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Repetition Priming and Automaticity: Common Underlying Mechanisms?

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Repetition priming and automaticity are both consequences of prior presentations. This article draws theoretical and empirical parallels between them, arguing that they result from a common mechanism, namely, the storage and retrieval of representations of individual exposures to specific items, or *instances*. Theoretically, repetition priming is viewed as the first few steps on the way to automaticity. Empirically, repetition priming and automaticity are shown to share three major characteristics: (a) The speed of processing increases as a power function of the number of exposures to a specific stimulus, (b) the benefit from repeated exposures is specific to individual items, and (c) the benefit is based on underlying associations between stimuli and the interpretations given to them in the context of specific experimental tasks.

The effects of prior exposure to stimuli are important in many areas of psychology, notably, the psychology of memory and the psychology of attention and automaticity. Students of memory typically investigate the effects of one or two stimulus exposures on performance on recognition or recall tasks. More recently, they have been concerned with the effects of one or two exposures on implicit measures of memory, such as repetition priming. By contrast, students of attention typically investigate the effects of several hundred stimulus exposures, concerning themselves with the extent to which the stimuli are processed automatically. Tests of automaticity can be interpreted as implicit measures of memory, so the two areas may be testing different ends of the same continuum. The purpose of this article is to begin to bridge the gap between the areas by exploring empirical parallels between repetition priming and automaticity and by presenting a theory that integrates them.

Automaticity is typically viewed as a special topic in the study of attention. It is interesting in that context because automaticity seems to be

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a way around the limitations of attention. According to theory, automatic processing does not demand (much) attention. It is fast because it is not subject to limitations on attentional capacity. It is effortless because it demands little (or no) attention, and effort increases with demand for attention. It is obligatory because is does not depend on attention to be instigated and brought to completion. Much of the research in the last 15 years focused on these claims, testing their limits and the implications for theories of attention (for reviews, see Kahneman & Treisman, 1984; Logan, 1985a; Schneider, Dumais, & Shiffrin, 1984). Most researchers accept the idea that automaticity is a product of learning. Many use learning as a way to produce automaticity. But until recently, few focused on the learning mechanism itself (but see Logan, 1988; Schneider, 1985).

Repetition priming is a special topic in the study of memory. It is observed in paradigms in which items are repeated, typically once or twice (e.g., Scarborough, Cortese, & Scarborough, 1977). Responses are usually faster on the second presentation than on the first, and this difference is called *repetition priming*. Much of the interest in repetition priming stems from dissociations between it and other measures of memory, notably recognition and recall, which suggests they tap different memory systems or different aspects of memory. According to theory, repetition priming reflects *implicit* memory, whereas recall and recognition reflect *explicit* memory (for reviews, see Jacoby & Brooks, 1984; Schacter, 1987). Most experiments are addressed to distinguishing between memory systems or aspects. Few focus on relations between repetition priming and learning. None have related repetition priming to automaticity.

The main empirical question asked in this article is whether automaticity and repetition priming share three characteristics: (1) *Power-Function Speed-Up*. Does repetition priming increase as a power function of the number of exposures, as speed increases with automatization? (2) *Item Specificity*. Is automaticity specific to stimuli experienced during the training as repetition priming is specific to the stimuli experienced during the study phase? (3) *Associative Basis*. Does repetition priming depend on associations between stimuli and responses or response classes as automaticity does? The experiments were intended to reveal the nature of the association.

These questions were asked primarily in a *lexical decision* task, in which subjects decided whether or not a given letter string was a word. The lexical decision task was one of the first in which repetition priming was demonstrated, so it seemed to be an appropriate vehicle for demonstrating potential continuities between repetition priming and automaticity.

AN INSTANCE THEORY OF AUTOMATICITY

The main motivation for these questions was a theory about the relation between attention and memory, which I developed to account for the acquisition of automaticity in an earlier paper (Logan, 1988). A theory that accounts for the effects of a hundred exposures should also account for the effects of one or two, so in this paper, the focus is on repetition priming. The three characteristics under investigation were central to the theory, reflecting its fundamental assumptions. To show that automaticity and repetition priming share these three characteristics is to show that they can be accounted for by the same theory, the *instance theory of automaticity*.

The instance theory rests on three main assumptions: *obligatory encoding, obligatory retrieval,* and *instance representation*. The assumption of obligatory encoding asserts that attention to an item or event causes it to be encoded into memory. It may not be encoded very well or very distinctively, but it will be encoded whether or not the person intends to encode it. The assumption of obligatory retrieval asserts that attention to an item or event causes whatever was associated with it in the past to be retrieved from memory. Retrieval may not always be successful but it is instigated nevertheless whether or not the person intends it. The assumption of instance representation asserts that each item or event is represented separately in memory, even if it is identical to a previously experienced item or event. Evidence for these assumptions is reviewed by Logan (1988).

Applied to automaticity, the theory claims that performance is automatic when it is based on the retrieval of prior events from memory rather than some general algorithmic computation. Automatization involves a transition from performance based on a general algorithm to performance based on memory retrieval. The idea is well illustrated by the acquisition of simple addition facts: Initially, children add with a general counting algorithm that will allow them to generate the sum of any two digits, but after practice, they retrieve sums directly from memory without counting (Ashcraft, 1982; Siegler, 1987). The theory assumes that the decision to rely on memory is based on a race between the retrieval process and the algorithm—whichever finishes first determines performance. Each memory trace is assumed to be retrieved separately and independently, so with practice, more traces enter the race and memory is more likely to win. Eventually, memory will win all the time and the person will abandon the algorithm and rely on memory entirely (for further details, see Logan, 1988).

The idea that automatization involves a transition from algorithm-based processing to memory-based processing contrasts with traditional approaches, which assume that the same algorithm is used throughout practice; processing remains the same but uses less attention (e.g., La Berge & Samuels, 1974; Logan, 1978) or is done in parallel rather than in series (e.g., Shiffrin & Schneider, 1977). The evidence, reviewed by Logan (1988), seems contrary to these approaches.

The instance idea can be easily applied to repetition priming: On the first exposure to an item, the person relies on some general algorithm. Obligatory encoding causes a representation of the item and its context to be stored in memory. On the second exposure to the item, the person can engage the algorithm or rely on memory retrieval. The race model applied to automaticity can also apply here: whichever finishes first determines performance. Performance will be faster on the second presentation than on the first because it depends on the faster of the two processes. The race with memory screens out the slower algorithmic responses and the race with the algorithm screens out the slower memory responses. Like automaticity, repetition priming can be viewed as a shift from algorithmic processing on the first presentation to a mixture of algorithmic and memory-based processing on the second.[1]

The idea of a transition from one kind of processing to another is similar to some approaches to repetition priming but contrasts with others. It is similar to Jacoby's approach, which argues that performance on repeated items is based at least in part on what they retrieve from memory (e.g., Jacoby, 1978, 1983; Johnston, Dark, & Jacoby, 1985). It is also similar to Feustal, Shiffrin and Salasoo's (1983) ideas about repetition effects in naming tasks. They argue that initial performance is based on retrieval from semantic memory, whereas performance with repetitions is based on retrieval from episodic as well as semantic memory.

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[1] It is important to distinguish between mixtures produced by a race model, such as the instance theory, and mixtures produced by a probability mixture model. A race model produces a mixture of two 'parent' distributions by drawing a sample from each of them and selecting the fastest one for the mixture. By contrast, probability mixture models produce a mixture of two distributions by drawing a single sample from one distribution with probability p or a single sample from the other with probability $1-p$. Probability mixture models could predict a power-function speed-up from one distribution representing the initial algorithm and another representing memory-based performance, provided that the probability of sampling from memory increased appropriately with practice. However, probability mixture models generally predict an increase in variability as the mixture probability deviates from 0 to 1.0, so variability should increase with practice. By contrast, race models predict a reduction in variability with practice (because the losers of the race restrict the range that the winner can occupy), and that is what is observed in real data (see Logan, 1988). The instance theory predicts a power-function reduction in the standard deviation with practice, with the exponent of the function constrained to be equal to the exponent for the power-function reduction in the mean. Logan (1988) derived, tested, and confirmed this prediction in 16 data sets, effectively ruling out probability mixture models.

By contrast, other theories assume that the underlying process does not change: Morton's (1969, 1979) *logogen* theory assumes that repetition changes either the threshold or the resting activation level in abstract units that recognize words. Balota and Chumbley (1984) argued that repeated stimuli are processed in the same way as nonrepeated stimuli but with greater *familiarity* or *meaningfulness*. These approaches have the virtue of providing explanations for first-presentation performance, but they are less general in their domains of application than the instance theory (i.e., they apply primarily to lexical decision tasks; the instance theory is intended to apply to all initial tasks).

I will return to the contrast between these theories in the General Discussion. The representation assumptions of the instance theory will be developed further to interface with theories of first-presentation performance. That development is important but it is not necessary to motivate the experiments.

Power-Function Speed-Up

Improvement in performance with practice is the hallmark of automaticity—performance becomes faster as it becomes more automatic. In a wide variety of tasks, from cigar rolling to solving geometry problems, the speed-up in reaction time is a power function of the number of practice trials (Newell & Rosenbloom, 1981). That is,

$$RT = a + bN^{-c}$$

where RT is reaction time, N is the number of practice trials, and a, b, and c are parameters of the power function. A is the asymptote, reflecting an irreducible limit on performance, b is the difference between initial and asymptotic performance, reflecting the amount to be learned, and c is the exponent, reflecting the rate of learning. Modern theories of skill acquisition and automaticity try to account for the power-function speed-up, treating it as a 'benchmark' prediction that the theories must make if they are to be taken seriously (e.g., Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981; Schneider, 1985; also see Crossman, 1959).

The instance theory predicts a power-function speed-up from the race between the algorithm and the various traces in memory. Memory retrieval is assumed to be a stochastic process and each trace is assumed to have the same distribution of retrieval times. Thus, the finishing time for a race involving n traces can be modeled as the minimum of n samples from the same distribution. Logan (1988) presented a formal proof that the minimum decreases as a power function of n. Intuitively, the power-function speed-up follows from two opposing tendencies that govern the race: On the one hand, there are more opportunities to observe an extreme value as sample size increases, so the expected value of the minimum will decrease as the number of traces in memory increases. On the other hand, the more extreme the value, the lower the likelihood of sampling a value that is even more extreme, so adding traces to the race will produce diminishing returns. The first factor produces the speed-up; the second produces the negative acceleration that is characteristic of power functions.

There is nothing in the repetition priming paradigm to prevent researchers from presenting items several times, even several hundred times, and calculating repetition priming relative to reaction times on the first exposure. So repetition priming should produce the same power-function speed-up as automatization. However, only a few researchers studied the effects of multiple repetitions: Forbach, Stanners, and Hochhaus (1974) presented words and nonwords up to four times in a lexical decision task and found more repetition priming with more repetitions. Scarborough et al. (1977) presented words and nonwords up to three times, and found a benefit for the first repetition but no additional benefit for the second. Logan (1988) presented words and nonwords up to 16 times and found that benefit increased with repetition. The beneficial reductions in reaction time were well fit by power functions.

The present experiments examined the effects of multiple repetitions in the lexical decision task and fitted power functions to the data to confirm and extend these findings.

Item Specificity

The instance theory assumes that the retrieval process is content addressable, so that an item retrieves traces of prior experiences with itself or with closely similar items. It does not retrieve traces of experiences with other items that differ in significant ways. This recruitment-by-similarity assumption is common to instance-theoretic explanations of episodic memory (e.g., Hintzman, 1976; Jacoby & Brooks, 1984), semantic memory (e.g., Landauer, 1975), categorization (e.g., Hintzman, 1986; Medin & Schaffer, 1978), judgment (e.g., Kahneman & Miller, 1986), and problem solving (e.g., Ross, 1984).

Repetition priming is clearly item-specific. Typically, benefit accrues only for items experienced during the study phase. It is often assessed by comparing performance on repeated items with performance on items presented for the first time, and the difference is usually substantial. Moreover, the benefit is often specific to the physical and conceptual format of the first presentation. Thus, there is little transfer from words to pictures and vice versa (Scarborough, Gerard, & Cortese, 1979) and there is little transfer to words that contain the same letters unless the repeated letters form a morpheme (e.g., BURN would prime BURNT but RUN would not prime RUNT) (Murrell & Morton, 1974).

Automaticity also seems to be specific to the stimuli experienced during training. Typically, transfer to new stimuli is very poor (for reviews, see Logan, 1985a, 1988; Schneider et al., 1984; Shiffrin & Schneider, 1977; for exceptions, see Schneider & Fisk, 1984; Smith & Lerner, 1986).

The present experiments sought further evidence that repetition priming and automaticity are specific to the stimuli experienced during training.

Associative Basis

The instance theory assumes that the memory representation involves associations between an item and the processing episode in which it participated, but it does not specify the nature of the association. The stimulus may be associated with the interpretation given to it under the current task set or it may be associated with the response executed to report the interpretation. Whether stimuli are associated with interpretations or responses is an empirical question, which is the primary focus of the experiments reported in this article.

The idea of an underlying associative basis contrasts with current approaches to automaticity and repetition priming. Shiffrin and Schneider (1977) and Schneider (1985) argued that automaticity increases the propensity for stimuli to attract attention in addition to or instead of increasing the associative strength. Morton (1969, 1979) argued that repetition lowers thresholds or increases baseline activation in logogens; Balota and Chumbley (1984) argued that repetition increases the familiarity or meaningfulness of the item. Thus, evidence of an associative basis would impose strong constraints on current theories.

Automaticity clearly depends on associations. In visual and memory search tasks, *consistent* mapping of stimuli onto responses leads to automaticity but *varied* mapping does not (for reviews, see Schneider & Shiffrin, 1977; Schneider et al., 1984). Subjects may see the same stimuli in varied and consistent mapping and respond to them equally often, so the differences are not due to stimuli or to simple stimulus or response frequency. Rather, it is associations between particular stimuli and responses that matters; the associations are preserved in consistent mapping but change in varied mapping.

However, the nature of the associations underlying automaticity is not clear. Most search studies confound consistent stimulus-to-response mapping with consistent stimulus-to-*interpretation* mapping. Subjects in a consistently mapped search task may always press the right key to when presented with a member of the search set, but in addition, they also consistently classify the probe item as a member of the search set before responding. Thus, subjects may associate the stimulus directly with the required response (i.e., "press the right key") or with the interpretation it is given in the context of the task (i.e., "member of the search set").

Two search studies permit a distinction between these possibilities: Shiffrin and Schneider (1977, Experiment 3) required subjects to discriminate consistently between two sets of characters but varied which set was targets and which was distractors throughout practice. Stimulus-to-interpretation mapping was consistent because each stimulus always belonged to the same set, but stimulus-to-response mapping varied; subjects responded "yes" and "no" to each stimulus equally often. Subjects learned the discrimination well, and over sessions, the set-size effect diminished, which Shiffrin and Schneider (1977) consider evidence of automaticity.

Subsequently, Fisk and Schneider (1984) reported a search study in which subjects searched consistently for the same targets among the same distractors, but varied the key they pressed to report "yes" or "no" over trials. These subjects showed as much evidence of learning as subjects who searched and responded consistently throughout practice.

Repetition priming may also depend on associations, but the evidence is less clear. There is no analog of the consistent vs varied manipulation that pervades the automaticity literature. However, a few studies show a context specificity or a judgment specificity in repetition priming that is suggestive of stimulus-to-interpretation associations: Oliphant (1983) found that reading a word in the experimental instructions produced no benefit for subsequent lexical decisions, Forster and Davis (1984) found no benefit from prior pronunciation on subsequent lexical decision, and Ratcliff, Hockley, and McKoon (1985) found no benefit from prior recognition judgments ("is this stimulus old or new") on subsequent lexical decisions.

On the balance, then, the existing data suggest that stimulus-to-interpretation mapping is more important than stimulus-to-response mapping. However, it is important to replicate the effects jointly with the other two characteristics of automaticity and repetition priming, to replicate them with a task other than search (i.e., lexical decision), and to show that repetition effects observed in a single session respond to consistency manipulations in the same way as more traditional measures of automaticity, which are observed over several sessions.

THE EXPERIMENTS

Four experiments were conducted to determine whether repetition priming and automaticity share the three characteristics described above and to determine whether stimulus-to-response or stimulus-to-interpretation associations underlie the effect of multiple repetitions. The three characteristics were addressed in each experiment; the results bearing on those issues will be summarized in the General Discussion. Stimulus-to-response associations were addressed in Experiments 1 and 2; stimulus-to-interpretation associations were addressed in Experiments 3 and 4.

The experiments in each pair differed in the way repetitions were scheduled. Experiments 1 and 3 involved a *repetition paradigm* that involved *training* and *transfer* phases. During training, words and nonwords were presented several times in a block of trials, in such a way that new and old, familiar and unfamiliar stimuli appeared in random order. The intent was to mimic typical procedures in studies of repetition priming. During transfer, the trained words and nonwords were presented once again randomly mixed with new control words and nonwords. The task changed in various ways in order to assess the associations that were learned during training.

Experiments 2 and 4 involved a *learning paradigm* in which the same set of words and nonwords were repeated over and over again for several repetitions. Here, the intent was to mimic typical procedures in studies of automaticity. The associations underlying learning were assessed by changing tasks between repetitions: Subjects saw all of the stimuli under one task set and then switched tasks before the next repetition. Each learning experiment involved two task sets that alternated between repetitions.

EXPERIMENT 1:

Transfer to Different Stimulus-to-Response Mapping

Experiment 1 addressed the possibility of stimulus-to-response associations by training subjects on one rule for mapping stimuli onto responses (e.g., press the right key for 'yes' and the left key for 'no') and transferring them to the opposite mapping (e.g., press the left key for 'yes' and the right key for 'no'). With this procedure, stimulus-to-interpretation mapping is consistent from training to transfer (since subjects always respond 'yes' to words and 'no' to nonwords) but stimulus-to-response mapping is not. If associations between stimuli and responses underlie automaticity and repetition priming, there should be very little benefit apparent on the transfer test. However, if associations between stimuli and interpretations underlie the effect, transfer to a different mapping rule should produce the same benefit as transfer to the same mapping rule.

Method

*Subjects.*Two groups of 26 Introductory Psychology students and paid volunteers served as subjects. All were native speakers of English and reported normal or corrected vision.

Apparatus and stimuli. The stimuli were five-letter words and nonwords. The words were 340 common nouns selected from the Kucera and Francis (1967) frequency norms, ranging in frequency from 8 to 787 per million with a mean of 75.27. The mean log frequency was 3.44 with a standard deviation of 1.0. Nonwords were constructed by replacing one letter of each word, resulting in 340 nonwords. In most cases, the nonwords were pronounceable.

The stimuli were displayed in upper case in the center of a point-plot CRT (Tektronix Model 604, equipped with P31 phosphor) controlled by a PDP 11/03 computer. Each letter was formed by illuminating about 20 points in a 5 × 7 matrix. They were displayed in the center of the screen. Viewed at a distance of 60 cm (maintained by a headrest), each word and nonword subtended 0.57 × 2° of visual angle.

Each trial began with a fixation point exposed in the center of the screen and a 900-Hz warning tone. The tone and fixation point were presented for 500 ms, followed immediately by the word or nonword for that trial, which was also presented for 500 ms. After the word or nonword was extinguished, a 1500 ms intertrial interval began.

Subjects responded by pressing the two outermost telegraph keys in a panel of eight mounted on a moveable board that sat between the headrest and the CRT.

Procedure. In the training phase, subjects performed a lexical decision task for 10 blocks of trials. In each block, one word and one nonword was presented 1, 2, 4, 6, 8, and 10 times for a total of 62 trials. The lag between successive repetitions varied randomly. The mean lag and the range of lags decreased as the number of presentations increased. A different sample of words and nonwords was selected each block. In total, 120 different stimuli were presented during training. A different set of stimuli was chosen randomly for each subject from the pool of 340 words and 340 nonwords. The order of words and nonwords and the various repetition conditions was random, and a different random order was prepared for each subject.

In the transfer phase, all subjects performed lexical decisions for 160 trials. The first 20 trials were 'fillers,' involving 10 new words and 10 new nonwords. The following 140 trials involved 10 new words and 10 new nonwords, and 10 words and nonwords from each number of presentations in the training phase. Half of the subjects used the same stimulus-to-response mapping rules at training and transfer and half used opposite rules at training and transfer.

In both phases, subjects were told they would see words and nonwords and their task was to discriminate between them by pressing the appropriate key as quickly and accurately as possible with the index fingers of their left and right hands. They were told to rest their fingers lightly on the keys between trials. Half of the subjects pressed the right key for 'yes' responses and half pressed the left key for 'yes' responses.

Data analysis. In this experiment and in subsequent ones, the reaction time data are presented as *benefit scores*. Benefit in the repetition phase was calculated by subtracting the mean reaction time for each number of presentations from the mean reaction time for the first presentation. In this calculation, first-presentation reaction times were averaged over the first presentation of all stimuli, whether they were ultimately presented once, twice, four times, etc. In general, reaction times for *n* presentations were calculated by averaging over the *n*th presentation of all stimuli that were presented *n* times or more. Mean reaction times for the first presentations are reported so that interested readers can calculate the reaction times for subsequent presentations.

Power functions were fitted to the mean reaction times from the training phase to see whether the speed-up observed here was characteristic of automatization. Goodness of fit was measured in two ways: First, by the product–moment correlation between observed and predicted reaction times, and second, by the root-mean-squared deviation between observed and predicted reaction times. The power function fits will be addressed in the General Discussion.

Benefit in the transfer phase was calculated by subtracting reaction times for old stimuli from reaction times to new stimuli. Mean reaction times for new stimuli are reported so that interested readers can calculate the reaction times to the old stimuli.

Results and Discussion

Training phase. Benefit scores from the repetition phase of the experiment are presented in the left panel of Fig. 1. The mean reaction time for the first presentation was 604 ms for words and 681 ms for nonwords for the same-mapping group and 588 ms for words and 662 ms for nonwords for the different-mapping group.

Benefit increased with the number of presentations, and the increase was greater for words than for nonwords. There were no substantial differences between the group that transferred to the same mapping and the group that transferred to the opposite mapping; there was no reason to expect differences at this point.

These effects were confirmed by ANOVA: The main effect of word vs nonword was significant, $F(1,50) = 119.43$, $p < .01$, $MS_e = 3220.48$, as was the main effect of presentations, $F(9,450) = 124.73$, $p < .01$, $MS_e = 1250.42$, and the interaction between word vs nonword and presentations, $F(9,450) = 7.89$, $p < .01$, $MS_e = 765.72$. No effect involving transfer groups was significant, neither the main effect nor the interactions.

Error rates were low, averaging 3%, and tended to correlate positively with mean reaction time. Since the theories at issue do not address them, error data will not be analysed or presented in detail.

Transfer phase. The benefit scores from the transfer phase are presented in the right half of Fig. 1. There was substantial benefit in the transfer phase. Benefit tended to increase with the number of presentations, and words showed more benefit than nonwords. There were no

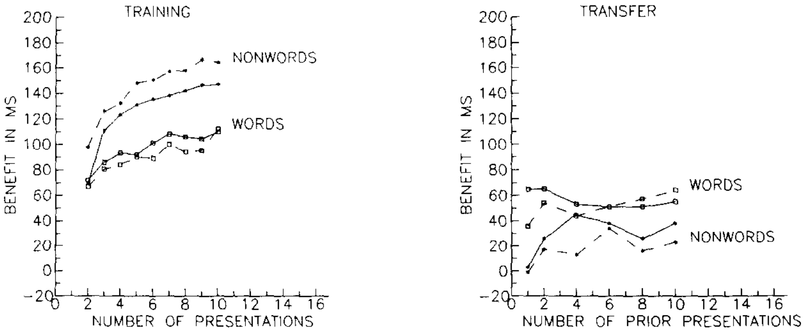

FIG. 1. Benefit scores for training (left panel) and transfer (right panel) in Experiment 1 as a function of number of presentations. Lexical status (word vs nonword) and consistent vs varied mapping at transfer are the parameters (consistent mapping, solid lines; varied mapping, broken lines). Both training and transfer tasks were lexical decision.

substantial differences between the group that transferred to the same-mapping rule and the group that transferred to the opposite-mapping rule.

These effects were confirmed by ANOVA: The main effect of word vs nonword was significant, $F(1,50) = 8.19$, $p < .01$, $MS_e = 17881.50$, as was the main effect of presentations, $F(5,250) = 2.61$, $p < .05$, $MS_e = 1885.84$. The main effect of transfer groups was not significant, $F(1,50) < 1$, $MS_e = 22663.66$, nor were any interactions between transfer group and the within-subject factors.

These results provide no evidence that stimulus-to-response associations play an important role in repetition priming or automaticity. If they did, the group that transferred to the opposite mapping should have shown less benefit at transfer than the group that transferred to the same mapping, but there were no significant differences between groups.

Two other aspects of the results are interesting: First, there was less benefit overall in the transfer phase than in the training phase. This suggests that there was some loss of information from memory in the interval from training to transfer. By contrast, previous studies of repetition priming showed little or no evidence of memory loss over much longer retention intervals (Ratcliff et al., 1985; Scarborough et al., 1977). The reasons for this difference are not obvious.

Second, words showed more benefit than nonwords in the transfer phase, whereas in the training phase of this experiment and the previous ones, words showed less benefit than nonwords. This may also reflect loss of information from memory, suggesting that nonwords are harder to remember than words.

EXPERIMENT 2:

Consistent vs Varied Stimulus-to-Response Mapping

Experiment 2 was intended to replicate the results of Experiment 1 with a different paradigm. Subjects were trained in the learning paradigm, in which they saw the same 10 words and 10 nonwords for 16 consecutive blocks. For the consistent mapping group, the stimulus-to-response mapping rule was the same for each block.[2] For the varied mapping group, the stimulus-to-response mapping rule changed after every block (i.e., after each presentation of the set of words and nonwords); subjects alternated between one rule (e.g., press right for 'yes') and the other (e.g., press left for 'yes') over blocks. If associations between stimuli and responses form the basis of automaticity and the multiple repetition effect, the varied

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[2] The consistent mapping data from this experiment were reported as Experiment 1 in Logan (1988). The primary focus of that report was power-function fits to the means and standard deviations simultaneously, constrained to have the same exponent.

mapping group should show less benefit over successive repetitions than the consistent mapping group. However, if associations between stimuli and their interpretations form the basis of automaticity and the multiple repetition effect, the consistent and varied mapping groups should show the same benefit over successive repetitions.

Method

Subjects. Two groups of 24 Introductory Psychology students and paid volunteers served as subjects. All were native speakers of English and all reported normal or corrected vision.

Stimuli. This experiment used a set of 340 four-letter words and 340 four-letter nonwords. The words were common nouns selected from the Kucera and Francis (1967) norms and ranged in frequency from 7 to 923 per million with a mean of 56.05. The distribution of log frequencies was matched exactly to the distribution of log frequencies for the five-letter words used in the previous experiment, with a mean of 3.44 and a standard deviation of 1.0. Nonwords were constructed by replacing one letter of each word and most of them were pronounceable.

Procedure. Each subject participated in an *experimental* condition and a *control* condition. In the experimental condition, subjects saw the same 10 words and 10 nonwords over and over again in random order for 16 20-trial blocks. In the control condition, they saw a new set of 10 words and 10 nonwords for 16 20-trial blocks. The 16 experimental blocks were run consecutively, as were the 16 control blocks. Half of the subjects in each group had the experimental blocks before the control blocks, and half had the opposite.

The consistent-mapping group responded in the same way each block; the varied mapping group switched mapping rules after each experimental and control block. Half of the subjects in each group began with one mapping rule (e.g., press the right key for 'yes' responses and the left key for 'no' responses) and half began with the opposite rule.

As in the previous experiment, the data were analysed as benefit scores. In the learning paradigm, benefit scores were calculated by subtracting the mean reaction time for each experimental block from the mean reaction time for the corresponding control block. These benefit scores remove differences in initial reaction time and control for general practice on the task.

Results and Discussion

The mean benefit scores for the two groups are presented in Fig. 2. For clarity, the benefit scores for words are presented in the left panel and those for nonwords are presented in the right panel. Error rate averaged 4% and was positively correlated with mean reaction time.

As in the previous experiment, benefit increased with presentations for both words and nonwords, and the effect was stronger for nonwords than for words. There was no consistent difference in benefit between the consistent-mapping group and the varied-mapping group, corroborating the effects observed with the repetition paradigm in the previous experiment.

These effects were confirmed by ANOVA: The main effect of word vs nonword was significant, $F(1,46) = 9.41, p < .01, MS_e = 14903.48$, as was the main effect of presentations, $F(15,690) = 5.42, p < .01, MS_e = 10663.68$, and the interaction between word vs nonword and presenta-

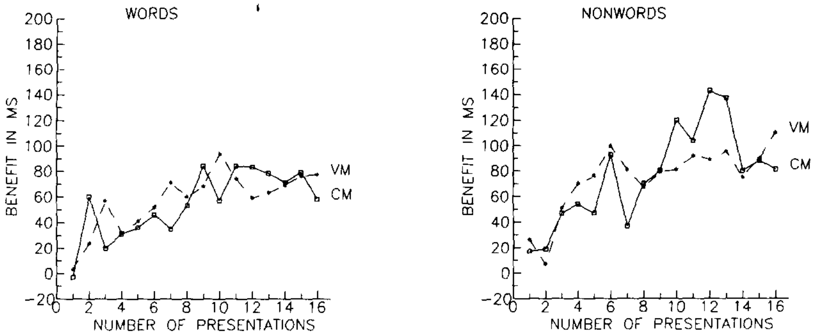


FIG. 2. Benefit scores for words (left panel) and nonwords (right panel) in Experiment 2 as a function of number of presentations. Consistent vs varied mapping is the parameter (consistent mapping, solid lines; varied mapping, broken lines). The training task was lexical decision.

tions, $F(15,690) = 1.88, p < .05, MS_e = 4699.94$. Notably, consistent vs varied mapping had no significant effects; neither the main effect nor the interactions with the within-subject factors was significant.

The results provide no evidence that stimulus-to-response associations provide an important basis for automaticity or repetition priming. If they did, the varied-mapping group should have shown less benefit over presentations than the consistent-mapping group, yet there was no difference between groups. The failure to find evidence for stimulus-to-response associations here and in the previous experiment, suggests that the associative basis of automaticity and repetition must lie elsewhere, perhaps in the interpretation given to the stimulus. The last two experiments addressed that possibility.

EXPERIMENT 3:

Transfer to a Different Interpretation

In Experiments 1 and 2 the stimuli were interpreted consistently as words or nonwords throughout training and transfer. Experiments 3 and 4 manipulated the interpretation given to the stimuli: Sometimes, subjects performed lexical decisions, interpreting stimuli as words or nonwords. Other times, they performed a *pronunciation decision* task, interpreting stimuli as pronounceable or unpronounceable and reporting their interpretation by pressing keys. The main question was whether experience interpreting a stimulus as a word or nonword would transfer to interpreting it as pronounceable or unpronounceable, and vice versa. If stimulus-to-interpretation associations form the basis of automaticity and repetition priming, then changing the interpretation from training to transfer or from one exposure to another should diminish the repetition effect, relative to control conditions in which the interpretation stays the same.

Experiment 3 used the repetition–transfer paradigm. Subjects were trained on lexical decisions and pronunciation decisions and transferred to pronunciation decisions.

Method

Subjects. Two groups of 24 Introductory Psychology students and paid volunteers served as subjects. All were native speakers of English and all reported normal or corrected vision.

Stimuli. In order to allow subjects to make lexical decisions and pronunciation decisions on the same stimuli, the set of 340 five-letter words and nonwords used in Experiment 1 was revised so that it contained two sets of nonwords, one pronounceable and one unpronounceable. As before, the nonwords were generated from the words by substituting letters. To make pronounceable nonwords, vowels were substituted for vowels and consonants for consonants, resulting in stimuli that two judges agreed were pronounceable. To make unpronounceable nonwords, consonants were substituted for vowels and vowels were sometimes substituted for consonants, resulting in stimuli that two judges agreed were not pronounceable.

Procedure. There were two groups of subjects, one trained on lexical decisions and one trained on pronunciation decisions. Both groups were transferred to pronunciation decisions. Subjects trained on lexical decisions saw words, pronounceable nonwords, and unpronounceable nonwords presented one, two, four, and eight times in a block, following the repetition paradigm. Each block involved 45 trials, and there were 10 training blocks altogether. The transfer task was pronunciation decision and involved only nonwords. There were 10 new pronounceable nonwords and 10 new unpronounceable nonwords as well as the 10 nonwords of each type from each number of presentations in the training phase.

Subjects trained on pronunciation decisions saw only pronounceable and unpronounceable nonwords during training. They were presented one, two, four or eight times per block of 30 trials, and there were 10 training trials altogether. Subjects were then transferred to the same pronunciation task, involving 10 new pronounceable nonwords and 10 new unpronounceable nonwords as well as the 10 nonwords of each type from each number of presentations in the training phase.

Instructions for the lexical decision task were the same as they had been in the previous experiments. For the pronunciation task, subjects were told to decide whether or not they could pronounce each stimulus and to indicate their decision by pressing the appropriate key. They were given examples of pronounceable (e.g., "blat") and unpronounceable (e.g., "bljt") nonwords and told how to respond to them. Subjects used the same key to indicate 'yes' and 'no' in training and in transfer for both the lexical decision task and the pronunciation task. Thus, for subjects in the lexical decision group, stimulus-to-response mapping was consistent for the unpronounceable nonwords but inconsistent for the pronounceable nonwords.

Results and Discussion

Training phase. Benefit scores from training trials for both groups are presented in the left panel of Fig. 3. For lexical decision subjects, mean reaction times on the first presentation was 599 ms for words, 715 ms for pronounceable nonwords, and 548 ms for unpronounceable nonwords. For pronunciation subjects, mean reaction time on the first presentation

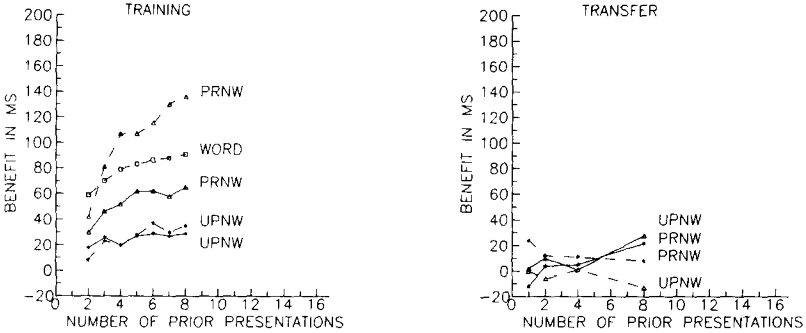


FIG. 3. Benefit scores for training (left panel) and transfer (right panel) in Experiment 3 as a function of number of presentations. Lexical status (word vs pronounceable nonword vs unpronounceable nonword) and consistent vs varied interpretation at transfer are the parameters (consistent interpretation, solid lines; varied interpretation, broken lines). The training tasks were pronunciation (consistent interpretation group) and lexical decisions (varied interpretation group); the transfer task was pronunciation for both groups.

was 563 ms for pronounceable nonwords and 565 ms for unpronounceable nonwords. As in the previous repetition-paradigm experiment, benefit was calculated by subtracting reaction time for the *n*th presentation from reaction time for the first presentation.

Benefit increased with presentations in all conditions, though the pattern was somewhat different in the two groups. For lexical decision subjects, pronounceable nonwords showed more benefit than words, but unpronounceable nonwords showed considerably less benefit. The pattern with pronounceable nonwords and words replicates the results of the previous experiments, reflecting the fact that most of the nonwords in the original stimulus set were pronounceable.

For pronunciation subjects, pronounceable nonwords showed more benefit than unpronounceable nonwords. The benefit for pronounceable nonwords was much smaller than that observed with lexical decision subjects, suggesting a levels-of-processing effect (cf. Logan, 1985b). Even though there was less benefit overall in the pronunciation task, it is important to note that multiple repetitions produce the same pattern of increasing benefit in a task other than lexical decision. The effect appears to be a general one, which is important if it is to be interpreted as the basis of automatization.

It was not feasible to compare the two groups in the same ANOVA because only the lexical decision group saw words. Instead, separate ANOVAs were conducted within each group. The lexical decision subjects showed a significant main effect of stimulus type (word vs pronounceable nonword vs unpronounceable nonword), $F(2,46) = 32.17$, $p < .01$, $MS_e = 7975.28$, a significant main effect of presentations, $F(6,138)$

$= 21.24$, $p < .01$, $MS_e = 1025.82$, and a significant interaction between stimulus type and presentations, $F(12,276) = 10.34$, $p < .01$, $MS_e = 397.43$. The pronunciation subjects showed a significant effect of stimulus type (pronounceable vs unpronounceable nonword), $F(1,23) = 30.33$, $p < .01$, $MS_e = 2645.32$, a significant effect of presentations, $F(6,138) = 7.16$, $p < .01$, $MS_e = 452.63$, and a significant interaction between them, $F(6,138) = 2.74$, $p < .05$, $MS_e = 349.09$.

Again, error rate was low, averaging 4%, and was positively correlated with mean reaction time.

Transfer phase. The benefit scores from the transfer phase are presented in the right panel of Fig. 3. As in the previous repetition-paradigm experiment, benefit in the transfer phase was calculated by subtracting reaction times for old stimuli from reaction times for new stimuli. For the group trained on lexical decisions (inconsistent interpretation at transfer), mean reaction time to new stimuli was 584 ms for pronounceable nonwords and 565 ms for unpronounceable nonwords. For the group trained on pronunciation (consistent interpretation at transfer), mean reaction time to new stimuli was 531 ms for pronounceable nonwords and 539 ms for unpronounceable nonwords.

The pattern of benefit on transfer depended on the consistency of interpretation: Subjects trained on pronunciation and transferred to pronunciation showed benefit that increased with the number of presentations, whereas subjects trained on lexical decision and transferred to pronunciation showed benefit that remained constant or decreased slightly.

This contrast between groups was confirmed by ANOVA: Although the main effect of groups did not reach significance, $F(1,46) = 1.85$, $MS_e = 314.24$, and the group × presentations interaction was only borderline, $F(3,138) = 2.25$, $p < .10$, $MS_e = 1693.96$, a contrast comparing the linear trend across presentations in the two groups was significant, $F(1,138) = 5.53$, $p < .05$, $MS_e = 1693.96$. In separate analyses in each group, the linear increase in benefit with presentations was significant in the group trained on pronunciation, $F(1,69) = 4.38$, $p < .05$, $MS_e = 1349.14$, but not in the group trained on lexical decision, $F(1,69) = 1.77$, $MS_e = 2038.78$.

The ANOVA on both groups also revealed a main effect of stimulus type (pronounceable vs unpronounceable nonwords), $F(1,46) = 4.93$, $p < .05$, $MSE = 3532.49$. No other effects were significant.

These results provide at least modest evidence that consistency of interpretation is an important factor determining automaticity and repetition priming. The effects were relatively small and the statistical support for them was not overwhelmingly strong. Thus, it was important to replicate them.

As a final point of interest, the consistent-interpretation group showed less benefit on transfer than on training, just as subjects in Experiment 1 showed less benefit at transfer than at training. This suggests that there was some loss of information from memory over the retention interval from training to transfer.

EXPERIMENT 4:

Consistent vs Varied Stimulus-to-Interpretation Mapping

Experiment 4 used the learning paradigm to assess the importance of consistent stimulus-to-interpretation mapping. Two groups of subjects were run. Each group saw two sets of words, pronounceable nonwords, and unpronounceable nonwords. One set was presented for 12 consecutive blocks of trials and the other set was presented for the next 12 blocks. The lexical decision group made consistent lexical decisions throughout the 12 blocks with one set of stimuli and alternated between lexical decisions and pronunciation decisions over the other 12 blocks with the other set of stimuli. The pronunciation group made consistent pronunciation decisions in one set of blocks and alternated between pronunciation and lexical decisions on the other set. If associations between stimuli and their interpretations form the basis of automaticity and repetition priming, both groups should show less growth in benefit over successive presentations when the task alternates between blocks (varied mapping) than when the task is consistent over blocks (consistent mapping).

Method

Subjects. Two groups of 24 Introductory Psychology students and paid volunteers served as subjects. All were native speakers of English and all reported normal or corrected vision.

Procedure. Subjects saw the same 10 words, 10 pronounceable nonwords, and 10 unpronounceable nonwords each block for 12 30-trial blocks. Each subject performed two sets of 12 blocks. A different sample of stimuli was selected randomly for each subject for each set of blocks, and the order of stimuli within blocks was randomized for each block. One group of subjects made lexical decisions for the 12 consistent-mapping blocks and began with lexical decisions for the 12 varied-mapping blocks. The other group made pronunciation decisions for the 12 consistent-mapping blocks and began with pronunciation decisions for the 12 varied-mapping blocks. The assignment of keys to 'yes' and 'no' responses was counterbalanced within each group. In the varied-mapping conditions, the assignment of keys to 'yes' and 'no' responses was the same for both tasks. Thus, stimulus-to-response mapping was consistent for words and unpronounceable nonwords but inconsistent for pronounceable nonwords in the varied mapping conditions.

There were no new-item controls in this experiment; all items were repeated. Consequently, benefit was calculated as in the experiments with the repetition paradigm, subtracting reaction time for the *n*th presentation of a stimulus from reaction time for the first presentation of the stimulus.

Results and Discussion

The left panel of Fig. 4 presents benefit scores from the lexical decision

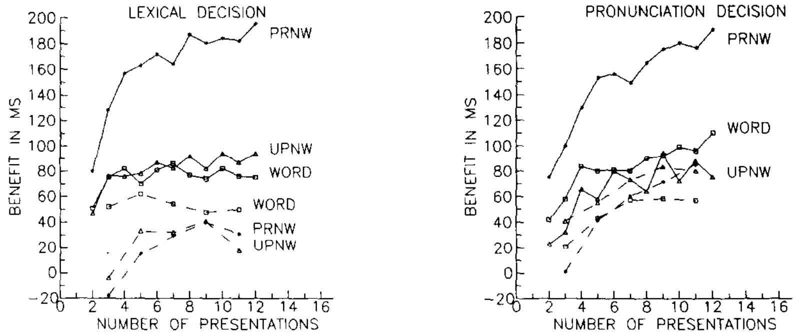


FIG. 4. Benefit scores for the lexical decision group (left panel) and pronunciation group (right panel) in Experiment 4 as a function of number of presentations. Lexical status (word vs pronounceable nonword vs unpronounceable nonword) and consistent vs varied interpretation are parameters (consistent interpretation, solid lines; varied interpretation, broken lines).

subjects (who performed consistent lexical decisions and began with lexical decision in varied-mapping conditions). Note that varied-mapping benefit is presented for the lexical decisions and not for the pronunciation decisions. The right panel of Fig. 6 presented benefit scores from the pronunciation subjects (who performed consistent pronunciation decisions and began with pronunciation in varied-mapping conditions). Varied-mapping benefit is presented for pronunciation decisions and not for lexical decisions. Error rates were low, averaging 5%, and correlated positively with mean reaction time.

In both groups, consistent interpretation produced more benefit than varied interpretation. The difference was greatest for pronounceable nonwords, but it was present even for words and unpronounceable nonwords. This is important because stimulus-to-response mapping was consistent across tasks for words (which always required a "yes" response) and unpronounceable nonwords (which always required a "no" response). Thus, consistency of interpretation has effects over and above any effects of consistent stimulus-to-response mapping.

The varied mapping conditions showed some benefit, but that may have been due to a general practice effect that was uncontrolled in calculating the benefit scores. Indeed, the consistent mapping conditions produced more benefit overall than was observed in previous experiments that separated general and specific practice effects.

These conclusions were supported by two separate ANOVAs, one on the lexical decision data and the other on the pronunciation data. In both ANOVAs, the presentation factor included only those presentations on which the same decision was made in consistent- and varied-mapping groups (i.e., presentations 3, 5, 7, 9, and 11).

For lexical decisions, there was a significant main effect of consistent vs varied mapping, $F(1,23) = 13.40$, $p < .01$, $MS_e = 73324.35$, and a significant main effect of stimulus type (words vs pronounceable nonwords vs unpronounceable nonwords), $F(2,46) = 5.27$, $p < .01$, $MS_e = 18708.59$. The main effect of presentations was significant, $F(4,92) = 5.74$, $p < .01$, $MS_e = 2748.75$, as was the interaction between stimulus type and presentations, $F(8,184) = 4.36$, $p < .01$, $MS_e = 1470.02$, and the interaction between mapping and stimulus type, $F(2,46) = 12.31$, $p < .01$, $MS_e = 19732.85$. Planned comparisons showed a significant mapping effect for words, $F(1,92) = 8.07$, $p < .01$, and for unpronounceable nonwords, $F(1,92) = 66.11$, $p < .01$, both MS_es $= 2997.13$, for which stimulus-to-response relations were consistent across interpretations.

For pronunciation decisions, there was a significant main effect of consistent vs varied mapping, $F(1,23) = 5.13$, $p < .05$, $MS_e = 66821.89$, a significant main effect of presentations, $F(4,92) = 18.39$, $p < .01$, $MS_e = 3513.13$, a significant interaction between stimulus type and presentations, $F(8,184) = 2.44$, $p < .05$, $MS_e = 1119.16$, and a significant interaction between mapping and stimulus type, $F(2,46) = 6.14$, $p < .01$, $MS_e = 15739.37$. Planned comparisons revealed a significant mapping effect for words, $F(1,92) = 15.11$, $p < .01$, but not for unpronounceable nonwords, $F(1,92) = 3.04$, $p < .10$, both MS_es $= 3315.42$. No other effects were significant.

Consistency of interpretation has important effects in the learning paradigm just as it did in the repetition paradigm of Experiment 3. It suggests that stimulus-to-interpretation associations underlie automaticity and repetition priming. Moreover, the present results replicate with two different tasks—lexical decision and pronunciation—which suggests that the effects of consistent stimulus-to-interpretation mapping might be quite general.

GENERAL DISCUSSION

The experiments were conducted to examine three empirical parallels between repetition priming and automaticity predicted by the instance theory and to test hypotheses about possible associative bases of repetition priming and automaticity. The results supported the predictions of instance theory and suggested that stimulus-to-interpretation associations underlie the effects. These conclusions suggest ways to elaborate the instance theory and make it more specific.

Power-Function Speed-Up

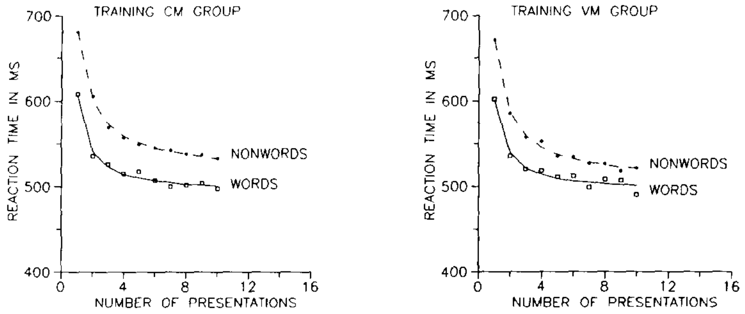
The instance theory predicts that reaction time will decrease as a power function of the number of repetitions (Logan, 1988), which is characteristic of automaticity. This prediction was tested by fitting power functions to the mean reaction times from each experiment (using STEPIT) (Chandler, 1965). The parameters of the fitted functions and two measures of goodness of fit (r^2 and *rmsd*, the root mean squared deviation between predicted and observed values) are presented in Table 1. The mean reaction times are plotted along with the power functions fitted to them in

TABLE 1
Parameters and Measures of Goodness of Fit for Power Functions Fitted to Mean Reaction Times from Each Experiment

	Fitted parameters			Goodness of fit	
	a	*b*	$-c$	r^2	*rmsd*
	Experiment 1				
Same mapping at transfer					
Word	495	112	1.277	.986	3.6
Nonword	514	166	0.955	.997	2.4
Different mapping at transfer					
Word	496	105	1.303	.968	5.3
Nonword	504	166	1.003	.996	2.9
	Experiment 2				
Consistent mapping					
Word	483	103	0.708	.856	9.2
Nonword	426	264	0.361	.953	9.8
Varied mapping					
Word	418	172	0.261	.896	8.2
Nonword	466	213	0.336	.912	10.8
	Experiment 3				
Pronunciation training					
Prnw	480	84	0.726	.983	2.7
Upnw	535	30	1.301	.939	2.3
Lexical decision training					
Word	503	96	1.271	.997	1.4
Prnw	430	289	0.311	.984	5.6
Upnw	465	85	0.268	.912	3.6
	Experiment 4				
Consistent lexical decision					
Word	508	79	1.793	.934	5.6
Prnw	505	227	0.774	.985	6.6
Upnw	458	98	1.109	.972	4.3
Consistent pronunciation decision					
Word	422	136	0.540	.964	5.4
Prnw	410	264	0.487	.988	5.8
Upnw	484	139	0.405	.873	9.6

Note. a, asymptote of power function; *b*, multiplicative parameter; $-c$, exponent; r^2, correlation squared; *rmsd*, root mean squared deviation between observed and predicted values, in milliseconds; Prnw, pronounceable nonwords; Upnw, unpronounceable nonwords.

EXPERIMENT 1



EXPERIMENT 2

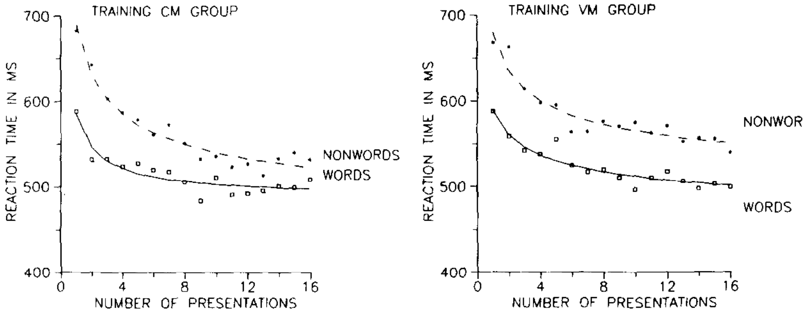


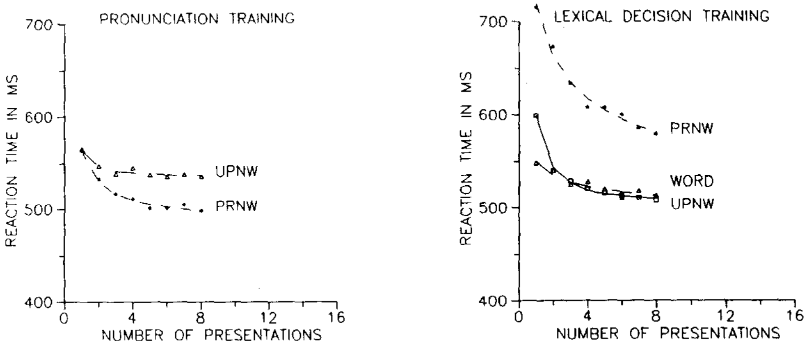
FIG. 5. Observed reaction times (points) and fitted power functions (lines) in training in Experiments 1 (top panels) and 2 (bottom panels). Lexical status (word vs nonword) is the parameter. Consistent mapping (CM) conditions are in the left panels and varied mapping (VM) conditions are in the right panels.

Figs. 5 and 6. Figure 5 contains data from Experiments 1 and 2 and Fig. 6 contains data from Experiments 3 and 4.

Power functions fit the data well in Experiment 1. Reaction times to words and nonwords were typically within 6 ms of predicted values (i.e., the maximum *rmsd* for the four sets of data was 5.2 ms). The fit was less impressive in Experiment 2, though the deviations from prediction seem unsystematic. In this experiment, as in typical learning experiments, practice with individual items was confounded with time on task, and factors like fatigue and nonspecific practice may perturb the underlying power functions. The fits were good in Experiment 3, even in the pronunciation task (the maximum *rmsd* was 5.6 ms). They were less good, though still quite reasonable, in Experiment 4, which used the learning paradigm. Thus, in general, the data were well fit by power functions, confirming the prediction of the instance theory.

The parameters of the power functions varied quite a bit between con-

EXPERIMENT 3



EXPERIMENT 4

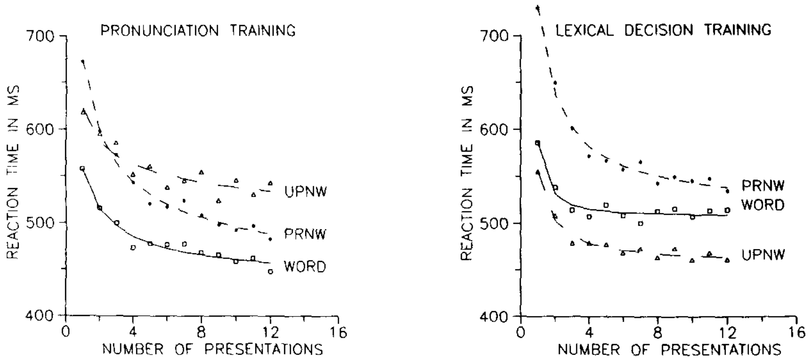


FIG. 6. Observed reaction times (points) and fitted power functions (lines) in training in Experiments 3 (top panels) and 4 (bottom panels). Lexical status (word vs pronounceable nonword vs unpronounceable nonword) is the parameter. Pronunciation decisions are in the left panels and lexical decisions are in the right panels.

ditions and experiments. Some of the variation in the asymptote, *a*, and multiplicative parameter, *b*, appears to be due to the stimuli. In the lexical decision task, for example, asymptotes were roughly the same for words and nonwords but the multiplicative parameter, representing the difference between initial and asymptotic performance, was greater for nonwords than for words in six of six cases.[3] According to the instance theory, asymptotic performance is purely memory-based, so the equivalence of asymptotes suggests equivalent memory for words and

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[3] In this analysis, a case is a within-experiment within-condition comparison. For example, the exponent was greater for words than for nonwords in every condition of every experiment (i.e., in five cases) except the varied mapping condition of Experiment 2.

nonwords.[4] The instance theory also says that initial performance is purely algorithm-based, so the difference in the multiplicative parameter reflects differences in the algorithm for words and nonwords.

Pronounceable nonwords had a lower asymptote than unpronounceable nonwords in three of four cases (i.e., two lexical decision cases and two pronunciation decision cases), suggesting better memory for pronounceable nonwords. Pronounceable nonwords had larger multiplicative parameters in four of four cases, indicating slower initial performance.

Across all conditions and tasks, there was substantial variability in the exponents, ranging from a low of 0.262 to a high of 1.793. Some of the variability was due to stimuli: In the lexical decision task, the exponent was greater for words than for pronounceable nonwords in five of six cases (counting the nonwords in Experiments 1 and 2 as pronounceable) and greater for words than unpronounceable nonwords in two of two cases. Differences in exponents are hard to interpret in the context of the instance theory because the race between the algorithm and memory distorts the exponent (for a formal analysis, see Logan, 1988).

Strictly speaking, the instance theory predicts a power-function speed-up only for responses based on memory retrieval. The race with the algorithm necessarily contaminates the power function, especially in the first few exposures to an item when the algorithm dominates performance (i.e., often wins the race). The very first exposure is based entirely on the algorithm (by definition) and it is easiest to see how the function is distorted by focusing on the first versus subsequent exposures: If the algorithm is substantially slower than memory retrieval, the first point on the observed power function will be higher than it should be; if the algorithm is substantially faster, the first point will be lower. These differences will affect the multiplicative parameter, as noted above, but they also affect the exponent, making it larger than it should be in the first case and smaller in the second. It is not obvious how to separate out the effects of the algorithm from estimates of the exponent produced by the memory retrieval process; that is a subject of ongoing investigation. For now, differences in exponents must remain uninterpreted.

The instance theory predicted the power-function speed-up apparent in the data and it provides interpretations for some of the variation in power-

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[4] Note that the asymptote of the power function does not represent the underlying retrieval time distributions directly. Instead, it represents the outcome of a race between n traces in memory; it represents the mean of the distribution of minima drawn from n samples from the underlying retrieval time distributions. The mean of the distribution of minima (i.e., the asymptotic reaction time) necessarily underestimates the mean of the underlying retrieval time distribution. Ways to derive the underlying retrieval time distribution from the observed reaction times are currently under investigation.

function parameters. This would appear to be a significant confirmation of the instance theory. However, the significance is limited by two factors: First, several other theories of skill acquisition predict a power-function speed-up (e.g., Anderson, 1982; Crossman, 1959; MacKay, 1982; Newell & Rosenbloom, 1981; Schneider, 1985), so the prediction does not uniquely confirm the instance theory. Second, I have not tried to rule out alternative functions, such as exponentials or hyperbolics, so the fits do not mean that power functions provide the best description of the data. Often, data well described by a power function are also well described by these other functions (see e.g., Kail, 1986; Newell & Rosenbloom, 1981). However, no theory predicts anything other than a power-function speed-up, so there was no point in seeing whether some other function fit better (i.e., there were no theoretically-relevant alternatives). Also, the relatively high r^2 values suggest that improvements in fit could only be marginal.

Instance theory aside, the power function fits reveal an important empirical parallel between automaticity and repetition priming: The learning function that characterizes automaticity also provides a good description of repetition priming. This motivates further search for theoretical and empirical parallels.

The experiments contrast with typical studies of automatization in that performance approached asymptote in a single session, whereas typically several sessions are required. The difference may be due to the number of stimuli used in these experiments compared to the number in more typical experiments. The instance theory predicts that learning is a function of the number of presentations of a particular stimulus. If the number of presentations is sufficiently high, performance can reach asymptote in a single session. If presentations are distributed over several sessions, then several sessions may be required to reach asymptote. Logan and Klapp (1989) tested this prediction explicitly, varying the number of stimuli they presented in an alphabet arithmetic task (i.e., subjects verified equations like $A + 2 = C$; $B + 3 = E$) and found that the more stimuli, the greater the number of sessions required to obtain asymptotic performance. However, when performance was plotted against the number of presentations of each stimulus, the different learning curves were superimposed. All that mattered was the number of times a stimulus had been presented.

Item Specificity

Each experiment showed evidence of the item-specific learning predicted by the instance theory. In repetition-paradigm experiments (Experiments 1 and 3), reaction times were faster to repetitions than to the first presentations even though repetitions and first presentations were randomly mixed. Moreover, reaction times were faster the more times an item was presented even though presentations were randomly mixed (e.g., the eighth presentation of one item may precede the third presentation of another). These effects were observed in both training and transfer (except in the varied interpretation condition of Experiment 3). If subjects had learned to make lexical decisions more rapidly regardless of whether items were new or old (i.e., if learning were nonspecific), reaction time should decrease in general as the session progressed but reaction times to new and repeated items should not differ and reaction time should not depend on the number of presentations. The data contradict these predictions.

In the learning-paradigm experiments (Experiments 2 and 4), reaction times were faster to repetitions than to new items and became progressively faster as the number of presentations increased. Nonspecific practice was the same for repeated and new stimuli. Repeated stimuli benefitted from specific and nonspecific learning, whereas new stimuli benefitted only from nonspecific learning. The data indicate substantial specific learning effects that increased with repetitions, as the instance theory predicts. If learning were nonspecific, reaction time should depend on the number of practice trials and not on the prior presentation history of individual stimuli. The data contradict this prediction.

The item-specificity observed in these experiments rules out pure *process-based* learning, which predict a general improvement in the ability to make lexical decisions and pronunciation decisions regardless of the item's history (e.g., Crossman, 1959; Kolers, 1976). Item specificity is consistent with the instance theory but it does not uniquely support it. Some current theories of skill acquisition and automaticity predict item-specific learning (e.g., Newell & Rosenbloom, 1981; Schneider, 1985), and some predict both specific and nonspecific learning (e.g., Anderson, 1982). Most theoretical approaches to repetition priming predict item-specific learning (e.g., Balota & Chumbley, 1984; Jacoby, 1983; Morton, 1969, 1979). The experiments make an empirical contribution by demonstrating item-specific learning in the same data set that shows evidence of a power-function speed-up and an underlying associative basis.

Associative Basis

The instance theory differs from the logogen model (Morton, 1969, 1979) and the familiarity model (Balota & Chumbley, 1984) in that it predicts an associative basis for repetition priming and automaticity whereas those models do not. The models make different predictions for repetition effects with nonwords: The instance theory predicts benefit for nonwords. Both words and nonwords generate associations, and the associations for words are different from those for nonwords, so retrieved associations could provide a basis for lexical decision. Repetition would strengthen associations for both words and nonwords.

Nonassociative models do not predict benefit for nonwords. In a strict logogen model, there are logogens only for words. Repetition can lower thresholds or raise baseline activation for words but not for nonwords. Nonword responses, made by default, would not be affected by repetition. They must remain slower than the slowest word response regardless of the number of repetitions.

In the familiarity model, lexical decisions are made by comparing the familiarity and meaningfulness evoked by a stimulus against a high and low criterion. Familiarity values above the high criterion permit a rapid "word" response; values below the low criterion permit a rapid "nonword" response. Values between the two criteria indicate that more analysis is required, which slows the response. If repetition increased familiarity, words would have been facilitated (because their familiarity would be more likely to be above the high criterion) but nonwords would have been inhibited (because their familiarity would be less likely to be below the low criterion).

There was benefit for nonwords in each experiment, which would appear to confirm the instance theory and other item-specific associative theories and disconfirm nonassociative theories. However, not every case of nonword benefit requires that interpretation. In the learning paradigm experiments (2 and 4), new and repeated stimuli occurred in separate blocks, so default responses to nonwords could have sped up as a consequence of a nonassociative speed-up in responses to words. In the repetition-paradigm experiments (1 and 3), the case is clearer. New and repeated stimuli were mixed randomly. Default responses to nonwords should have been slower than the slowest word response regardless of the number of presentations, but the observed reaction times decreased with repetition. Some responses to repeated nonwords were faster than responses to new words. An associative basis seems to be the best explanation of the data. However, these data do not indicate what was associated with what.

Experiments 1 and 2 suggest that associations between stimuli and responses do not underlie repetition priming and automaticity. Transfer to different stimulus-response mappings was excellent; it was no different than 'transfer' to the same stimulus-response mapping. Experiments 3 and 4 suggest that associations between stimuli and the interpretations given to them under the task set do underlie repetition priming and automaticity. Transfer to different interpretations was poor, compared to transfer to the same interpretation, even when stimulus-to-response mapping was consistent.

The experiments support the idea that repetition priming has an associative basis, as automaticity does, and specify the nature of the associations, namely associations between stimuli and their interpretations. The close parallels between repetition priming and automaticity suggest that the instance theory of automatization may generalize to repetition priming as well. The remainder of this section focuses on implications of the results for further developments of the instance theory.

Interfacing Instance Theory with Theories of Initial Performance

Essentially, the instance theory argues that an initial algorithm is replaced by memory retrieval as items are repeated. The theory focuses on memory retrieval and says little about the initial algorithm. This focus is appropriate because the same memory process should appear in every case of automaticity, though the initial algorithms may vary substantially from case to case. In principle, the set of initial algorithms that can be replaced by memory retrieval may be infinite. There may be no single characteristic or set of characteristics common to all or even most of the algorithms that can be replaced by memory retrieval. Thus, there is not much to say about algorithms in general. The main requirement is that they provide responses to novel stimuli (see Logan, 1988).

In any single application, however, one must know the nature of the algorithm to understand how it will interface with the memory process. One must know what memory traces are produced by using the algorithm and how the information they contain can support performance on the task without the algorithm. What is encoded will depend on what is attended, so one must know what things a person attends to in performing the algorithm, which external stimuli, which internal states, and so on.

The lexical decision and pronunciation tasks in the present experiments offer several alternatives. It would be relatively easy, for example, to combine the instance theory with existing theories of initial performance. Thus, initial lexical decisions could be performed by a logogen system or a familiarity model, and subsequent ones would depend on a race against instance-based memory retrieval. However, this approach requires assumptions about memory structure and process that an instance theorist would want to avoid. Interfacing with the logogen model requires accepting the distinction between episodic and semantic memory (i.e., logogens are part of semantic memory; instances are episodic phenomena), which is currently controversial (cf. Tulving, 1984, and commentary). A strict instance theorist would want a completely episodic account of all uses of memory, including initial lexical decision performance.

Interfacing with the familiarity model may appear less troublesome, because in principle, meaningfulness and familiarity could be assessed by examining episodic memory.[5] However, both models involve learning, and it may be difficult to work out the interactions between the learning mechanisms as they appear in performance data. The instance theory so far has assumed that the algorithm does not change with practice.

Multiple repetitions of nonwords may present a problem. According to the familiarity model, each repetition increases familiarity (in some unspecified way). The model argues that one repetition or two may be enough to drive a nonword's familiarity above the lower criterion and thereby slow down the nonword response. These same few repetitions would provide instances to be retrieved, so observed reaction times may decrease as expected. However, after several repetitions, a nonword's familiarity may exceed the higher criterion and lead to a fast decision that it is a word. This decision could disrupt several aspects of performance, slowing reaction time and increasing error rate dramatically. Nothing of the kind was observed in the present experiments, although 16 presentations may not have been enough to produce the effect. Regardless, the familiarity model must predict fast "word" responses to nonwords after some finite number of repetitions, and this is sufficient reason to consider other possibilities.

The data exert an important constraint on the interface: They suggest that stimulus-to-interpretation associations are the basis of the instance memory effects. Interfacing would be a lot easier if only stimulus-to-response associations were important. Instance retrieval could bypass the cognitive system entirely, so even the sketchiest description of lexical decision performance would suffice. Fortunately, the data require a more interesting interpretation.

Episodic Consequences of Lexical (and Other) Decisions

A purely episodic account of repetition priming and automaticity must explain what kinds of episodic information support initial performance on the task, what kinds of episodic information are produced by performing the task, and how that episodic information is used to support automatic performance. I propose that two kinds of information present themselves to memory in the performance of tasks: an *assertion* and a *justification*. The assertion is the response the subject makes in compliance with task

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[5] Balota and Chumbley (1984) mention a similar idea in a footnote. They argue that at short lags, subjects may remember the response associated with nonwords and execute it without going through the usual familiarity model. The present data argue against stimulus-to-response associations and the importance of short lags (also see Logan, 1988, Experiment 3). However, Balota and Chumbley did anticipate the need to supplement their model with associative memory.

instructions. It expresses a proposition, a predicate that the subject believes to be true, about a particular referent (e.g., the letters on the screen form a word). The justification is the evidence that supports the assertion, that provides reason to believe the assertion is true. Together, the assertion and justification make up the subject's interpretation of the stimulus under the current task set.

The assertion is made intentionally. Subjects expect their key presses to be interpreted as speech acts expressing propositional content and experimenters interpret them that way. Subjects must attend to the assertion in some way, and as an object of attention, it will be encoded into memory. The justification may also require some form of attention and it may also be encoded into memory. It need not be attended, however. It is sufficient that the assertion is attended and remembered.

The instance theory would explain automaticity and repetition priming as a change in the justification for making the same assertion: At all levels of practice, subjects call words words and nonwords nonwords. But they do so for different reasons. Early in practice, lexical decisions may be made by inference based on what is retrieved from memory. Retrieving a meaning, a syntactic role, a pronunciation, or some combination of them may support (justify) an inference that a stimulus is a word (Carr, Posner, Pollatsek, & Snyder, 1979). Retrieving specific episodic information could also justify a word decision. For example, having seen it in a book is good evidence that it is a word since few books contain nonwords (psychology texts notwithstanding). Failing to retrieve a meaning, a syntactic role, pronunciation, or specific episodic information may justify an inference that it is a nonword.[6]

Later in practice lexical decisions are still made by inference based on memory retrieval, but what is retrieved changes. If the item is repeated, the subject may retrieve a trace of a prior assertion and use it to justify the

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[6] To justify a "nonword" decision, the subject would need some criterion for deciding that nothing had been retrieved. A common hypothesis is a temporal deadline based on the expected finishing time for words. Another hypothesis is that the decision is based on relations between levels of processing: The subject could decide "nonword" if no evidence of wordness had been retrieved from memory by the time the letters can be identified. The letter-level criterion could be realized semantically (as a certain amount of activation in logogen-like letter detectors) or episodically (as retrieving a certain number of letter names or contexts in which the letter occurred in response to the stimulus). The second hypothesis would allow for greater independence between "word" and "nonword" decisions, which seems desirable in the light of the data. (In Experiments 3 and 4, reaction times to pronounceable nonwords were slower than reaction times to words, as the word-based deadline predicts. However, reaction times to unpronounceable nonwords were actually faster than reaction times to words, at least in the initial presentation, contrary to the predictions of a word-based deadline.)

current assertion: Remembering that one said the item was a word before is reasonable justification for saying it is a word now; similarly for nonwords.

At each stage of practice, regardless of the justification, the subject attends to the fact (proposition) that the stimulus is a word (or a nonword) and that is enough to commit it to memory. As practice progresses, instances of prior assertions will become more readily available. The race model applies to the retrieval times of the various justifications, and eventually, prior assertions will dominate the race against other justifications. If the task changes, however, prior assertions may no longer justify current ones. A change in a peripheral aspect of the task, such as the response that expresses the assertion, should not affect performance (much). Prior assertions still justify current ones. But a change in the assertion, e.g., from lexical decision to pronunciation decision or vice versa, should have strong effects: What justifies the inference that something is a nonword does not justify an inference that something is pronounceable.[7] In principle, it should be possible to predict transfer between tasks by analyzing their propositional content. Positive transfer should occur whenever propositions asserted in one context can justify propositions to be asserted in another.

In this model, one kind of memory retrieval is replaced by another. Does that mean that an algorithm is replaced by memory retrieval, as the instance theory claims? Can the first kind of retrieval be interpreted as an algorithm? Strictly speaking, it is more of a heuristic than an algorithm, but it serves as an algorithm in the sense intended by instance theory: It is a general procedure that allows the subject to classify all stimuli presented in the experiment, whether new or repeated (see Logan, 1988). Thus, the model asserts that an algorithm is replaced by memory retrieval.

The model takes a position on two issues in the implicit memory literature. First, it suggests implicit and explicit tasks tap the same memory system in different ways (cf. Hintzman, 1986, 1988; Jacoby, 1983); they do not tap different memory systems (cf. Tulving, 1984). The assertion is a proposition, and there is good evidence that subjects can recognize and recall propositional content (e.g., Kintsch, 1974). Thus, the memory system will support explicit memory tasks. In automaticity and repetition priming, propositions are probably remembered implicitly. Subjects must

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[7] Some justifications transfer across tasks and others do not. A prior assertion that x is a word justifies the assertion that it is pronounceable; a prior assertion that x is unpronounceable justifies the assertion that it is a nonword (excluding, perhaps, people's names). However, prior assertions that x is pronounceable do not justify assertions about lexical status and prior assertions that x is a nonword do not justify assertions about pronounceability.

be aware of (making) the assertion but may not be aware of the justification (i.e., what they retrieved that justifies the assertion).

Second, it suggests that the memory system underlying automaticity and repetition priming is probably declarative. Subjects assert propositions and the propositions are remembered. However, it could also be procedural: The assertion (the declaration) is an act and the act could be remembered (or reenacted) at retrieval time. I prefer the declarative interpretation but I cannot rule out the procedural one.

Broader Implications

The close parallels between automaticity and repetition priming described in this article suggest that repetition priming may share other characteristics with automaticity beside a general speed-up with practice. Repeated items may be processed with less effort, as Johnston and Uhl (1976) have found. Repeated items may be processed in an obligatory fashion, which may explain the ubiquity and robustness of repetition effects (i.e., subjects may not be able to ignore memory for prior presentations). Similarly, automaticity may share other characteristics with repetition priming, such as good retention over long intervals (e.g., Feustal et al., 1983; Ratcliff et al., 1985; Scarborough et al., 1977). Few studies have addressed retention of the ability to process automatically (but see Kolers, 1976), though common lore would suggest excellent retention (e.g., ''one never forgets how to ride a bicycle''). These further parallels remain empirical questions that await future research.

The most provocative implication of the parallels uncovered in this article is the possibility that a single, general instance theory can account for a broad range of cognitive phenomena. Already, instance theories account for phenomena in episodic memory (e.g., Hintzman, 1976, 1988; Jacoby & Brooks, 1984), semantic memory (e.g., Landauer, 1975), automatization (e.g., Logan, 1988), categorization (e.g., Hintzman, 1986; Jacoby & Brooks, 1984; Medin & Schaffer, 1978), judgment (e.g., Kahneman & Miller, 1986), problem solving (e.g., Ross, 1984), and now, repetition priming. It would be a tremendous accomplishment to integrate these separate theories, pulling together common themes and resolving inessential differences, to create a single, general theory. The success of the instance theory in the present paper suggests that a general theory is tantalizingly close.

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