2%, 54.7%, and 72.0% in the short-unfilled, short-filled, long-unfilled, and long-filled RSI conditions, respectively. Thus, the present experiment replicated the error-priming effect reported by Campbell (1987a) and suggests that the effect is measurable by using the present methods over a range of about 10 trials.

Lag-by-Lag Analysis of the Error–Priming Effect

Additional analyses of Lags 1 through 20 were performed to further evaluate differences among the conditions and to assess the time course of the error–priming effect in more detail. For each subject, the number of errors matched at each lag was divided by the number of matching opportunities to obtain a match proportion or probability. The mean match probability was then computed for each lag on the basis of

[1] The higher percentage of matches for the long-RSI condition is not a result of extra repetitions of problems. An ANOVA using data only from Blocks 1 and 2 also showed a strong main effect of short versus long RSI, $F(1, 185) = 7.49$, $MS_e = 442.336$, $p < .01$. As in the original analyses, there was no statistical evidence for an interaction ($F < 1$). The possible main effect of filled versus unfilled intervals was somewhat stronger, $F(1, 185) = 2.63$, but did not reach conventional significance levels.

[2] Recall that the lower percentage of expected matches for larger lags results from the decreasing number of matching opportunities as lag increases. An ANOVA on deviation scores based only on the 1–10 lag range indicated, in agreement with the overall analysis, that only the main effect of short versus long RSI was significant.

subjects that had at least one matching opportunity at a given lag. Under the binomial model, the expected mean probability is equal to the chance probability of a match ($p = .0333$), which is constant across lags. We also computed the standard errors of the expected means by using the binomial model. This involved first computing for each subject the standard deviation of the match probability for each lag, which is given by the square root of pq/n, where n is the subject's number of matching opportunities. The standard error is the average standard deviation for each lag divided by the square root of the number of subjects contributing matching opportunities at that lag. These values determined from the binomial model with $p = .0333$ represent the true standard errors expected under the null hypothesis of no error–priming effect, whereas standard errors based on the observed probabilities of a match would be contaminated by the error–priming effect itself. The means and standard errors for Lags 1 to 20 for each of the four conditions are presented in the Appendix.[3]

Figure 1 presents a summary of the lag-by-lag analysis of each condition and shows the observed matching probabilities relative to the baseline probability of .0333. To smooth out the curves beginning at a lag of two trials, each point is the average of the observed mean probabilities for pairs of successive lags. The reason for excluding a lag of one from the smoothing is obvious from Figure 1: In three of the conditions (short-unfilled, short-filled, and long-unfilled) the observed probability of a match at a lag of one is *below* chance. The effect was clearest in the short-unfilled RSI condition, where the observed mean match probability for a lag of one has a z score of -2.03 ($p = .021$) relative to .0333. The deviation below chance also reaches or approaches significance both in the short-filled ($z = -1.61$, $p = .054$) and long-unfilled ($z = -1.70$, $p = .045$) conditions. In the long-filled RSI condition, the observed value for a lag of one is at chance ($z = 0.2$). The finding of matching probabilities below chance strongly implicates response suppression or inhibition operating over a lag of at least one trial. The lag-of-one matches (30 in all) were no more likely in the first half of a session (17) than in the second half (13), suggesting that the inhibition effect was present during early trials.

Looking past a lag of one, the positive error–priming effect observed by Campbell (1987a) emerges. The maximum deviation above chance occurred at a lag of nine trials in the short-unfilled condition and at a lag of six trials in the short-filled condition (see the Appendix). The maximum observed matching probabilities were about 2.5 to 3 times higher than the .0333 expected by chance [max observed = .083 with a short-unfilled RSI ($z = 3.39$); max observed = .100 with a short-filled RSI ($z = 5.85$)]. For the two long RSI conditions, the positive region of the curve had its maximum value at a lag of three trials. The maximum matching probabilities were about the same as in the short RSI conditions [.103 with a long-unfilled RSI ($z = 6.03$) and .096 with a long-filled RSI ($z = 6.04$)]. There is no consistent evidence for a measurable effect past a lag of 10 trials.

No definite conclusions appear to be warranted regarding possible effects of filling the intertrial interval with the alphabet task versus having unfilled intervals. The lag-by-lag results are possibly consistent with the hypothesis that filling the interval attenuated the inhibition effect because the probability of a match was somewhat lower at a lag of one with an unfilled-interval than with a filled interval. This is consistent with the nonsignificant trend toward a higher percentage of matches overall when the interval was filled (see Table 2). Nonetheless, any such possible effect is evidently small relative to the overall effect of time or trials. Given that interpolated activity had no clear systematic effects, the observed matching probabilities at each lag were averaged over the filled and unfilled manipulation. Preliminary analyses of the raw data for the short and long RSI conditions also suggested that RSI had little effect on the general form of the error–priming effect (but see below). Specifically, both conditions reached their maximum values at approximately 30 s, and there was considerable overlap in the two functions.

To examine the overall time course of error priming, the raw error-matching data for Lags 1 to 20 from the short RSI and long RSI conditions (averaged over the filled and unfilled conditions) were combined. For the short RSI conditions each lag of one trial corresponded to 5.47 s (allowing for the 4.5-s RSI and the 972-ms average retrieval time per trial). For the long RSI condition, one trial lag was equal to 8.33 s (the 7.5-s RSI plus the 832-ms average RT per trial). The set of 40 matching probabilities and times was smoothed by using a resistant smoothing procedure (Minitab, 1988), and the first 33 points were plotted as a function of time. Figure 2 shows the resulting relation between error matching probability and elapsed time since the earlier generation of the corresponding answer. The combined function clearly shows the nonmonotonic form of the error–priming effect, with error-matching below chance for recently retrieved answers and reaching a maximum positive effect after approximately 30 s. The pattern was sufficiently systematic to warrant an attempt to fit a theoretical function to the smoothed data.

An Interpretation and Fit of the Error–Priming Function

According to the model of error priming outlined by Campbell (1987a), retrieval of an answer activates the corresponding representation in memory, and the residual activation temporarily increases the probability of another retrieval of that answer. Activation subsequently decays. Under this simple model, the residual activation is maximum immediately after retrieval, and the error–priming effect should be maximum at a lag of one trial and should decrease monotonically thereafter. The nonmonotonic shape of the error–priming function across lags indicates that the mechanisms involved are more complex than Campbell assumed. The fact that the

[3] The means in the Appendix are expressed as percentages rather than probabilities. Note also that the random simulations described earlier confirmed the binomial model at the level of individual lags and showed that the mean of the randomly generated mean proportions for each lag was always very close to the .0333 value expected under the binomial model and that the standard errors from the random model matched closely those generated from the binomial model. Detailed results of the random analyses are available from the first author.

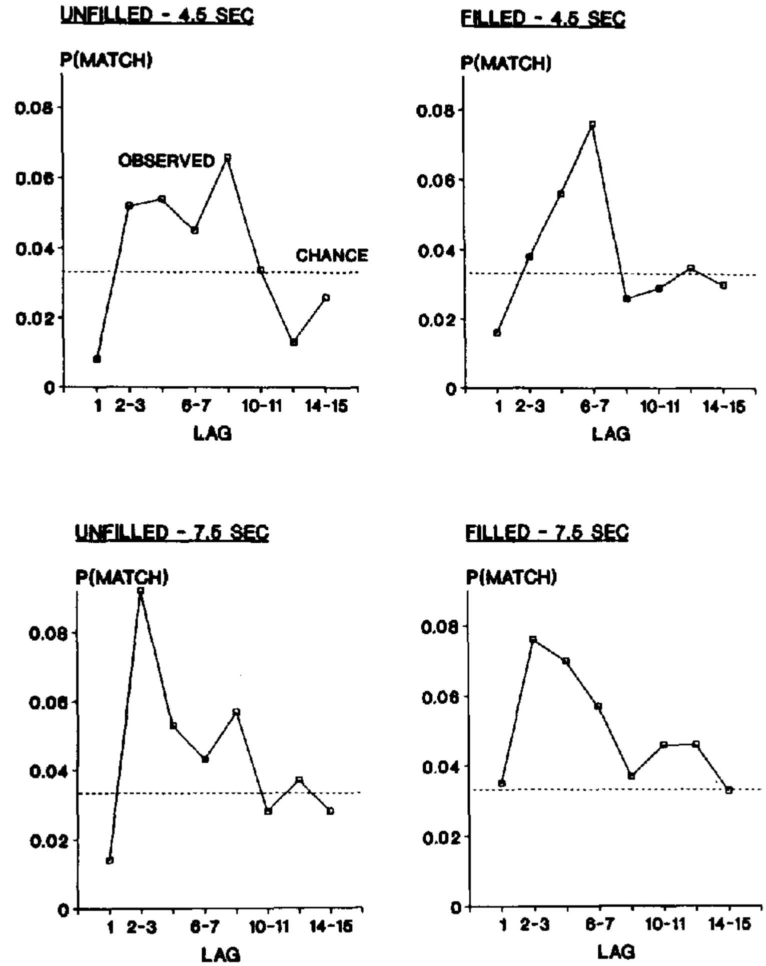

Figure 1. Mean answer–error matching probabilities (*P*) as a function of trial lag.

observed matching probabilities were at or below chance at a lag of one in all four conditions suggests that some process temporarily suppresses or inhibits a second retrieval of recently retrieved items. The positive error-priming effect (i.e., interference) observed by Campbell does not appear until at least one trial has intervened and reaches its maximum a few trials later. It appears, therefore, that the error-priming effect may involve inhibitory mechanisms in addition to the excitatory mechanisms proposed by Campbell.

Beginning with the basic assumptions of Campbell's (1987a) account, a two-process model assumes that simple arithmetic problems activate multiple candidate answers, including the correct response. So long as activation is maintained at a sufficiently high level (e.g., through active rehearsal), the corresponding memory structure is highly accessible. Once active processing ceases, the excitatory input begins to decay, and the activation level of the memory structure decreases. Memory structures corresponding to multiplication answers also receive inhibitory inputs, however, with the effects of inhibitory and excitatory factors being additive. The level of activation of earlier answers is determined by the net effect of the positive and negative inputs. At a lag of one, inhibitory inputs to a potentially incorrect response are stronger than excitatory inputs, and the negative component of the error priming function is observed.

Both excitatory and inhibitory influences decay across subsequent trials, and inhibitory inputs appear to decay more rapidly than excitatory inputs. Once the level of inhibition has decayed to below the level of excitation, the positive component of the error-priming function emerges. Positive priming occurs when the candidate set activated by a problem now includes one or more answers that are already in a state of net elevated activation because of recent activation by earlier problems and because of inhibition levels that are no longer adequate to suppress the response. The excitatory input from a current problem combines (perhaps multiplicatively; see Campbell, 1987a) with this residual net activation, resulting in an increase in retrieval probability for the recently activated answers. Thus, the combination of excitatory and inhibitory components produces the observed nonmonotonic error-priming function.

To confirm that opponent excitatory and inhibitory influences on match probability can describe the present results, we fit the data in Figure 2 by a mathematical model that combined separate positive and negative exponential functions. The asymptote for the composite equation was set at the chance probability of a match (.0333), and the intercept of the positive exponential at time 0 was set at 1.00, the maximum possible value for a match probability. The intercept for the negative exponential function and decay rates for both functions were estimated by using the SAS nonlinear regression procedure NLIN. Note that inhibition may start later than excitation and at a lower value than the nominal intercept for the inhibitory exponential at time zero.

Figure 2 includes the function described by the best fit nonlinear equation. Excitatory influences begin at 1 at time 0 and decay at a constant rate of .062 units (95% confidence interval of .058–.066). The theoretical curve for inhibitory influences has an intercept of 1.091 (1.077–1.105) at time zero and decays at a rate of .072 units (.067–.077). As Figure 2 shows, the fit of the equation is quite good (r^2 = .95 with the smoothed data and .58 with the raw data), and the major characteristics of the data are clearly reproduced. The early negative priming effect arises because the excitatory influences are initially below the value for inhibitory influences, producing a net suppression effect. Because inhibitory effects decay faster than excitatory effects, the inhibitory component eventually falls below the excitatory component. After 10 s the positive region of the error–priming function emerges, reaches its maximum, and remains above baseline 80 s or so. Because some of the assumptions underlying the model are necessarily arbitrary at this time, no specific theoretical significance should be attached to the values of individual parameters, although inhibition must start above excitation and decay more rapidly to fit the data. The good overall fit demonstrates the plausibility of a model of error priming based on differentially decaying excitatory and inhibitory influences.

The Effect of RSI Reconsidered

Considerable overlap and variability in the raw data from the two RSI conditions, as well as possible effects of differences

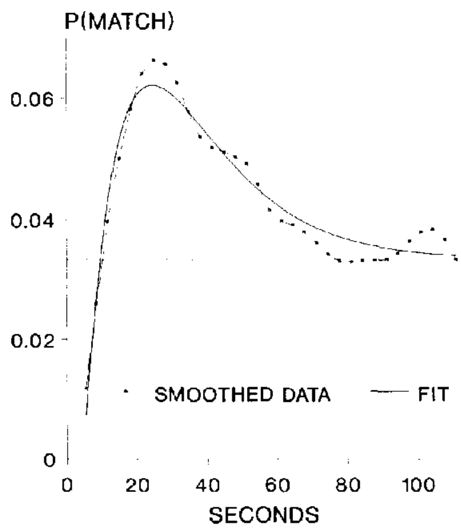

Figure 2. Mean observed answer–error matching probabilities (*P*, smoothed) as a function of elapsed time from generation of answer. (Best fit = function based on exponentially decaying excitatory and inhibitory influences [see text for details].)

in speed–accuracy criteria (see Table 1), preclude strong conclusions regarding the effects of RSI on the time course of error-priming. These considerations led us to emphasize the form of error priming combined over the short and long RSI conditions. Nonetheless, there was overall a higher percentage of errors matched in the long-RSI than in the short-RSI condition; to pursue this finding, the data for the two RSI conditions were separately smoothed as before and plotted as a function of time. On the basis of a comparison of the two smoothed functions, the maximum positive error–priming effect was obtained after 27 s with the short RSI and after 33 s with the longer RSI. The peaks for the smoothed functions were somewhat lower than was suggested by the raw data (maximum match probability = .053 for the short RSI and .063 for the long RSI, vs. values in the .08–.10 range in the raw data). When plotted as a function of time, the short RSI function consistently fell below the long RSI function over the entire range of the effect, a pattern that was not obvious in the unsmoothed data. The smoothed short RSI curve returned to chance after about 60 s, whereas the long RSI function remained above chance to a range of approximately 100 s. These results suggest that the higher percentage of errors matched with the longer RSI resulted both from a higher error-matching probability at each point in time and from an increased duration for the positive error–priming effect.

General Discussion and Conclusions

The observed error–priming effect was quite complex. The probability that an error matches an answer to an earlier multiplication problem is at or below baseline shortly after a correct retrieval, later increases to a maximum value, and then decreases to the baseline level. This curvilinear error–priming effect raises questions about (a) the two-process model, (b) the nature of the apparent negative influences on matching probabilities, and (c) the possible relation between error priming and other memory phenomena within and outside the domain of mental arithmetic.

A simple two-process model for the observed pattern of error priming can be built on the assumption that the error–priming effect reflects primarily the state of activation of internal representations of multiplication answers, with independent sources of excitation and inhibition. The likely sources of excitation are residual activation from recently encoded problems and retrieved answers. Possible sources for inhibition of the answer are considered below. The absolute level of activation of an answer would be determined by the additive influence of the decaying excitatory and inhibitory factors, with inhibition decaying more rapidly than excitation and both gradually decaying to baseline after 1 or 2 min.

According to this model, effects of RSI could be accounted for by differences in the decay or intercept parameters for inhibition or excitation. For example, if inhibition is a mechanism for controlling interference from related problems, more inhibition might be produced in response to increased interference when trials are closely spaced. This model is probably too simple, however, because it does not consider that the error–priming effect reflects the *relative* state of activation of an answer in the context of many other problems and answers. When trials occur closely spaced, a given trial presumably occurs within more background noise from previous retrievals than when trials are more widely spaced. Consequently, the influence of a specific retrieval on later errors will be more diluted by other retrievals when the RSI is short than when it is longer. Similarly, some of the decrease in the effect of error priming at longer lags may simply be due not to decreased activation over time but to an increased probability that a stronger competing response occurs on the intervening trials. Thus, a cautious interpretation of the two process model is that the positive and negative components involve multiple factors that raise and lower the relative activation level of multiplication answers, thereby influencing the probability of a specific retrieval error.

Several mechanisms of inhibition are possible. Negative priming effects may reflect intentional inhibition or suppression of answers similar to that induced by manipulating stimulus–response contingencies so that one experimental event predicts occurrence or nonoccurrence of another event (e.g., Blaxton & Neely, 1983; Zbrodoff & Logan, 1986). In the present experiment, each block of trials involved 31 different answers, and thus once an answer had occurred as a correct response, the probability was zero that it would occur again as a correct answer within the trial block. Subjects were not explicitly informed of this constraint, but it is possible that they deduced nonrepetition as a feature of the task and deliberately suppressed answers once given. The mechanism of such inhibition is sometimes characterized as a "criterion shift," an elevating of the activation required for retrieval. The concept of inhibitory inputs that we have suggested is functionally equivalent in that additional excitatory energy would be required to counteract effects of inhibition.

This active, deliberate view of the inhibitory component of error priming encounters several difficulties. First, filling the RSI interval had modest effects, if any, on the pattern of error priming. This manipulation, if strong enough, should have reduced any deliberate factors that contributed to the negative error-priming effect. A second difficulty is that the incidence of lag-of-one matches was uniformly lower over early and late trials within a session. This means that inhibition emerged early during a session and conceivably was present before subjects had an opportunity to discover the response contingencies. However, people have considerable experience with multiplication, and inhibitory retrieval strategies for dealing with interference from related problems may have been acquired preexperimentally (cf. Geiselman & Bagheri, 1985). Moreover, a few multiplication problems may be sufficient to sensitize subjects to the problem of interference from preceding answers.

The inhibition effect we observed could also involve more general, potentially automatic memory mechanisms. According to this account, retrieving a correct answer entails the active suppression of other answers activated by the problem, and the more activated an incorrect answer is, the more inhibition it may receive. On a given trial, the most activated competitor would be the answer retrieved on the preceding trial, so that lag-of-one answers would receive the strongest inhibiting signals. Problems from earlier trials may be weak enough not to attract inhibition but strong enough to intrude once the most recent response is inhibited. This view of retrieval is analogous to inhibitory processes that have been proposed and verified in selective attention (e.g., Dalrymple-Alford & Budayr, 1966; Neill, 1977; Neill & Westberry, 1987; Tipper, 1985a, 1985b) and also have been implicated in other memory retrieval paradigms (e.g., Johnson & Clark, 1988; Roediger & Neely, 1982).

Whether deliberate or automatic, inhibition appears to take time to initiate (cf. Blaxton & Neely, 1983). Campbell (1987b) showed that presenting a related incorrect answer for 300 ms prior to receiving a multiplication problem increased RTs and errors, contrary to the negative priming effects at short lags in the present experiment. These findings are not inconsistent if 300 ms is too short a time for inhibitory processes to operate. The onset of inhibition and its maximum value cannot be determined from our data, and the onset could be quite late, even as late as presentation of the succeeding problem.

The positive component of the error-priming function corresponds to an increased probability of a retrieved answer being retrieved again later and may be related to generation effects observed in recall tasks (e.g., Slamecka & Graf, 1978). The generation effect is the finding that recall probability for an item is increased when the item is generated rather than simply read, an effect that has been obtained with arithmetic stimuli (Gardiner & Rowley, 1984). Although generation effects last at least several minutes (i.e., the time between study and test) and we found no evidence of error priming after 10 trials (about 1 min), there may be enduring residual effects of previous retrievals that are not detected by error priming. As noted earlier, a retrieved answer's activation could still be substantially above base rate after 10 intervening trials but be low relative to the activation levels of more recently generated items that are promoted as errors. The present results therefore do not eliminate the possibility that excitatory factors operate over intervals much longer than 1 min, leaving open the possibility that the error–priming effect and the generation effect involve related mechanisms.

We have suggested several possible connections between the error–priming effect and other phenomena of memory and attention. It is currently an open question whether the error–priming effect can be obtained under different conditions with other types of stimuli, but the basic representations that underlie retrieval of arithmetic facts are probably not unique. The answer to a simple arithmetic problem can be viewed as a name for an arbitrary stimulus; in the same way that *three* is a verbal label for *3*, *twelve* is the verbal label for 3×4. According to this view, retrieval of an arithmetic fact involves, in principle, the same mechanisms as retrieval of any other relation in verbal associative or semantic memory. There may be special features of the arithmetic domain, however, that promote the error–priming effect. For many adult subjects, retrieval of most simple arithmetic facts is quite effortless (LeFevre, Bisanz, & Mrkonjic, 1988; Zbrodoff & Logan, 1986), indicating particularly strong and accessible associations. This, together with the complicated "fan" structure (Anderson, 1983) of the stimuli (i.e., dozens of relations built upon 10 basic elements), may result in a retrieval domain that is especially susceptible to subtle excitation and inhibition of items within the memory structure. It remains for future research to determine how pervasive in other cognitive domains are the processes that underlie error-priming in mental arithmetic.

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Appendix

Means and Standard Errors for the Four Conditions

	4.5-s RSI				7.5-s RSI			
	Unfilled		Filled		Unfilled		Filled	
Lag	*M* %	*SE*	*M* %	*SE*	*M* %	*SE*	*M* %	*SE*
1	0.75	1.27	1.59	1.08	1.43	1.12	3.53	1.01
2	5.79	1.29	3.73	1.09	8.03	1.14	5.59	1.03
3	4.60	1.30	3.80	1.11	10.32	1.16	9.55	1.03
4	3.96	1.33	6.28	1.12	3.75	1.18	6.03	1.04
5	6.77	1.36	4.82	1.12	6.81	1.20	7.92	1.05
6	6.40	1.40	10.00	1.14	4.52	1.22	6.66	1.10
7	2.62	1.42	5.14	1.15	3.99	1.26	4.64	1.11
8	4.94	1.44	2.52	1.19	4.87	1.28	4.12	1.12
9	8.31	1.47	2.72	1.23	6.44	1.29	3.27	1.14
10	1.14	1.48	2.98	1.27	2.39	1.30	5.86	1.17
11	5.66	1.52	2.91	1.31	3.27	1.33	3.09	1.21
12	1.81	1.56	4.50	1.31	4.46	1.39	5.04	1.26
13	0.80	1.58	2.44	1.36	2.98	1.42	4.24	1.30
14	2.69	1.66	3.62	1.40	2.01	1.46	1.92	1.35
15	2.50	1.70	2.41	1.45	3.66	1.50	4.61	1.40
16	2.95	1.74	3.96	1.48	1.74	1.55	2.02	1.44
17	3.64	1.85	2.83	1.50	2.07	1.57	2.38	1.51
18	5.57	1.90	1.82	1.55	5.81	1.65	2.65	1.51
19	4.96	1.99	2.72	1.62	4.81	1.67	1.08	1.56
20	4.16	2.04	3.23	1.75	1.14	1.73	4.28	1.63

Note. RSI = response–stimulus interval. *M* % = mean percentage answer–error matches per lag (for each subject for each lag the number of answer–error matches was taken as a percentage of the number of matching opportunities). Means are based on subjects with at least one matching opportunity at the corresponding lag. The expected mean percentage by chance at each lag is 3.33 according to the binomial model with $p = .0333$. *SE* = standard error of the expected mean percentage determined from the binomial model.

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