Time course of forgetting exhibited in repetition priming of semantic comparisons

DAN J. WOLTZ
University of Utah

VALERIE J. SHUTE
Armstrong Laboratory, Brooks Air Force Base, Texas

We report two studies that used a semantic comparison task to investigate forgetting in repetition priming over various delay intervals. Experiment 1 investigated the form of forgetting in priming effects (latency savings) over intervals up to 90 min. Logarithmic, exponential-power, and power forgetting functions fitted the data equally well, but they made different predictions about the degree of priming after longer delay intervals. Experiment 2 tested these predictions by assessing repetition savings after an 8-day delay. A power function provided the best account of priming loss. The findings are discussed with respect to the longevity of implicit memory measures and the previously observed dissociations between implicit and explicit memory measures.

Several previous studies have demonstrated remarkably persistent facilitation from single repetitions of relatively simple processes. For example, Jacoby and Dallas (1981) and Jacoby (1983) found that direct priming of words presented in a tachistoscopic word identification task lasted over 24 hr. Similarly, Scarborough, Cortese, and Scarborough (1977) found facilitation for repeated lexical decision trials to last several days. Roediger and Blaxton (1987) found facilitation after one week from priming word fragment completion items, even when the priming occurred in a different sensory modality. Finally, Sloman, Hayman, Ohta, Law, and Tulving (1988) found that facilitation from priming words in a fragment completion task persisted for over one year.

One conclusion reached by several memory theorists (e.g., Schacter, 1987; Tulving & Schacter, 1990) from this and other evidence is that implicit memory phenomena such as repetition priming are long lasting compared with explicit memory phenomena such as recall and recognition (see also Cave & Squire, 1992; Feustel, Shiffrin, & Salasoo, 1983; Kolers, 1976; Komatsu & Ohta, 1984). Despite the apparent

AMERICAN JOURNAL OF PSYCHOLOGY
Winter 1995, Vol. 108, No. 4, pp. 499–525

popularity of this conclusion, relatively little is known about the time course of forgetting observed for implicit memory measures. That is, little evidence has been reported that characterizes the functional form of forgetting in common implicit memory measures. In contrast, explicit memory measures for forgetting functions have been more extensively researched (Wickelgren, 1972, 1974a, 1974b, 1976; Wixted & Ebbesen, 1991).

The current experiments looked at forgetting in a single implicit memory phenomenon, namely, performance facilitation or priming from repeating semantic comparison trials that require participants to decide whether two words have equivalent meanings (e.g., *moist damp*). We measured latency savings on repeated trials of this type over delay intervals ranging from a few seconds to 8 days. This memory measure is considered implicit in nature because retention (i.e., facilitation) is assessed without referring participants to the prior event responsible for the facilitation.

The present study describes the time course of forgetting in this priming measure by comparing the fit of different mathematical functions that have been successful in describing forgetting in explicit memory measures. We believe that understanding the form of forgetting for repetition priming measures can provide a clearer account of the hypothesized persistence of implicit memory phenomena. With enough consistent evidence, such understanding may eventually contribute to the development of theories of forgetting mechanisms.

However, this goal of describing the time course of forgetting for repetition priming is somewhat controversial. Much has been written lately regarding the difficulty of comparing both forgetting rates and forgetting functions (Bogartz, 1990a, 1990b; Loftus, 1985a, 1985b; Loftus & Bamber, 1990; Slamecka, 1985; Wixted, 1990; Wixted & Ebbesen, 1991). Theoretical conclusions can be drawn about the fit of a mathematical model of forgetting only if the assumption is valid that the measurement scale of the forgetting data represents equal intervals on the underlying psychological dimension of interest (e.g., memory strength). It is, of course, difficult if not impossible to justify such an assumption, and we can make no such claim regarding our latency savings measure of repetition priming.

In response to this problem, Wixted and Ebbesen (1991) have suggested that the difficulties surrounding the scaling issue might be bypassed by looking for empirical consistencies. That is, if one mathematical function more regularly fits a variety of forgetting data compared with other functions, this provides empirical evidence in favor of that model without directly addressing the scaling issue. Moreover, Wixted and Ebbesen (1991) reported comparisons of six different mathematical functions for describing forgetting data from markedly different memory experiments. A power function best described the course of forgetting in each case, thus providing support for the notion that empirical consistency may exist across various forgetting measures. In this article, we have extended the Wixted and Ebbesen strategy of investigating empirical consistency by evaluating the fit of various mathematical functions to data from an implicit memory measure of repetition priming.

EXPERIMENT 1

Repetition effects have been previously reported for semantic comparison trials (Woltz, 1988, 1990). In previous studies, facilitation (latency savings) from identity repetitions showed an immediate decline with one intervening trial between prime and target trials. However, no further decline of repetition effects was observed over lags of up to 15 trials spanning approximately one minute (Woltz, 1990).

This experiment measured repetition effects in the semantic comparison task over longer delays. Trials were repeated at several intervals up to 90 min. Presuming that loss of priming effects would be evident over this time frame, we investigated whether the form of decline would be consistent with mathematical models fitting recall and recognition data. We evaluated the fits of logarithmic, power, exponential, and exponential-power models that have been shown to fit a variety of memory data (Wickelgren, 1972, 1974a, 1974b, 1976; Wixted & Ebbesen, 1991).

METHOD

Participants

Participants were 342 Air Force recruits in their 11th day of basic training at Lackland Air Force Base, TX. Approximately 16% were eliminated because performance scores indicated lack of effort (i.e., high error rates; failure to complete all experimental tasks). Another 4% of the participants were eliminated because English was not their primary language. Of the final 274 participants, 210 were male and 64 were female. All were high school graduates, and approximately 20% had at least some college work.

Apparatus

Experimental tasks were administered on Zenith Z–248 microcomputers with standard keyboards and EGA color video monitors. Materials were presented on the monitors in 24 × 80 character text mode. Software was written to achieve millisecond timing on response latency recording.

Procedure

Participants were tested in groups of 25–35. Each individual had a testing carrel containing a microcomputer and participated for 3.5 hr in a series of experimental tasks. We report data from only one experimental task here.

At the beginning of each session, participants practiced locating keys on the computer keyboard. All instructions were computer administered, and proctors were available to answer questions. After the initial orientation, each participant performed five blocks of the repeated semantic comparison task. The five blocks were separated in time by an intervening associative learning task involving words and nonsense syllables (CVC trigrams) (for details see Woltz & Shute, 1993).

Repeated semantic comparison. Each trial consisted of two words presented in the center of the computer display, one on top of the other separated by approximately 1 cm. Each trial was preceded by an attention cue (one asterisk) presented for 1,000 ms followed by a blank screen for 500 ms. The two words were then presented and remained on the screen until the participant responded by pressing either an *L* key (for *Like*) or a *D* key (for *Different*), depending on whether the words were judged to be synonyms or unrelated. Instructions were given to respond as quickly as possible without sacrificing accuracy. Response feedback was designed to encourage both response speed and accuracy. An individual's trial response latency was presented for 1,000 ms following correct responses. The word *WRONG,* a low tone, and the message *BE MORE CAREFUL* followed errors for 4,000 ms. A blank screen followed all feedback frames for 500 ms. After each set of 72 trials, participants were presented summary feedback of percentage correct and median latency, and they were reminded to respond as quickly as possible without making errors.

Participants performed an initial block of 288 semantic comparison trials (an additional 20 warm-up trials preceded the 288 but were not considered part of the experimental design). One third of Block 1 trials were repeated at relatively short lags. Three orthogonal factors defined the repetitions within Block 1: (a) positive- versus negative-match on first exposure trials (e.g., *moist damp* vs. *moist blue* as a first exposure), (b) same- versus different-match on second exposure relative to first exposure, and (c) repetition lag of second exposure after first exposure (second exposure 1, 2, or 8 trials later). A complete representation of the repeated trial design was achieved within every set of 36 trials.

Repetition lags in Block 1 were accomplished in the following manner. The 288 trials were presented as four sets of 72 trials. Each set of 72 trials contained eight 9-trial sequences. The first trial in each 9-trial sequence was a Lag 8 first exposure. The next 7 trials represented the first and second exposures of Lags 1 and 2 in a randomly determined order for each 9-trial sequence of each participant. A nonrepeated filler trial always intervened between the first and second exposure of Lag 2 trials, and two additional filler trials were randomly assigned (for each sequence of each participant) to potential filler slots before, between, or after Lag 1 and Lag 2 trials. The 9th trial of each 9-trial sequence was always a Lag 8 second exposure.

Blocks 2–5 differed in structure from Block 1. Each of these blocks began with 10 warm-up trials followed by 72 trials that were equally divided among three levels of previous exposure. One third of the nonpractice trials in each block had not been presented previously (*first exposures*). One third had been presented once in Block 1 as fillers (*second exposures*). One third had been presented twice in Block 1 as repetitions (*third exposures*). First-exposure trials were balanced for positive and negative match within each block. Second- and third-exposure trials were always exact repetitions of Block 1 trials, and were balanced within block for match type and order of Block 1 presentation. That is, each of Blocks 2–5 contained (a) 6 fillers (3 positive and 3 negative) from each quarter of Block 1, and (b) 6 repeated trials (1 positive and 1 negative of each repetition lag) from each quarter of Block 1. Third-exposure trials always presented an exact repetition of the first-exposure trial from Block 1, even if the second-exposure trial in Block 1 was converted to the opposite match type (i.e., if *moist damp* was repeated as *moist blue* in Block 1, the third exposure would always be *moist damp*).

There were 288 stimulus sets (word triplets) used for the semantic comparison trials. Each stimulus set consisted of a stem word, a synonym of the stem, and a word semantically unrelated to the stem but equivalent in length (e.g., *moist, damp, blue*). Stimulus sets were randomly assigned to design cell and trial block for each participant. An additional 60 stimulus sets of word triplets were randomly assigned to warm-up trial conditions for each individual.

RESULTS

Error rates over all trial conditions were $M = 5.83\%$ ($SD = 2.71$). Error rate was positively correlated with response latency across the 56 trial conditions ($r = .32$) and across individuals ($r = .13$). Thus, faster latency was associated with fewer errors. The analysis of repetition effects was conducted with latency data only. All statistical tests used a p value of .05 as the criterion for significance.

Consistent with previous research using this task, substantial priming effects were found at short repetition lags. Mean response latency for the first-exposure trials of Block 1 was $M = 1{,}111$ ms ($SD = 214$) and $M = 1{,}233$ ms ($SD = 258$) for positive and negative trials, respectively. Savings were computed as the difference between first and second exposure latency within each trial condition, and means for these difference scores are presented in Table 1. Data represented in Table 1 were consistent with previous findings in that (a) identical repetitions (positive-positive and negative-negative) produced greater savings than nonidentical repetitions, $F(1, 273) = 1{,}210.07$, $MSE = 17{,}058$; (b)

Table 1. Block 1 mean latency savings (in milliseconds) for repeated semantic comparison trials by trial condition from Experiment 1 (*N* = 274)

Repetition type		Repetition lag (trials)		
First exposure	Second exposure	1	2	8
Positive	Positive	316	239	284
Positive	Negative	188	124	132
Negative	Positive	36	47	64
Negative	Negative	283	205	215

Note. Latency savings were computed as the difference between second exposure latency and first exposures of the same match (positive or negative) within each repetition lag.

positive first-exposure trials produced greater savings than negative first exposures, $F(1, 273) = 412.23$, $MSE = 10{,}265$, especially if the repetition was not identical as indicated by a significant First Exposure × Repetition Type interaction, $F(1, 273) = 19.41$, $MSE = 30{,}675$; and (c) Lag 1 repetitions produced greater savings than Lags 2 and 8, $F(1, 273) = 52.24$, $MSE = 24{,}297$, and Lag 8 produced slightly more savings than Lag 2, $F(1, 273) = 12.13$, $MSE = 18{,}270$.

Greater savings at Lag 8 than Lag 2 may seem counter to expectations, but this replicates an earlier finding (Woltz, 1990). Although Lag 8 trials occur on average slightly later in trial blocks than do Lag 2 trials, this does not explain the greater savings at Lag 8. That is, the tendency is for slower rather than faster responses across trials in a block, which produces a slight underestimate of savings at Lag 8 relative to Lag 2 (see Woltz, 1990). Alternatively, this phenomenon may represent a form of consolidation that operates in the range of two to eight intervening trials.

Substantial priming effects were also found at the longer lags. Table 2 shows mean latency savings for Blocks 2–5 which presented second- and third-exposure trials approximately 30, 50, 70, and 90 min, respectively, after the Block 1 first exposures. Latency savings were computed here as the difference between new and repeated trials within each trial block. As seen in Table 2, savings were reduced from those seen in Table 1. (Compare positive-positive and negative-negative savings in Block 1 with positive-none and negative-none savings in Blocks 2–5.) Nevertheless, savings across all conditions of the later blocks were reliably greater than zero, $F(1, 273) = 930.85$, $MSE = 67{,}848$.

Table 2. Blocks 2–5 mean latency savings (in milliseconds) for repeated semantic comparison trials by trial condition from Experiment 1 ($N = 274$)

Block 1 exposure		Block			
First	Second	2	3	4	5
	Positive trials				
Positive	None	167	166	143	133
Positive	Negative	156	165	141	126
Positive	Positive	188	176	166	159
	Negative trials				
Negative	None	92	85	78	71
Negative	Positive	87	68	62	62
Negative	Negative	107	110	96	78

Note. Latency savings were computed as the difference between repeated trial latency (second or third exposure) and new trial latency within each repetition type and block. Blocks 2–5 were delayed by approximately 30, 50, 70, and 90 min, respectively.

A small but significant overall effect was found in Blocks 2–5 from seeing a trial twice rather than once in Block 1, $F(1, 273) = 4.05$, $MSE = 10{,}303$. However, as shown in Table 2, this effect was a function of the consistency of the Block 1 exposures. Priming was greater on third-exposure trials that had identical first and second exposures in Block 1 (i.e., positive-positive and negative-negative in Table 2) compared with third exposures that had nonidentical first and second exposures (positive-negative and negative-positive in Table 2), $F(1, 273) = 42.61$, $MSE = 14{,}816$. Additional analyses revealed that identical third exposures had greater savings than identical second exposures (a difference of 18 ms), $F(1, 273) = 23.62$, $MSE = 15{,}312$, but that savings for nonidentical third exposures and identical second exposures did not differ (a difference of –8 ms), $F(1, 273) = 2.94$, $p > .05$. Thus, a slight benefit accrued from two exposures rather than one in Block 1, but only if the second exposure in Block 1 was identical to the first.

In addition to the substantial decline of priming effects between short and long lags (compare Tables 1 and 2), means in Table 2 also reveal that repetition priming effects declined across Blocks 2–5, $F(3, 271) = 6.76$. In univariate analyses, only the linear trend was significant, $F(1, 273) = 20.17$, $MSE = 24{,}899$. Forgetting did not differ in Blocks 2–5 as a function of match type, $F(3, 271) < 1$, or the number of exposures in Block 1, $F(3, 271) < 1$.

Mathematical functions for describing forgetting

Figure 1 displays mean savings from both Block 1 and Blocks 2–5 by average lag time.[1] Although the decline of priming over Blocks 2–5 (30–90-min delays) was linear, it is clear from Figure 1 that a linear model of forgetting did not fit the combined data from Block 1 and Blocks 2–5. Several alternative models were fit to the data in an effort to account for the negatively accelerated forgetting seen in Figure 1 for both positive and negative trials. Models were first tested on mean latency savings by match type and lag (12 data points) using nonlinear least-squares regression.[2] Different parameter estimates were allowed for positive and negative trial savings.

The first function that we tested represented exponential forgetting:

$$S_i = ae^{-bT_i} \tag{1}$$

where S is the latency savings for a repeated event at time i, a is the initial savings at time = 0 (the time of the original processing event), b is the forgetting rate, and T is the time at interval i since the original processing event. The exponential model, which has primarily been useful in describing physical phenomena such as radioactive decay, predicts reductions in savings by a constant fraction at all lag intervals.

The exponential model (Equation 1) had only a modest fit to the mean savings data (R^2 = .899). Figure 2 represents the exponential model fit, where log savings should be a linear function of lag time. As found by Wickelgren (1972) and demonstrated in Figure 2, the simple exponential model overestimated forgetting at longer intervals. In other words, the proportion of savings lost per lag interval declined with longer delays, but the exponential function failed to capture this because it predicts loss by a constant fraction at all delays.

Three models were then tested that describe a diminishing rate of loss with time. The first was a logarithmic model first suggested by Ebbinghaus (1885/1964). Next was an exponential-power model (Wickelgren 1972, 1974b). Finally, we tested a power function (Anderson, 1983; Wickelgren, 1974a, 1976; Wixted & Ebbesen, 1991). First consider the logarithmic function:

$$S_i = a - \mathrm{b}\log(T_i) \tag{2}$$

where S is the latency savings for a repeated event at time interval i, a is the savings after one unit of time has elapsed since the original processing event, b is the forgetting rate, and T is the time at interval i since the original processing event.

The logarithmic model (Equation 2) had a better fit to the mean savings data (R^2 = .994) than did the exponential model. Figure 3 illustrates the fit of the logarithmic function, where latency savings

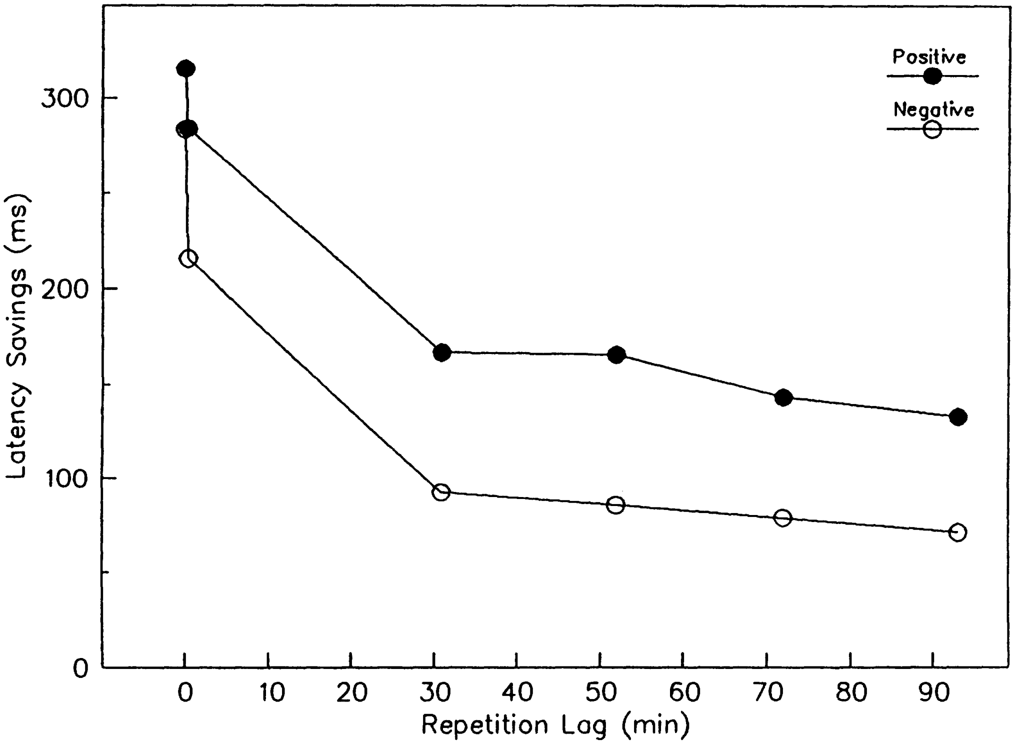

Figure 1. Experiment 1 mean latency savings for repeated semantic comparison trials by lag time

should be a linear function of log lag time. This result corresponds to the findings of Ebbinghaus (1885/1964) in that a logarithmic model described his relearning savings for nonsense syllables over delay intervals up to 31 days. As seen in Figure 3, positive and negative trial savings had similar forgetting rate parameters. When the model was constrained to estimate the same rate parameter for positive and negative trial savings, the fit was reduced only slightly to $R^2 = .990$.

Next we tested the exponential-power model proposed by Wickelgren (1972):

$$S_i = ae^{-bT_i^{(1-c)}} \qquad (3)$$

where S is the latency savings from a repeated trial at time interval i, a is the savings at time = 0 (the time of the original processing event), b is the forgetting rate, T is the time at interval i since the original processing event, and c represents resistance to forgetting. The c parameter modifies the standard exponential function by allowing for a slowdown in forgetting with time. Wickelgren (1972) and Begg and Wickelgren (1974a) reported that optimal fits were obtained for recognition tests of a wide variety of verbal materials when c was in the vicinity of .75.

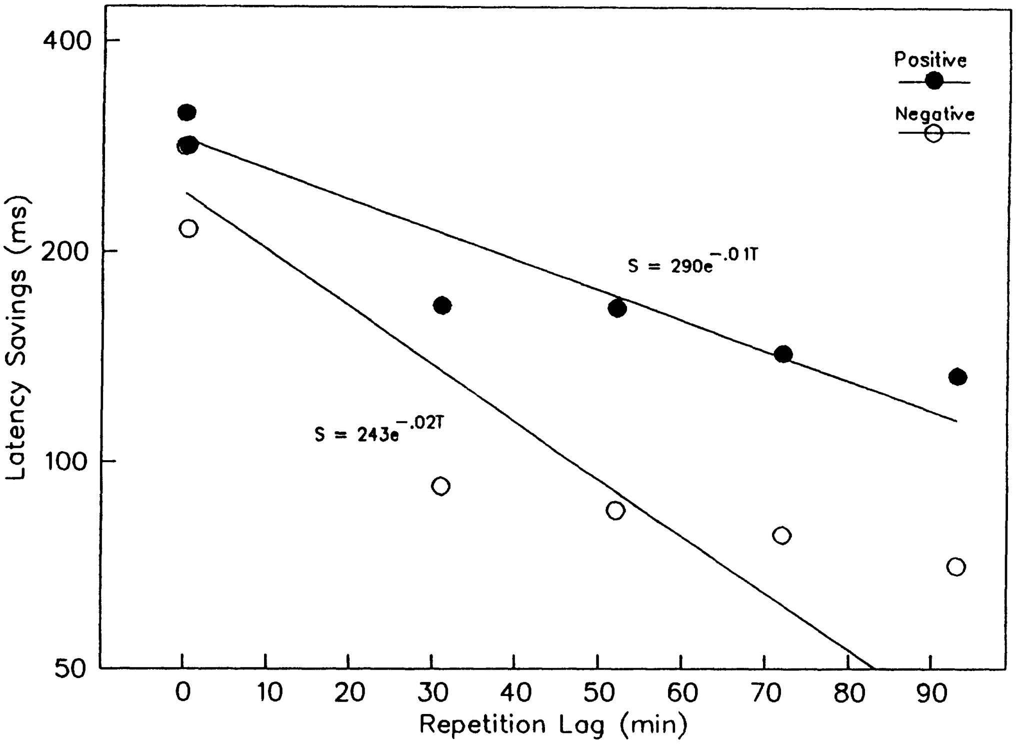

Figure 2. Exponential model fit to mean latency savings for repeated trials in Experiment 1 (log savings plotted on time)

Two versions of Wickelgren's power-exponential model (Equation 3) were tested. A 2-parameter version fixed c to be .75 and a 3-parameter version allowed c to be estimated. The 2-parameter model fit (R^2 = .993) was nearly as good as the 3-parameter model fit (R^2 = .998), supporting Wickelgren's (1972) contention that c = .75 describes resistance to forgetting with respect to simple verbal materials. In the 3-parameter model, the estimated values for c were .76 for positive trial savings and .89 for negative trial savings.

Figure 4 represents the 2-parameter exponential-power model fit. According to this model, log savings should be a linear function of time to the .25 power. As seen in Figure 4, positive and negative trial savings had different forgetting rate parameters. When the 2-parameter model was constrained to estimate the same rate parameter for positive and negative trial savings, the fit was reduced to R^2 = .947.

Finally, we tested the power function which has been proposed to account for forgetting data by several researchers (Anderson 1983; Wickelgren 1974a, 1976; Wixted & Ebbesen, 1991):

$$S_i = aT_i^{-b} \tag{4}$$

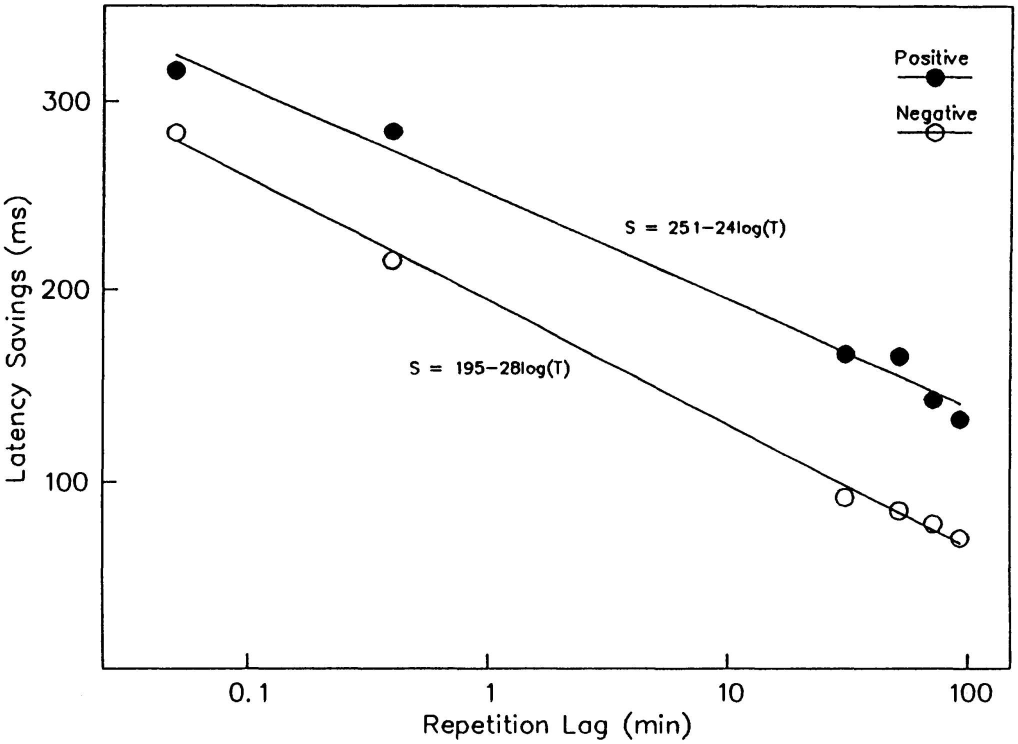

Figure 3. Logarithmic model fit to mean latency savings for repeated trials in Experiment 1 (savings plotted on log time)

where S is the latency savings from repeating an event at time interval i, a is the savings after one unit of time has elapsed since the original processing event, T is the time at interval i since the original processing event, and b is the forgetting rate. Like the logarithmic and exponential-power models, the proportion of change (priming loss) declines with time in the power function. Wixted and Ebbesen demonstrated that the power function fits a variety of forgetting measures from both human and animal memory studies.

Similar to the logarithmic and exponential-power functions, the power function of Equation 4 fit the mean data well (R^2 = .985). Figure 5 represents the power function's fit, where log savings should be a linear function of log time. Again, note that positive and negative trial savings had different forgetting rate parameters. When the model was constrained to estimate the same rate parameter for positive and negative trial savings, the fit was reduced to R^2 = .937.

In addition to fitting mean data, we also fit the four mathematical functions to individual subject data for the 12 data points shown in Figures 2–5. Results of the individual model fits were consistent with sample mean model fits. The exponential model (Equation 1) had the lowest fits (*Mdn* R^2 = .70). The logarithmic, exponential-power, and

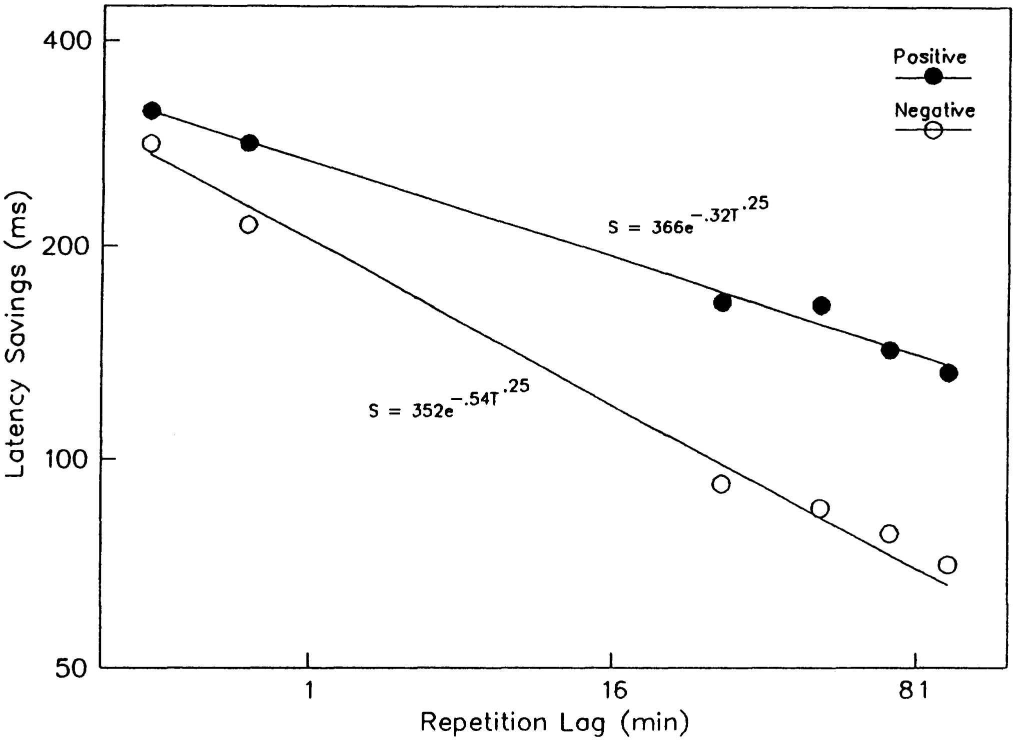

Figure 4. Exponential-power model fit to mean latency savings for repeated trials in Experiment 1 (log savings plotted on time raised to the .25 power)

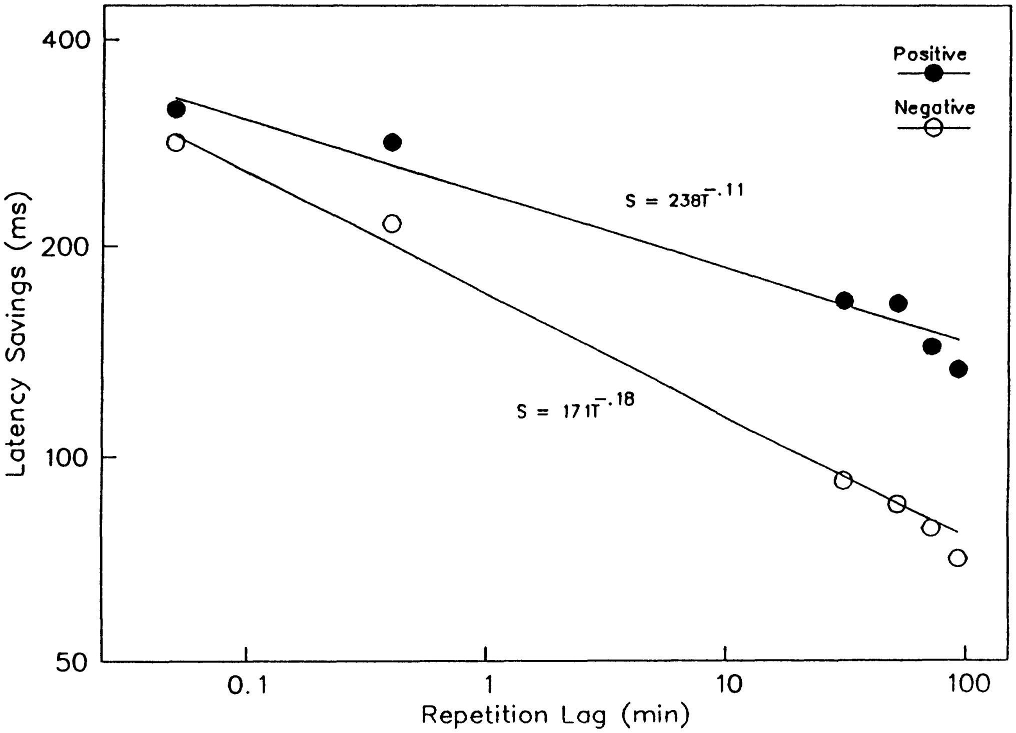

Figure 5. Power function fit to mean latency savings for repeated trials in Experiment 1 (log savings plotted on log time)

power functions had comparable fits (*Mdn* R^2 = .76; *Mdn* R^2 = .77; *Mdn* R^2 = .78, respectively).

DISCUSSION

Priming effects for repeated semantic comparison trials were still evident after filled delays up to 90 min (approximately 100 ms of facilitation on trials that typically take less than 1,250 ms). Such persistence is not surprising given that repetition priming effects have been detected after one year for other verbal processing tasks (Kolers, 1976; Sloman et al., 1988).

Of most interest, repetition priming effects declined systematically over the lag intervals investigated. In particular, forgetting in repetition priming conformed to models previously used to describe forgetting in explicit memory measures. Logarithmic, exponential-power, and power functions fit mean and individual data with approximately equal accuracy. Although they differ, all three models conform to Jost's second law formulated almost a century ago which states that forgetting decreases with age of a memory trace (see Hovland, 1951). The data from this experiment could not distinguish between the fits of these three functions, but their differences over longer intervals will become apparent later in Experiment 2.

A final finding of interest was that an additional priming exposure resulted in a small but reliable increase in facilitation after delays of 30–90 min. This benefit occurred only if both priming trials were identical to the target. When the second prime differed from both the first prime and the target (e.g., *moist damp* became *moist blue* for the second priming trial only), there was no benefit from the second prime. On the other hand, there was no apparent disruption due to this incongruent second prime. That is, facilitation from seeing one congruent and one incongruent priming trial was equivalent to facilitation from seeing only one congruent priming trial. This is consistent with the notion that separate memory representations are formed for each trial and that facilitation from previous trials is a function of a decreasing minimum time to retrieve an identical instance (see Logan, 1988, 1990).

EXPERIMENT 2

Discrimination between the three best fitting models in Experiment 1 was not possible because only a few relatively close lag intervals were investigated. Despite equivalent fits, the logarithmic, exponential-power, and power functions estimated from Experiment 1 data made different predictions about the magnitude of savings after longer delay intervals. Experiment 2 tested these predictions with repetition lags of 8 days rather than 30–90 min. The semantic comparison task from Experiment 1 was used except that a delay of 8 days was introduced between Block 1 and Blocks 2–5.

METHOD

Participants

Experiment 2 included 250 male and female students participating in an 8-day study on the acquisition of Pascal programming skills from an intelligent tutoring system (see Shute, 1991). They were recruited from local colleges and technical schools and selected to match demographic and general ability characteristics of the Air Force enlisted population. We eliminated approximately 19% of the total sample from analyses presented here for failure to complete both Day 1 and Day 8 semantic comparison trials. Approximately 13% of the remaining group were eliminated because performance scores indicated lack of effort (i.e., high error rates). Of the remaining 176 participants, 144 were male and 32 were female. All were high school graduates or equivalent (mean age = 22 years, *SD* = 3), and were paid for their participation in 40 hr of testing and instruction.

Procedure

Groups of 15–20 students participated in the 8-day study at Lackland Air Force Base, TX. For the experimental task reported here, the testing apparatus and general procedures were identical to Experiment 1.

On the morning of Day 1, a brief orientation to the entire Pascal programming study was given. Participants then took 6 hr of cognitive ability tasks, with short breaks between tasks and a 1-hr break for lunch. Block 1 of the semantic comparison task from Experiment 1 was administered during this time. Different groups of participants received a different ordering of the cognitive tasks, but the semantic comparison task was administered within the first 3 hr of the morning session for all participants.

Days 2–6 consisted of instruction in Pascal programming delivered on artificial intelligence workstations. This treatment and its results are reported elsewhere (Shute, 1991). On the morning of the 7th weekday of each individual's participation, those who had completed the Pascal tutor took another battery of cognitive tasks. Blocks 2–5 of the semantic comparison task from Experiment 1 were administered contiguously within this battery. Again, different groups of participants received a different ordering of the tasks, but all received the semantic comparison blocks within the first 3 hr of their 7th day. Because participants took the semantic comparison task on the 1st and 7th days of the study and a weekend interrupted every participant's 7 days, 8 days always intervened between first and second administrations of the repeated semantic comparison task.

RESULTS

Mean repetition priming effects are presented in Tables 3 and 4. Data in Table 3 describe savings during Block 1 (Day 1). These data were consistent with Experiment 1 data and with previous findings (Woltz, 1990). Table 4 presents mean savings on Blocks 2–5 (Day 8). In Table 4, it is clear that repetition effects were still evident 8 days after the priming trials, $F(1, 175) = 103.53$, $MSE = 63{,}665$. This was true for both positive and negative repeated trials, although facilitation was greater for positive trials, $F(1, 175) = 50.40$, $MSE = 36{,}250$.

Table 4 also shows that after 8 days there was no reliable effect of seeing a trial twice rather than once on Day 1, $F(1, 175) = 1.93$, $p > .05$. This was in contrast to Experiment 1, which showed such an effect when the lag interval was less than 2 hr. This result suggests that facilitation gained from an additional priming exposure may decline more rapidly than the facilitation gained from the first exposure.

If repetition savings existed after 8 days, the primary question of interest here was whether the logarithmic, exponential-power, or power function from Experiment 1 would best predict the magnitude of savings. First, we confirmed that the subjects in Experiments 1 and 2 did not differ on their performance on Block 1 trials (recall that Block 1 was equivalent for both groups). No reliable differences were found on mean first exposure latency, $F(1, 448) < 1$; on mean savings for exact repetitions, $F(1, 448) = 2.35$, $p > .05$; or on the effect of Lags 1–8, $F(2, 447) = 1.48$, $p > .05$.

The logarithmic function fit to Experiment 1 sample mean data predicted savings after 8 days of 24 ms for positive repeated trials and negative savings for negative repeated trials. In contrast to these predicted savings after 8 days, there were observed savings of 75 ms (95% confidence interval: 62–88) for positive trials and 27 ms (95% confidence interval: 13–41) for negative trials. It is evident from the predicted and observed savings that the logarithmic function estimated from Experiment 1 data failed to accurately describe the savings at longer delay intervals in Experiment 2. To illustrate the relatively poor fit of the logarithmic model for savings across both experiments, mean data from Tables 3 and 4 were plotted along with Experiment 1 mean data. Figure 6 shows expected and observed values for the logarithmic model where savings should be a linear function of log time. As seen in this figure, logarithmic function fit savings data for lags of 90 min and less, but it did not generalize to savings by an equivalent sample after 8 days. The fit of this model to mean data from both samples combined (24 observations) was $R^2 = .954$.

Table 3. Block 1 mean latency savings (in milliseconds) for repeated semantic comparison trials by trial condition from Experiment 2 ($N = 176$)

Repetition type		Repetition lag (trials)		
First exposure	Second exposure	1	2	8
Positive	Negative	282	194	265
Positive	Negative	164	111	134
Negative	Positive	−1	16	35
Negative	Negative	259	191	231

Note. Latency savings were computed as the difference between second exposure latency and first exposures of the same match (positive or negative) within each repetition lag.

Table 4. Blocks 2–5 mean latency savings (in milliseconds) for repeated semantic comparison trials by trial condition from Experiment 2 ($N = 176$)

Day-1 exposure		Block on Day 8			
First	Second	2	3	4	5
	Positive trials				
Positive	None	82	68	80	81
Positive	Negative	57	48	80	82
Positive	Positive	64	54	74	94
	Negative trials				
Negative	None	20	53	10	46
Negative	Positive	11	34	38	32
Negative	Negative	12	22	8	32

Note. Latency savings were computed as the difference between repeated trial latency (second or third exposure) and new trial latency within each repetition type and block.

The 2-parameter exponential-power model fit to Experiment 1 sample mean data predicted savings after 8 days of 13 ms for positive repeated trials and 1 ms for negative repeated trials. Comparing these predicted savings to the 95% confidence intervals for the observed savings (62–88 ms for positive trials and 13–41 ms for negative trials), it is evident that the exponential-power function estimated from Experiment 1 data did not accurately describe the savings at longer delay intervals in Experiment 2. To illustrate the poor fit of the exponential-power model for savings across both experiments, mean data from Tables 3 and 4 were plotted along with Experiment 1 mean data.

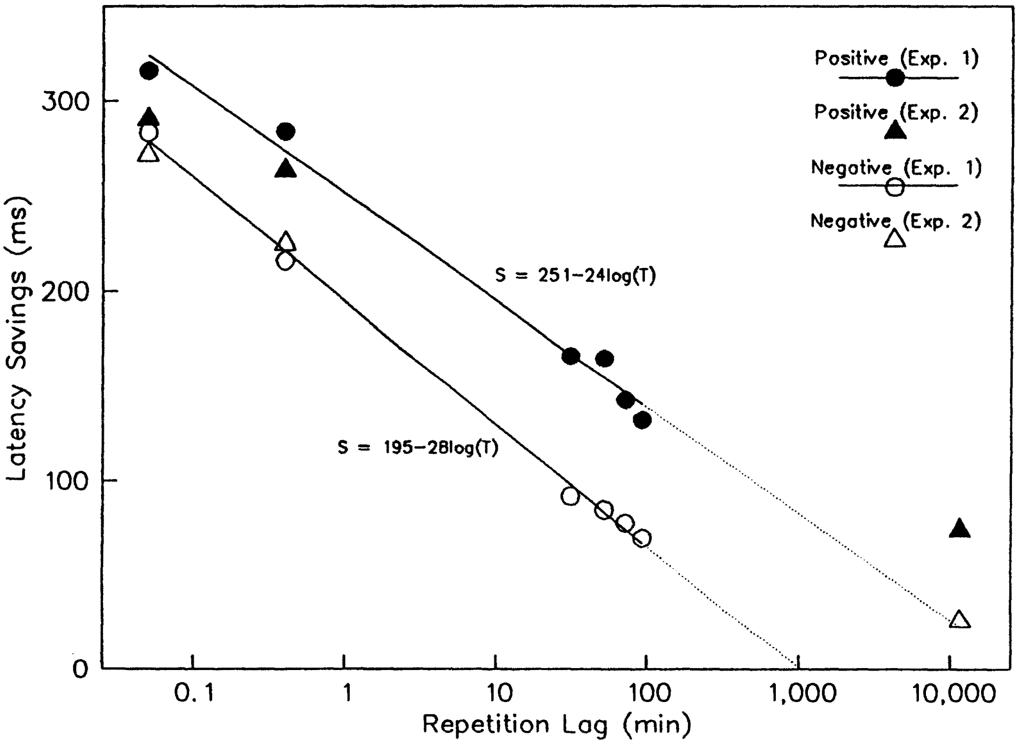

Figure 6. Expected and observed savings after 8 days according to the logarithmic model fit to mean latency savings from Experiment 1 (savings plotted on log time)

Figure 7 shows expected and observed values for the 2-parameter exponential-power model where log savings should be a linear function of time raised to the .25 power. As seen in this figure, the exponential-power model fit savings data for lags of 90 min and less, but this model did not generalize to savings by an equivalent sample after 8 days. Allowing the *c* parameter to be estimated rather than fixed at .75 did not improve the predicted savings at Day 8. The fit of the 2-parameter exponential-power function to mean data from both samples combined (24 observations) was $R^2 = .935$.

In contrast to the logarithmic and exponential-power functions, the power function estimated from Experiment 1 data predicted measurable savings for both positive and negative trials after 8 days. Predicted values were 87 ms for positive repeated trials and 33 ms for negative repeated trials. Comparing these with the 95% confidence intervals for the observed values (62–88 ms for positive trials and 13–41 ms for negative trials), it is clear that the power function predicted these savings more accurately than the other models. Again, mean data from Tables 3 and 4 were plotted along with Experiment 1 mean data to illustrate the fit of this model across both experiments.

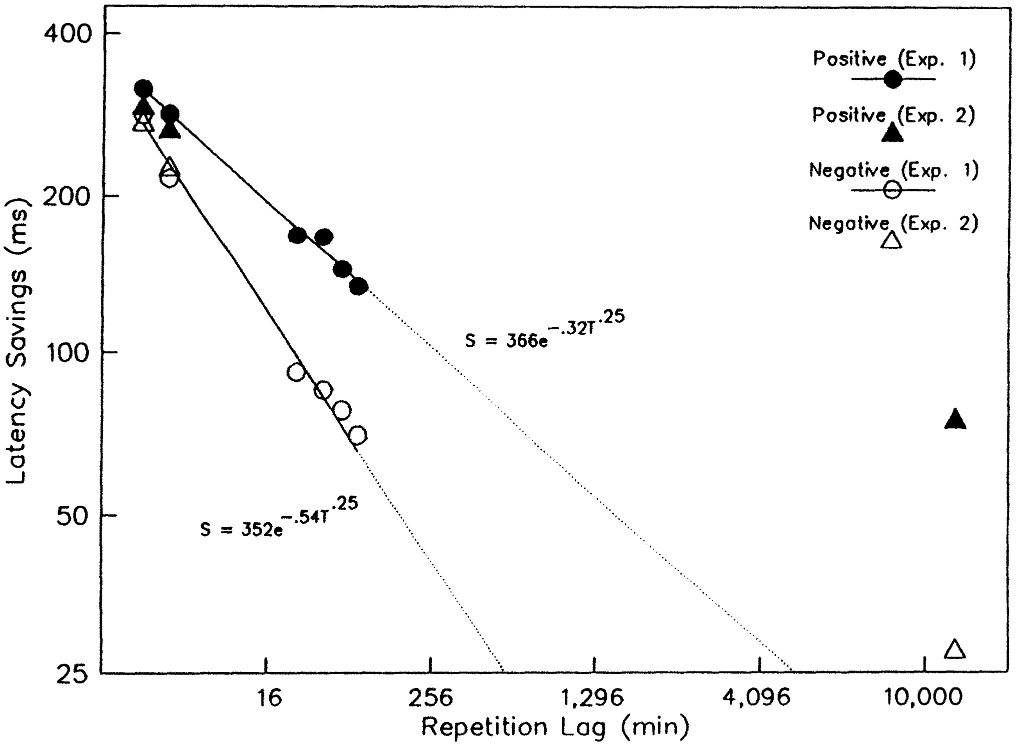

Figure 7. Expected and observed savings after 8 days according to the exponential-power model fit to mean latency savings from Experiment 1 (log savings plotted on time raised to the .25 power)

Figure 8 shows expected values (calculated from Experiment 1 data only) and observed values for the power function where log savings should be a linear function of log time. As seen in this figure, the model fit savings over both experiments notably better than did either the logarithmic or exponential-power functions depicted in Figures 6 and 7. The fit of the power function to mean data from both samples combined (24 observations) was $R^2 = .979$.

Although the power function fit the savings data across both experiments best, Figure 8 shows that model parameters from Experiment 1 slightly overestimated savings after 8 days in Experiment 2. In both Experiments 1 and 2, deviation from a linear fit in log-log space appeared to be largely due to the observed values at Lag 1 (0.05 min). Because Lag 1 repetitions were unique in that there were no intervening trials (thus previous trial contents would presumably be in working memory), we also fit the power function to Experiment 1 savings excluding Lag 1. When this was done, predicted savings after 8 days were 75 ms for positive trials and 28 ms for negative trials. As shown in Figure 9, the omission of Lag 1 savings improved

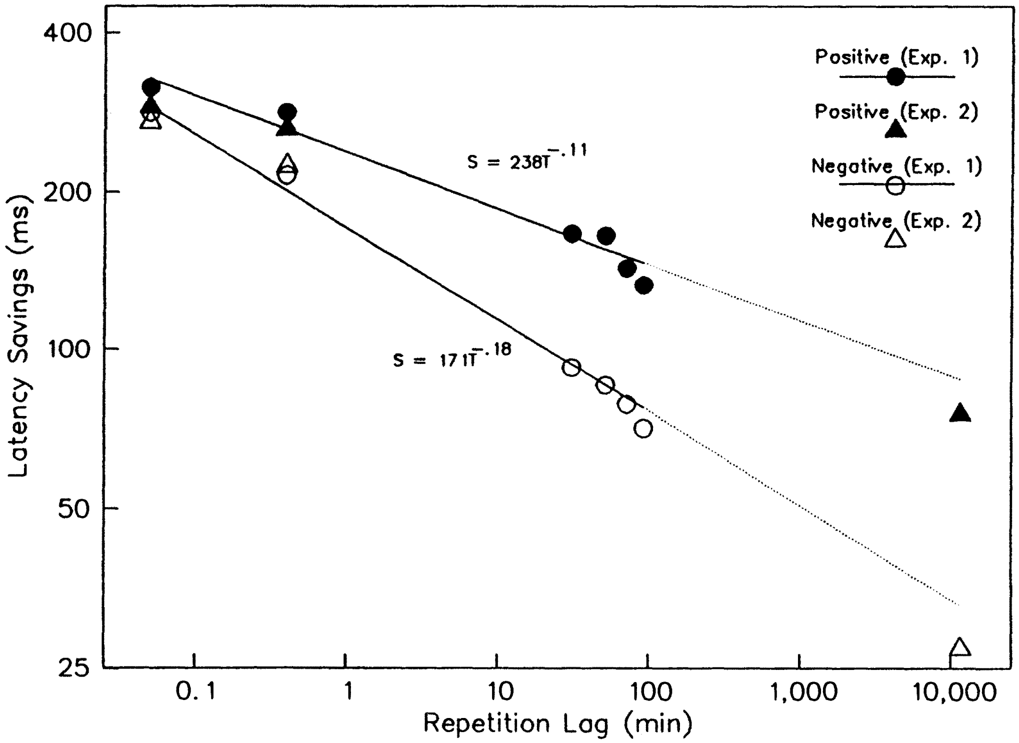

Figure 8. Expected and observed savings after 8 days according to the power function fit to mean latency savings from Exp. 1 (log savings plotted on log time)

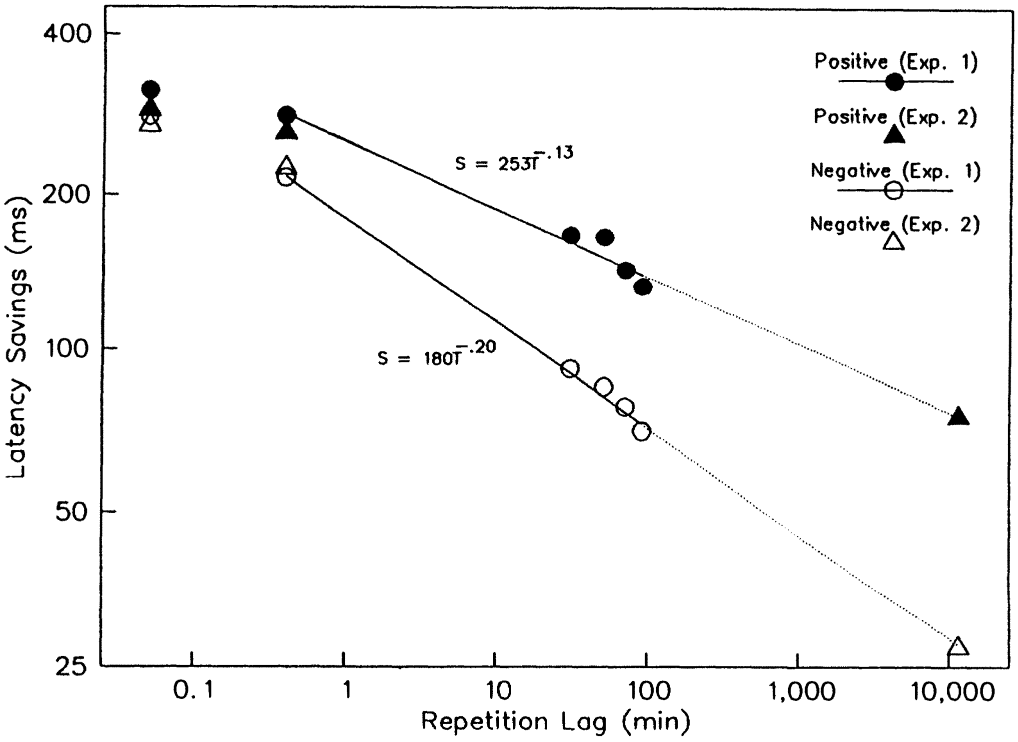

Figure 9. Expected and observed savings after 8 days according to the power function fit to mean latency savings from Exp. 1 excluding Lag 1 (log savings plotted on log time)

the prediction of savings after 8 days (compare Figure 9 with Figure 8).

DISCUSSION

There were reliable repetition priming effects in the semantic comparison task with 8 days intervening between prime and target trials. This result may not seem particularly surprising given the longevity of priming effects seen in other tasks (Kolers, 1976; Sloman et al., 1988). However, unlike the current study, most previous studies of the persistence of repetition priming have used tasks that place relatively high demands on perceptual processes and relatively low demands on semantic processes (e.g., the word-stem completion task used by Sloman et al., 1988; the lexical decision task used by Scarborough et al., 1977; the tachistoscopic word recognition task used by Jacoby, 1983). Related to this, Tulving and Schacter (1990) have argued that repetition priming effects are dependent on a perceptual memory system that is separate from semantic memory. In light of this, the long-lasting repetition priming effects observed for a task placing heavy demands on semantic processing are of some consequence.

The magnitude of the repetition effects reported here, even after 8 days, suggests that they cannot be wholly perceptual in nature. That is, Woltz (1990) estimated the effects of perceptual consistency on repetition priming in the semantic comparison task to be on the order of 25 ms. The savings found for repeated positive trials after 8 days in the current study was approximately three times this value. Thus, the persistent nature of repetition priming effects could not be entirely perceptual in nature.

Regarding the time course of priming loss, the finding of primary importance was that only one of the three models that fit data from Experiment 1 was able to predict the savings at longer delays in Experiment 2. The logarithmic model (Ebbinghaus, 1885/1964) and the exponential-power model (Wickelgren, 1972, 1974b) failed to adequately predict savings after 8 days, whereas the power model (Anderson, 1983; Wickelgren, 1974a, 1976; Wixted & Ebbesen, 1991) predicted the savings at longer lags with some degree of accuracy.

In his early work on forgetting, Wickelgren (1972, 1974b) rejected the power function along with several other models in favor of the exponential-power function for describing forgetting in *d′* measures of recognition. Despite rejecting the power function, Wickelgren (1972) reported that it did fit data from his experiments as well as the exponential-power model did. It was rejected because in one experiment, estimates of power function forgetting rates varied over short and long delays. In subsequent work, however, Wickelgren (1974a, 1976) proposed a memory model with power function forgetting. Similarly, Anderson (1983) included a power function for describing long-term memory retention in his adaptive control of thought (ACT*) theory. Unfortunately, most of the evidence supporting the power function's fit to forgetting data was never published. Wixted and Ebbesen (1991), however, have provided empirical support for the power function in reporting that it consistently fit a variety of forgetting data better than did other models including the exponential-power function.

A recent study provided direct evidence for the fit of a power function to forgetting in repetition priming effects. Grant and Logan (1993) reported two experiments with a lexical decision task that investigated both the buildup of priming effects as a function of the number of repetitions and the loss of priming as a function of delay interval. Delay intervals ranged from 5 min to 2 months. Of relevance to the current study, priming effects for words were fit best by the power function compared with the other functions tested here. However, this was not the case with priming effects for nonwords. Here, the fit of other functions (e.g., logarithmic, exponential-power, and hyperbolic functions) was as good as or better than that of the power function. This raises a question about the importance of preexisting long-term memory representations in priming, and specifically in the functional form of forgetting for priming effects. In any event, repetition priming effects in the lexical decision task that accrue from multiple exposure to words are long lasting, and they decline systematically over a wide range of delay intervals according to a power function. This finding is consistent with the evidence reported here regarding long-term priming effects in the semantic comparison task.

Finally, the power function fit to the data from Experiments 1 and 2 required a different forgetting rate parameter for positive and negative trial repetitions, with facilitation on negative trials declining faster than that for positive trials. This observation is theoretically meaningful only under the assumption that our scale of measurement (i.e., latency savings) represents equal intervals on the psychological dimension of memory strength. Moreover, the interpretation of rate parameter differences is further complicated because trial type (positive versus negative) was confounded with response hand (right versus left). Nevertheless, the observed difference in forgetting rate parameters resembles other researchers' conclusions that retention differs for positive and negative trials of a task. Schulman (1974) investigated memory for trials of a semantic verification task (e.g., *Is a corkscrew* *an opener?* or *Is a dungeon a scholar?*). He found superior recall and recognition for positive (congruent) trials. Also related to this may be the finding that negative trials (nonwords) in a lexical decision task show less repetition priming and faster forgetting than positive trials (e.g., Dannenbring & Briand, 1982; Forbach, Stanners, & Hochhaus, 1974; Scarborough et al., 1977). Such findings may be due to greater activation in existing semantic memory structures during positive compared with negative trials. However, an alternative explanation is simply that events positively matching a goal state are coded in some way that is more memorable. Regardless of the reason, the possibility of forgetting differences between positive and negative semantic processing events is worth further investigation using both implicit and explicit memory measures.

GENERAL DISCUSSION

Of primary interest in this research was the fact that the same power function parameters described repetition priming effects in two experiments that differed in repetition delay time by several orders of magnitude. One implication of this finding is that we can, with caution, extrapolate the loss of facilitation over even longer delay intervals.

We estimated when facilitation would not differ reliably from zero ($p < .05$) using the standard error of mean savings at Day 8. For negative trials, facilitation was predicted to be immeasurable (i.e, declining to 14 ms) after approximately 8 months. For positive trials, however, facilitation was predicted to be immeasurable (i.e., declining to 13 ms) only at a point well beyond an individual's life expectancy. Even the most conservative prediction using a lower bound estimate of forgetting rate suggests that savings should still be reliable several hundred years after priming.

The extrapolation for positive trial savings suggests that forgetting in repetition priming from a single semantic processing episode is so slow that the memory effect might be considered permanent. However, we recognize that extrapolation beyond observed data is dangerous. Furthermore, we need to emphasize some qualifications that pertain to this particular extrapolation. First, observed savings after a week, and any longer periods, are probably contingent upon exact replication of the original exposure conditions. The requirement for exact replication includes stimulus feature consistency (see Jacoby & Hayman, 1987; Masson, 1986; Roediger & Blaxton, 1987; Woltz, 1990), but it may also include consistency of the general experimental context (i.e., the laboratory setting). In other words, although we entertain the possibility that memory representations underlying these repetition priming effects may be operative for many years, we recognize that it probably takes highly specific processing demands to activate them. Second, although Kolers (1976) and Sloman et al. (1988) found prior processing effects to exist after a year, the extrapolation mentioned above may overestimate the longevity of repetition effects for several reasons. That is, savings could decline more rapidly over longer periods than those investigated because (a) subjects' activities in subsequent months and years would differ from those experienced in the 8-day study (i.e., they would probably be more varied), and (b) aging may produce physiological and psychological changes not represented in the 8-day period. Despite these mitigating factors, the predicted longevity of repetition priming effects is worth testing at considerably longer intervals.

A final point of interest concerns the fit of the power function to forgetting in an implicit memory task. Several researchers have suggested that implicit memory measures show less forgetting than explicit memory measures (Cave & Squire, 1992; Jacoby & Dallas, 1981; Fuestel, et al. 1983; Kolers, 1976; Komatsu & Ohta, 1984; Tulving, Schacter, & Stark, 1982). This has been counted as one of several observed dissociations between implicit and explicit memory measures (e.g., Schacter, 1987; Tulving & Schacter, 1990). The fit of the power function to repetition priming data in the current studies brings into question the extent of this dissociation. After all, the power function appears to be the leading candidate for fitting forgetting data from explicit memory measures such as recall and recognition (Anderson, 1983; Wickelgren, 1974a, 1976; Wixted & Ebbesen, 1991). Although much more evidence is needed to argue this forcefully, it seems possible that implicit and explicit measures may possess the same functional form of forgetting. Implicit measures may exhibit slower forgetting rates simply because they are more sensitive memory measures (see Nelson, 1978).

Given the indeterminate relationship between the measurement scales of both implicit and explicit memory measures and the psychological variable of interest (memory strength), this previous statement should be considered a speculation rather than a conclusion. As advocated by Wixted and Ebbesen (1991), support for this speculation requires more empirical comparisons of forgetting functions such as those reported here, but ideally involving a variety of implicit memory measures.

Notes

The research reported in this article was conducted within the Learning Abilities Measurement Program (LAMP), a multiyear basic research project of the Air Force Human Resources Directorate, Armstrong Laboratory, which is partially sponsored by the Air Force Office of Scientific Research. This work was also partially supported by a grant to Dan J. Woltz from the Air Force Office of Scientific Research, Cognition Program.

We thank Patrick Kyllonen, Raymond Christal, Scott Chaiken, William Tirre, and William Alley for suggestions during the conduct of this research. We are also indebted to programmers from the OAO Corporation, especially Cynthia Garcia, Trace Cribbs, Richard Walker, and Janet Hereford. Finally, we thank Wayne Wickelgren, Norman Slamecka, John Wixted, Janet Gibson, and two anonymous reviewers for helpful comments on earlier drafts of this article.

Correspondence concerning this article should be addressed to Dan Woltz, Department of Educational Psychology, 327 Milton Bennion Hall, University of Utah, Salt Lake City, UT 84112. E-mail: woltz@gse.utah.edu. Received for publication September 10, 1993; revision received May 5, 1994.

1. Lag 2 data from Table 1 were omitted because savings at this lag are consistently less than savings for later lags. Savings at this lag are thought to reflect a consolidation period in addition to forgetting (see also Woltz, 1990).

2. We also evaluated the various mathematical functions on priming expressed as the percentage of change between primed and unprimed conditions, the difference in rate of responding (1/latency) between primed and unprimed conditions, and the percentage of change in rate of responding between primed and unprimed conditions. The rank order of model fits did not change across these different methods of expressing priming, so results are reported only for the latency difference expression of priming.

References

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Begg, I., & Wickelgren, W. A. (1974). Retention functions for syntactic and lexical vs semantic information in sentence recognition memory. *Memory & Cognition, 2,* 353–359.

Bogartz, R. S. (1990a). Evaluating forgetting curves psychologically. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 138–148.

Bogartz, R. S. (1990b). Learning-forgetting rate independence defined by forgetting function parameters or forgetting function form: Reply to Loftus and Bamber and to Wixted. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 936–945.

Cave, C. B., & Squire, L. R. (1992). Intact and long-lasting repetition priming in amnesia. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 509–520.

Dannenbring, G. L., & Briand, K. (1982). Semantic priming and the word repetition effect in a lexical decision task. *Canadian Journal of Psychology, 36,* 435–444.

Ebbinghaus, H. (1964). *Memory* (H. A Ruger & C. E. Bussenius, Trans.). New York: Dover. (Original work published 1885)

Feustel, T. C., Shiffrin, R. M., & Salasoo, A. (1983). Episodic and lexical contributions to the repetition effect in word identification. *Journal of Experimental Psychology: General, 112,* 309–346.

Forbach, G. B., Stanners, R. F., & Hochhaus, L. (1974). Repetition and practice effects in a lexical decision task. *Memory & Cognition, 2,* 337–339.

Grant, S. C., & Logan, G. D. (1993). The loss of repetition priming and automaticity over time as a function of degree of initial learning. *Memory & Cognition, 21,* 611–618.

Hovland, C. I. (1951). Human learning and retention. In S. S. Stevens (Ed.), *Handbook of experimental psychology* (pp. 613–689). New York: Wiley.

Jacoby, L. L. (1983). Perceptual enhancement: Persistent effects of an experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 21–38.

Jacoby, L. L., & Dallas, M. (1981). On the relationship between autobiographical memory and perceptual learning. *Journal of Experimental Psychology: General, 110,* 306–340.

Jacoby, L. L., & Hayman, C. A. G. (1987). Specific visual transfer in word identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 456–463.

Kolers, P. A. (1976). Reading a year later. *Journal of Experimental Psychology: Human Learning and Memory, 2,* 554–565.

Komatsu, S. I., & Ohta, N. (1984). Priming effects in word fragment completion for short and long retention intervals. *Japanese Psychological Research, 26,* 194–200.

Loftus, G. R. (1985a). Consistency and confoundings: Reply to Slamecka. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 817–820.

Loftus, G. R. (1985b). Evaluating forgetting curves. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 397–406.

Loftus, G. R., & Bamber D. (1990). Learning-forgetting independence, unidimensional memory models, and feature models: Comment on Bogartz (1990). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 916–926.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492–527.

Logan, G. D. (1990). Repetition priming and automaticity: Common underlying mechanisms? *Cognitive Psychology, 22,* 1–35.

Masson, M. E. J. (1986). Identification of typographically transformed words: Instance-based skill acquisition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12,* 479–488.

Nelson, T. O. (1978). Detecting small amounts of information in memory: Savings for nonrecognized items. *Journal of Experimental Psychology: Human Learning and Memory, 4,* 453–468.

Roediger, H. L., & Blaxton, T. A. (1987). Effects of varying modality, surface features, and retention interval on priming in word-fragment completion. *Memory & Cognition, 15,* 379–388.

Scarborough, D. L., Cortese, C., & Scarborough, H. S. (1977). Frequency and repetition effects in lexical memory. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 1–17.

Schacter, D. L. (1987). Implicit memory: History and current status. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 501–518.

Schulman, A. I. (1974). Memory for words recently classified. *Memory & Cognition, 2,* 47–52.

Shute, V. J. (1991). Who is likely to acquire programming skills? *Journal of Educational Computing Research, 7,* 1–24.

Slamecka, N. J. (1985). On comparing forgetting rates. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 812–816.

Sloman, S. A., Hayman, C. A. G., Ohta, N., Law, J., & Tulving, E. (1988). Forgetting in primed fragment completion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 223–239.

Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science, 247,* 301–306.

Tulving, E., Schacter, D. L., & Stark, H. A. (1982). Priming effects in word fragment completion are independent of recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 336–342.

Wickelgren, W. A. (1972). Trace resistance and the decay of long-term memory. *Journal of Mathematical Psychology, 9,* 418–455.

Wickelgren, W. A. (1974a). Single-trace fragility theory of memory dynamics. *Memory & Cognition, 2,* 775–780.

Wickelgren, W. A. (1974b). Strength/resistance theory of the dynamics of memory storage. In D. H. Krantz, R. C. Atkinson, R. D. Luce, & P. Suppes (Eds.), *Contemporary developments in mathematical psychology: Learning, memory and thinking* (pp. 209–242). San Francisco: W. H. Freeman.

Wickelgren, W. A. (1976). Network strength theory of storage and retrieval dynamics. *Psychological Review, 83,* 466–478.

Wixted, J. T. (1990). Analyzing the empirical course of forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 927–935.

Wixted, J. T., & Ebbesen, E. B. (1991). On the form of forgetting. *Psychological Science, 2,* 409–415.

Woltz, D. J. (1988). An investigation of the role of working memory in procedural skill acquisition. *Journal of Experimental Psychology: General, 117,* 319–331.

Woltz, D. J. (1990). Repetition of semantic comparisons: Temporary and persistent priming effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 392–403.

Woltz, D. J., & Shute, V. J. (1993). Individual difference in repetition priming and its relationship to declarative knowledge acquisition. *Intelligence, 17,* 333–359.