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Nonword repetition in lexical decision: Support for two opposing processes

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We tested and confirmed the hypothesis that the prior presentation of nonwords in lexical decision is the net result of two opposing processes: (1) a relatively fast inhibitory process based on global familiarity; and (2) a relatively slow facilitatory process based on the retrieval of specific episodic information. In three studies, we manipulated speed-stress to influence the balance between the two processes. Experiment 1 showed item-specific improvement for repeated nonwords in a standard "respond-when-ready" lexical decision task. Experiment 2 used a 400-ms deadline procedure and showed performance for nonwords to be unaffected by up to four prior presentations. In Experiment 3 we used a signal-to-respond procedure with variable time intervals and found *negative* repetition priming for repeated nonwords. These results can be accounted for by dual-process models of lexical decision (e.g., Balota & Chumbley, 1984; Balota & Spieler, 1999).

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One of the most often used tasks in the field of visual word recognition is the lexical decision task. In lexical decision, participants have to decide as quickly and accurately as possible whether a presented letter string is a word (e.g., CHAIR) or a nonword (e.g., GREACH). The general assumption that underlies the use of the lexical decision task is that the speed and accuracy of responding to word stimuli indicate the efficiency with which word representations are activated or retrieved from lexical memory. Several variables are thought to reflect the speed of retrieval from lexical memory. For instance, Scarborough, Cortese, and Scarborough (1977) found that performance for high-frequency words was better than performance for low-frequency words. This phenomenon is known as the *word frequency effect*. Another extensively studied phenomenon in the lexical decision task is the effect of prior study. Performance is better for words that have been encountered previously in the experimental context than for words that have not. This *repetition priming effect* for words was also demonstrated by Scarborough et al. (1977).

Although the facilitatory effect of prior presentations for words is well documented, much less is known about repetition priming effects for nonwords such as GREACH. The bias toward studying repetition priming for words rather than nonwords might be due to a focus on processes that operate in lexical memory. What can we learn from nonwords when these nonwords are not represented in lexical/semantic memory? First, several recent studies have stressed the fact that lexical decision is more than just lexical activation. The important role of decisional and strategic processes is exemplified by the impact of nonword lexicality on performance for word stimuli. Stone and Van Orden (1993) showed that illegal (e.g., BTESE) nonwords were easier to classify than legal nonwords (e.g., nonwords such as GREACH). Moreover, when the nonword stimuli looked less like words, responses to word stimuli were facilitated, and the word frequency effect was attenuated. Results like these (see also Stone & Van Orden, 1989) demonstrate that the processing of nonwords is an integral part of lexical decision performance.

A second reason to study performance for nonwords in lexical decision is their theoretical relevance in the debate between abstractionist (i.e., lexical/semantic) versus episodic theories of word identification (for reviews, see Bowers, 2000; Tenpenny, 1995). It has been argued that since nonwords are novel stimuli having no representation in lexical/semantic memory, any improvement in classifying nonwords as a result of prior presentation is due to an episodic process.[1] For instance, Logan (1988, 1990) found substantial facilitatory repetition priming effects for nonwords, and his episodic instance theory successfully fitted observed learning curves for nonwords (i.e., the increase in performance with the number of earlier presentations). Thus, the study of nonword repetition priming can potentially inform us to what extent lexical decision performance is influenced by episodic retrieval.

The foregoing illustrates that repetition priming for nonwords can reveal important information about word identification. Unfortunately, empirical results on nonword repetition

[1] Several researchers (e.g., Dorfman, 1994; Tenpenny, 1995) believe that an episodic account of facilitatory nonword repetition priming is not strictly necessary. Also, Bowers (2000) has argued that facilitatory nonword repetition priming is to some extent mediated by newly constructed *perceptual* codes. For clarity of exposition, we evaluate the plausibility of these alternative accounts in a later section and assume for now that facilitatory nonword repetition priming is at least partly caused by automatic retrieval of specific episodes.

priming in lexical decision have been mixed (for a review, see Tenpenny, 1995). Several researchers (e.g., Bowers, 1994; Duchek & Neely, 1989; Feustel, Shiffrin, & Salasoo, 1983; McKoon & Ratcliff, 1979) have noted that when a nonword is previously presented in a task other than lexical decision, no effects or slightly inhibitory effects are often observed in the later lexical decision task. However, when a nonword is previously presented in a lexical decision task, facilitatory effects are usually found (e.g., Logan, 1988, 1990). This pattern of results has led many researchers (e.g., Bowers, 1994; Bodner & Masson, 1997; Feustel et al., 1983; Smith & Oscar-Berman, 1990; Tenpenny, 1995) to believe that when the previous presentation of a nonword is in the lexical decision task, the repetition priming effect is the net result of two opposing processes: (1) an inhibitory familiarity process, and (2) a facilitatory episodic process. Logan (1990) has argued that this facilitatory process "is based on underlying associations between stimuli and the interpretations given to them in the context of specific experimental tasks" (p.1). It is important to note that the opposing processes account of nonword priming in lexical decision explains why inhibitory or null effects of nonword repetition priming are almost never observed in other word recognition tasks except lexical decision (e.g., Bowers, 1994, p. 544; Feustel et al., 1983): Only in lexical decision is there a potential conflict between the amount of pretrial exposure to a stimulus (i.e., familiarity) and the correct response.

Despite the fact that theoretical claims have been made regarding opposing processes operative in lexical decision for nonword repetition priming, few studies have systematically explored this issue. The hypothesis of two opposing processes is largely based on the comparison of results obtained across different studies, using different stimulus materials and different study and test procedures. The aim of the present study was to obtain more evidence for the operation of two opposing processes within a single study.

To evaluate the possibility that two opposing processes (i.e., retrieval of episodic instances vs. global familiarity) mediate repetition priming for nonwords, a variable is needed that affects the balance between these opposing processes. In this study, we opted to manipulate *speed-stress*. In the field of memory research, it is generally believed that high speed-stress will increase the participant's reliance on familiarity and at the same time reduce the contribution of retrieval of specific episodic traces (for a review, see Yonelinas, 2002, p. 460, p. 477; see also Hintzman & Curran, 1994; Joordens & Hockley, 2000, p. 1547; Juola, Fischler, Wood, & Atkinson, 1971; Ratcliff & McKoon, 1995, p. 758). This belief, based on empirical results reviewed in Yonelinas (2002), is reflected by the fact that almost all dual-process models for recognition memory incorporate a relatively fast familiarity process and a slower acting process of recollection (e.g., Mandler, 1980).

A dual-process model for lexical decision was proposed by Balota and colleagues (e.g., Balota & Chumbley, 1984, Figure 1; Balota & Spieler, 1999). In their model, it is assumed that participants maximize their performance by using a sequential decision process. In the first stage, a fast computation of overall familiarity is performed. When the computed familiarity value is higher or lower than preset criterion values, this allows a relatively accurate and fast "WORD" or "NONWORD" response, respectively. When the computed familiarity value is not very diagnostic, a more detailed and time-consuming analysis is carried out. We speculate that such a detailed process could involve episodic access to previous exposures, as envisioned by Logan (1988).

If speed-stress affects the balance between a fast operating familiarity process and a slower episodic retrieval process, as is strongly suggested by previous research in recognition memory, the effect of repetition priming for nonwords can be systematically manipulated.

Specifically, an increase in speed-stress should heighten the influence of the familiarity component and lower the influence of the episodic retrieval component. For nonwords, these processes work in opposition, such that involvement of the familiarity component leads to performance deficits for repeated nonwords, and involvement of the episodic retrieval component leads to performance benefits. Hence, an increase in speed-stress should reduce the facilitatory nonword repetition priming effect as observed by Logan (1990). Under severe speed-stress, effects of prior exposure might even become inhibitory.

Eliminating confounding factors

A problem in the interpretation of existing data is that in some studies nonword repetition was confounded with other variables. In the study of item-specific nonword repetition priming, it is crucial to eliminate two confounding factors: (1) time-on-task effects, and (2) criterion-shift effects. First, if the study status of a letter string is not independent of the total number of lexical decision trials that preceded the letter string, time-on-task effects could provide an alternative explanation for any observed priming effects. That is, if repeated stimuli are presented later in the lexical decision task than nonrepeated stimuli, any priming effects could be due to a combination of (1) a general practice effect, causing an increase in performance for repeated stimuli, and (2) fatigue, causing a decrease in performance for repeated stimuli.

The second complicating factor is the possibility that faster responses to repeated nonword stimuli could in certain designs be due entirely to a *criterion-shift*. Suppose the activation or retrieval of nonwords is not influenced by prior presentations, but the activation or retrieval of words is. For instance, assume that repetition priming strengthens representations in semantic memory but leaves nonwords unaffected, because nonwords are not represented in semantic memory. Further assume that the decisional mechanism can be characterized as a signal-detection problem. That is, the word/nonword decision might be based on a one-dimensional continuum of activation caused by the stimulus in lexical/semantic memory. Such a decisional system is illustrated in Figure 1. In general, words cause more activation in lexical/semantic memory than nonwords, and this provides the basis for the decision. Activation values to the right of the criterion lead to a "WORD" response, and activation values to the left of the criterion lead to a "NONWORD" response. In models of this sort, it is often assumed that the distance from the observed activation value to the response criterion is inversely related to response latency: The closer the observed activation value is to the response criterion, the longer the observed response latency (e.g., Hockley & Murdock, 1987; Ratcliff & McKoon, 1988). In the hypothetical situation described above, repeated words cause more lexical activation than nonrepeated words, causing the distribution for words to shift to the right. This rightward shift of the word distribution enables a more efficient setting of the response criterion, as indicated by the dotted line. The new response criterion leads to an increase in performance for nonwords without any change in amount of activation for repeated nonwords compared to nonrepeated nonwords. Hence, facilitatory nonword repetition priming might be attributed to item-specific word repetition. Therefore, if the proportion of repeated letter strings increases over the course of an experiment, and

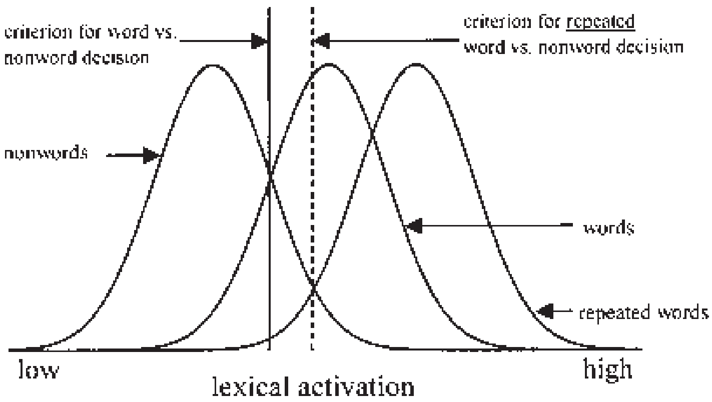

Figure 1. Selective repetition priming for words can generate repetition priming effects for nonwords. The leftmost distribution corresponds to nonword stimuli, the middle distribution corresponds to nonrepeated word stimuli, and the solid line indicates the criterion value on a global lexical activation dimension for making a decision between these two classes of stimuli. Previous presentations leave the nonword distribution unaffected, but shift the word distribution to the right. The new optimal response criterion, indicated by the dotted line, increases performance for nonwords.

facilitatory nonword repetition priming is observed, an alternative explanation can be given to account for the results. This alternative explanation assumes that selective word repetition priming enables more efficient criterion placement that also benefits nonwords.

In the experiments reported here, we have eliminated the confounding factors mentioned above by the use of a blocked design (cf. Hintzman & Curran, 1997, Exp. 2; Logan, 1988, Exp. 3; Smith & Oscar-Berman, 1990). This design is illustrated in Figure 2, and consists of a sequence of blocks. Suppose each stimulus is presented up to five times (as in Experiments 1 and 2), and each block consists of 60 trials (30 words and 30 nonwords). Consequently, each block contains 60/5 = 12 stimuli of each of the five priming conditions (1st, 2nd, 3rd, 4th, and 5th presentation). Every block contains all stimuli from the previous block, except for those stimuli that were presented for the fifth time in the previous block and are replaced by a set of new stimuli. Details of this procedure are described in the Method section. Since the proportion of repeated versus nonrepeated items is held constant throughout the experiment, the optimal response criterion remains fixed. The blocked design eliminates the effects of time-on-task on repetition effects, because the presentation condition of a stimulus and the total number of trials preceding the stimulus are not confounded. A final advantage of the blocked design is that the number of trials between successive repetitions is independent of the number of times the stimulus has been presented. In other words, in the blocked design there is no confounding between the time since the last presentation of the stimulus and the total number of prior presentations (Logan, 1988).

In all experiments reported here, we repeated word and nonword stimuli in lexical decision using the blocked design mentioned above. Over the three experiments reported here speed-stress was gradually increased. Consistent with an account of repetition priming for nonwords in terms of two opposing processes, this resulted in a reversal of the nonword repetition priming effect.

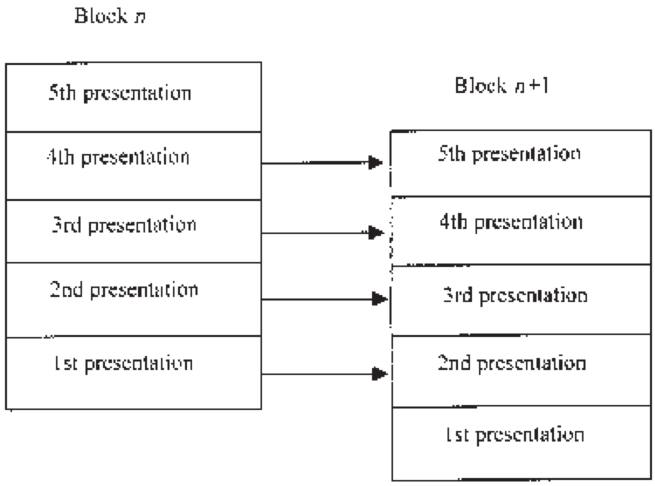

Figure 2. The blocked design used for Experiments 1–3. Stimuli are repeatedly presented in consecutive blocks. In this example, stimuli are presented up to five times. The group of stimuli that has been presented for the fifth time in block n is replaced by a group of new stimuli in block n+1.

EXPERIMENT 1

In Experiment 1, participants performed a regular (i.e., respond-when-ready) lexical decision task. As in all experiments reported here, we used three classes of stimuli: HF words, LF words, and pronounceable nonwords (i.e., nonwords such as GREACH).

Method

Participants

A total of 35 students of the University of Amsterdam participated for course credit. All participants were native speakers of Dutch and reported normal or corrected-to-normal vision.

Stimulus materials

The experimental stimuli consisted of 48 high-frequency (HF) words, 48 low-frequency (LF) words, and 96 pronounceable nonwords. Nonwords were created by changing one letter of an existing Dutch word. Frequency counts were obtained from the CELEX norms (Baayen, Piepenbrock, & Van Rijn, 1993). The frequency of occurrence for all HF words was higher than 30 per million (mean frequency 189 per million). The frequency of occurrence for the LF words ranged between 1 and 5 per million (mean frequency 2.2 per million). For each stimulus class (i.e., LF words, HF words, and nonwords) one third of the stimuli were four letters long, one third were five letters long, and one third were six letters long. In addition to the experimental stimuli there were 48 fillers, consisting of 12 HF words, 12 LF words, and 24 nonwords. The filler stimuli had the same general characteristics as those of the experimental stimuli.

Design

The experiment consisted of a total of 960 lexical decision trials. The stimuli were presented for up to five presentations over the course of the experiment. The experiment was designed in such a way that the presentation condition (i.e., 1st, 2nd, 3rd, 4th, or 5th presentation) of a stimulus and the total number of trials preceding the stimulus were not confounded. Therefore, any change in performance over the number of presentations of a stimulus is due to a stimulus specific repetition effect and cannot be ascribed to some general practice effect, skill learning, or fatigue.

The experiment consisted of 16 "blocks" of 60 trials each. In each block 30 words (15 HF and 15 LF) and 30 nonwords were presented. Stimuli were never repeated within a block. The transition from one block to another block was not marked in any way, and from the point of view of the participants the experiment consisted of one long sequence of trials. The 16 blocks consisted of four "filler" blocks at the beginning of the experiment followed by 12 experimental blocks. The first four filler blocks were needed to arrive at a design in which each block of 60 trials consisted of 12 trials for each presentation condition. These 12 trials always consisted of 3 trials on which a HF word was presented, 3 trials on which a LF word was presented, and 6 trials on which a nonword was presented.

Table 1 gives an overview of the presentation scheme of the stimuli. As can be seen in Table 1, in the first block of 60 trials all stimuli were presented for the first time. The 60 trials of the first block consisted of 48 filler stimuli and 12 experimental stimuli. In the second block, 12 new stimuli were introduced, and 48 stimuli were presented for the second time. The 12 new stimuli presented for the first time were all experimental stimuli. Of the 48 stimuli that were presented for the second time, 12 were experimental stimuli, and 36 stimuli were fillers. In this manner, 12 old stimuli (either fillers or experimental stimuli, depending on the block) were deleted in each block, and 12 new experimental stimuli were added. From Block 5 onwards each block consisted of only experimental stimuli, 12 for each of the five presentation conditions.

All trials (i.e., both filler and experimental stimuli) from Block 1 to Block 4 were excluded from the data analyses, thus including only trials from Block 5 to Block 16. This was done to assure that trial number and presentation condition were uncorrelated. Thus, for each participant a total of 720 experimental trials (12 blocks of 60 trials) were presented. For the LF words and HF words there were 36 observations for each presentation condition. For the nonwords there were 72 observations for each presentation condition.

TABLE 1
Number of presentations as a function of stimulus and number of repetitions

	Stimulus			*Presentation*				
Block	*Total*	*Filler*	*Exp*	*1*	*2*	*3*	*4*	*5*
1	60	48	12	60	0	0	0	0
2	60	32	24	12	48	0	0	0
3	60	24	32	12	12	36	0	0
4	60	12	48	12	12	12	24	0
5	60	0	60	12	12	12	12	12
6	60	0	60	12	12	12	12	12
:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:
16	60	0	60	12	12	12	12	12

Note: Exp = Experimental.

Procedure

Participants received spoken and written instructions explaining the lexical decision task. Participants were instructed to respond as quickly and accurately as possible. Each trial started with the 1000-ms presentation of a trial marker (##). Next, the trial marker was replaced by the stimulus. The stimulus remained visible in the centre of the screen until the participant responded or 1,500 ms had elapsed. Participants gave a "NONWORD" response by pressing the "z" key of the keyboard with the left index finger and a "WORD" response by pressing the "?/" key with the right index finger. When the participant made an error, the message "FOUT" (Dutch for "error") was presented for 1,500 ms. When no response was given after 1,500 ms, the message "TE LAAT" (Dutch for "too late") was presented for 1,500 ms. The next trial immediately followed the previous one. For each participant the order of the trials was randomly determined (within the constraints of the presentation scheme of the experiment). Participants were allowed a short break after 480 trials.

Results

The results of Experiment 1 are presented in Table 2. ANOVAs were performed on the mean latencies of correct responses and on error percentages. In all experiments reported here, the topic of interest is whether performance decreases or increases monotonically with the number of prior presentations. The corresponding statistical analysis is given by a linear trend analysis, which we report throughout this paper. One participant was excluded from the analysis because his error rate exceeded that of the average of the other participants by more than 2.5 standard deviations.

Facilitatory effects of repetition priming were observed for nonwords, HF words, and LF words. More specifically, nonwords were responded to faster as the number of presentations increased from 1 to 5, $F(1, 33) = 21.1$, $MSE = 863$, $p < .001$. No effect of nonword repetition priming was apparent from the error rates, $F < 1$. HF words were responded to faster, $F(1, 33) = 27.7$, $MSE = 863$, $p < .001$, and more accurately, $F(1, 33) = 12.0$, $MSE = 12$, $p < .01$, as the number of presentations increased from 1 to 5. LF stimuli were also responded to faster, $F(1, 33) = 130.7$, $MSE = 1273$, $p < .001$, and more accurately, $F(1, 33) = 145.0$, $MSE = 68$, $p < .001$, as the number of presentations increased from 1 to 5.

TABLE 2
Mean reaction times[a] and error rates[b] in Experiment 1 as a function of target word status and the number of presentations

	Number of presentations									
	1		*2*		*3*		*4*		*5*	
Target	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*
HF	583	4.9	555	2.7	542	3.0	543	2.4	546	1.8
LF	685	27.6	610	8.9	597	5.1	593	4.4	583	3.0
NW	628	3.7	620	3.7	607	3.2	600	3.9	601	3.5

Note: HF: high-frequency words. LF: low-frequency words. NW: nonwords.
[a] In ms. [b] In percentages.

Discussion

The results from Experiment 1 are straightforward: All types of stimuli (i.e., nonwords, HF words, and LF words) profited from previous presentations. The repetition priming effect was especially pronounced for LF words, particularly from the first presentation to the second. For nonwords, the overall 27-ms facilitatory repetition priming effect was highly reliable. In this experiment, the repetition priming effect for nonwords (27 ms) amounted to about 73% of the repetition priming effect for HF words (37 ms). We postpone a theoretical discussion on the mechanisms underlying facilitatory nonword repetition priming until the General Discussion. For now, we would like to point out that the finding of facilitatory nonword repetition priming is consistent with earlier findings by Logan (1988, 1990). Logan obtained larger effects of nonword repetition priming than those observed in this experiment, perhaps because Logan used few intervening trials between successive repetitions (an average of 12 or 24 intervening items) and a more limited set of stimuli.

EXPERIMENT 2

Experiment 2 was identical to Experiment 1, except for the application of a response deadline. Participants were instructed to respond before 400 ms, and to encourage timely responding we included a series of tones and provided visual feedback on response latency. Note that in the standard paradigm used in Experiment 1, response *latency* is usually the dependent measure of interest. In contrast, Experiment 2 and 3 focus on the effect time stress has on response *accuracy*.

Method

Participants

A total of 36 students of the University of Amsterdam participated for course credit. All participants were native speakers of Dutch and reported normal or corrected-to-normal vision.

Stimulus materials and design

The stimulus materials and design were identical to those of Experiment 1.

Procedure

The procedure was identical to that of Experiment 1, with two important exceptions related to the deadline procedure. First, during the 1,000-ms presentation of the trial marker (i.e., ##), two 1,000 Hz tones were presented for 10 ms on every trial. The first tone was presented 400 ms after the onset of the trial marker, and the second tone was presented 400 ms after the onset of the first tone, immediately preceding the presentation of the stimulus. Participants were instructed to respond before the third *imaginary* tone. Schouten and Bekker (1967) used a similar procedure, with the exception that Schouten and Bekker also actually presented the third tone. One of the reasons for not presenting the third tone during stimulus processing was that we wanted to approximate the situation to that in Experiment 1 as closely as possible. In order to emphasize the importance of timely responding even further, we used the time-band method (e.g., Wickelgren, 1977) illustrated in Figure 3, top panel. An incorrect response was followed by an error message (identical to the one from Experiment 1) that replaced the time-band

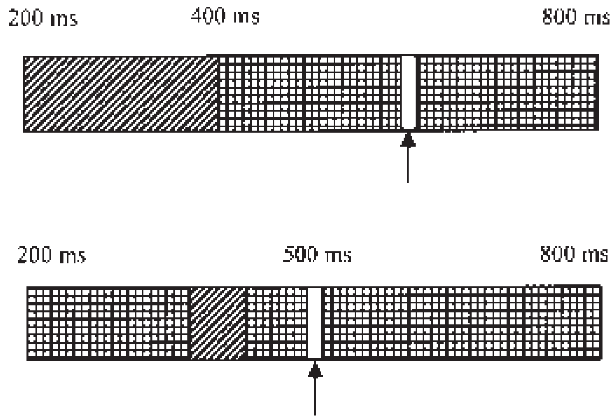

Figure 3. The time-band feedback methods. Top panel (Experiment 2): The shaded area to the left of the middle was coloured green, and the checkerboard-patterned area to the right of the middle was coloured red. The arrow beneath the bar and the small white rectangle on the bar indicated the observed response time of the participant. In this example, the participant exceeded the temporal deadline of 400 ms and responded about 600 ms after stimulus onset. Bottom panel (Experiment 3): The shaded area in the middle was the 50-ms wide target area and was coloured green. The checkerboard-patterned areas on either side of the target area were coloured red. In this example, the participant missed the target area and responded at about 500 ms after stimulus onset, whereas perfect timing would have resulted in a response time of 400 ms.

feedback. Late responding (i.e., no response after 800 ms since stimulus onset) was followed by the appropriate feedback (i.e., "too late" in Dutch) for 1,500 ms.

Results

The results of Experiment 2 are presented in Table 3. ANOVAs were performed on error percentages and on the mean latencies of correct responses. Two participants were excluded from the analysis because their error rates or response latencies exceeded the average of those of the other participants by more than 2.5 standard deviations.

Nonwords did not show repetition priming effects. As can be seen in Table 3, nonwords were classified most accurately on their first presentation and least accurately on the final fifth presentation. However, the overall trend toward an inhibitory effect of repetition priming for nonwords was not significant, $F(1, 33) = 1.9$, $MSE = 89$, $p > .15$. Response latencies for correct nonword classification were not affected by previous presentations, $F(1, 33) = 1.1$, $MSE = 611$, $p > .30$.

As in Experiment 1, facilitatory effects of repetition priming were observed for both HF stimuli and LF stimuli. More specifically, HF words were responded to more accurately as the number of presentations increased from one to five, $F(1, 33) = 7.1$, $MSE = 120$, $p < .05$. HF words were also classified correctly faster as the number of presentations increased from one to five, $F(1, 33) = 13.2$, $MSE = 658$, $p < .01$. LF words were responded to more accurately as the number of presentations increased from one to five, $F(1, 33) = 40.9$, $MSE = 245$, $p < .001$. LF words were also classified correctly faster as the number of presentations increased from one to five, $F(1, 33) = 7.2$, $MSE = 1081$, $p < .05$.

TABLE 3
Mean reaction times[a] and error rates[b] in Experiment 2 as a function of target word status and the number of presentations

	Number of presentations									
	1		2		3		4		5	
Target	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*	*RT*	*Error rate*
HF	456	26.4	438	17.4	432	17.4	427	17.3	436	18.5
LF	482	50.7	460	33.8	464	30.2	453	27.7	462	26.7
NW	477	25.4	480	28.5	480	25.7	478	27.9	485	29.3

Note: HF: high-frequency words. LF: low-frequency words. NW: nonwords.
[a] In ms. [b] In percentages.

Discussion

The main result is that nonword stimuli did not benefit from previous presentations. In our opinion, it is a remarkable finding that no repetition priming is found for a stimulus that is presented up to five times in exactly the same task. As in Experiment 1, HF words and LF words were facilitated by previous presentations. These effects of repetition priming for words were substantial and appeared in both response latency and response accuracy. Again, these facilitatory effects were most pronounced for the first couple of presentations.

In sum, speed-stress eliminated the facilitatory nonword repetition priming effect observed in Experiment 1, but the repetition priming effect for words was still present. The elimination of nonword repetition priming in the present experiment is consistent with the notion that increasing speed-stress reduces the contribution of a facilitatory episodic process. In the Introduction we discussed the hypothesis that apart from a facilitatory episodic process an inhibitory familiarity process is involved in nonword repetition priming. This hypothesis would gain considerable credibility if we would observe an inhibitory repetition priming effect for nonwords under conditions of extreme speed-stress.

Inhibitory nonword repetition priming under speed-stress has recently been observed in two experiments using the lexical decision task (Hintzman & Curran, 1997, Exp. 2, as re-plotted in Wagenmakers , Steyvers, Raaijmakers, Shiffrin, van Rijn, & Zeelenberg, 2004, Exp. 2). The main difference in methodology between these studies and Experiment 2 reported here is that the former used a signal-to-respond procedure (i.e., participants were instructed to respond immediately after presentation of a tone) where the tone could be presented at variable times after stimulus onset. The results showed that, in addition to the usual facilitatory repetition priming effects for HF and LF words, the probability of erroneously classifying nonword stimuli as words is higher on the second presentation than on the first presentation (i.e., inhibitory nonword repetition priming). These studies suggest that adjusting the design used in Experiment 2 to incorporate variable deadlines could produce inhibitory nonword repetition priming. This hypothesis was tested in Experiment 3.

EXPERIMENT 3

In Experiment 3, participants were instructed to respond exactly at various, randomly intermixed time intervals after stimulus onset (i.e., 350, 400, 450, 500, 550, and 600 ms). We used the same general procedure as that in Experiment 2 to encourage timely responding (i.e., a series of tones and time-band feedback). We anticipated this task to be very difficult and therefore provided extensive training. In addition to HF words, LF words, and nonwords that differed from an existing word in one letter (e.g., GREACH), we included a set of pronounceable nonwords that were created by changing two letters from an existing word (e.g., ANSU).[2] All stimuli were presented twice in a blocked design.

Method

Participants

A total of 43 students of Indiana University participated for monetary reward. All participants were native speakers of English and reported normal or corrected-to-normal vision.

Stimulus materials

We used four types of experimental stimuli: (1) 168 HF English words, each occurring more than 30 times per million according to the CELEX lexical database (Baayen et al., 1993); (2) 168 LF English words, each occurring one or two times per million; (3) 168 pronounceable nonwords created by replacing one letter of an existing word (e.g., GREACH derived from PREACH); and (4) 168 pronounceable nonwords differing by at least two letters from any word (e.g., ANSU). The first three stimulus categories were matched on neighbourhood structure (i.e., a neighbour is a word differing from another word in one letter, so TIED is a neighbour of LIED): These categories had roughly the same summed logarithmic word frequency of the neighbours. All stimuli were four, five, six, or seven letters long, occurring in the respective proportions 2:2:2:1. In addition to the experimental stimuli there were 72 fillers and 72 lexical decision practice stimuli, each group consisting of 18 HF words, 18 LF words, 18 "one letter replaced" nonwords, and 18 "two letters replaced" nonwords. Both fillers and lexical decision practice stimuli had the same general characteristics as those of the experimental stimuli. Finally, the stimuli ">" and "<" were used to familiarize the participants with the variable speeded-response procedure.

Design

The experiment consisted of three phases:

1. A general, nonlexical practice phase during which participants were familiarized with the variable speeded-response procedure. To this aim, we required participants to classify arrows (">" and "<"). Throughout the experiment, participants were required to respond at one of six times after the onset of the target stimulus (i.e., deadlines): 350, 400, 450, 500, 550, and 600 ms. The general practice phase consisted of 300 trials.

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[2] Due to a programming error, some nonwords that were created by changing two letters from a "parent" word differed only by *one* letter from yet another word. Despite this inaccuracy, the data showed substantial differences between the two types of nonword.

2. A lexical decision practice phase. In this phase, participants had to make 96 lexical decisions to 72 different stimuli (i.e., one block of 48 new stimuli followed by a block of 24 new stimuli and 24 stimuli from the first block).
3. The experimental phase. This phase consisted of 30 blocks of 48 trials each, resulting in a total of 1,440 trials. In each block except the first, half of the stimuli were new, and half of the stimuli had been presented in the previous block (i.e., the blocked design was used). As in the previous experiments, the transition from one block to another block was not marked in any way, and from the point of view of the participants the experiment consisted of one long sequence of trials. The first block consisted of 48 filler stimuli. In the final block, the remaining 24 filler stimuli were added to 24 experimental stimuli that had been presented in the previous block. Each block consisted of an equal number of word and nonword stimuli, and each of the six deadlines occurred eight times in one block. Only responses to experimental stimuli were analysed. The experimental stimuli were assigned to each of the six deadlines in a counterbalanced design. The order of the trials was randomly determined for each participant. Participants were allowed two short breaks, one after 480 trials in the experimental phase, and one after 960 trials in the experimental phase.

Procedure

The procedure was identical to the procedure of Experiment 2, with the following exceptions. First, the time-band feedback method was adjusted (see Figure 3, bottom panel). Instead of requiring participants to respond *before* a deadline, as in Experiment 2, participants were now required to respond within one of six specific time windows. Each time window was 50 ms wide and centred on the desired response time. To help participants give a timely response, we used three tones instead of two. The first tone was presented 500 ms after presentation of the trial marker (##), and the time between the three successive tones was constant and equalled the desired response time (i.e., one of the six deadlines). The last tone immediately preceded the presentation of the stimulus, and participants were instructed to respond at the fourth *imaginary* tone.

Results

The results of Experiment 3 are presented in Figure 4 and Table 4. Figure 4 shows the accuracy data, and Table 4 shows the response latencies. ANOVAs were performed on the mean latencies of correct responses and on error percentages. The data of 14 participants were excluded from the analysis, either because of excess error rate (i.e., an overall logarithmic d' lower than 1.0) or because of bad timing (i.e., an average of more than 50 ms off the goal RT). One participant failed to comply with the task instructions completely.[3] Of the remaining 29 participants, only data within a 200-ms window centred around the goal RT were analysed. This resulted in the exclusion of 16.1% of the data. Other methods of analysis (e.g., binning the data or using different window sizes) yielded similar results.

Figure 4 shows that for nonwords differing in only one letter from an existing word (i.e., "one letter replaced" nonwords), sizeable inhibitory effects of repetition priming were

[3] The difficulty of the variable speeded-response procedure is also witnessed by the fact that Hintzman and Curran (1997, Exp. 2) had to exclude 6 out of their initial 25 participants, either because of low accuracy or because of bad timing.

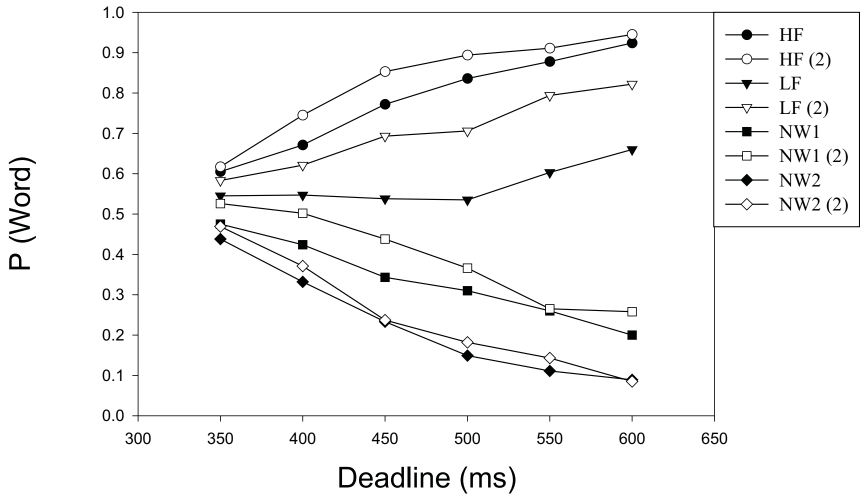

Figure 4. Results from Experiment 3. Repeated nonwords are responded to less accurately than novel nonwords. P(Word): probability of responding "WORD", HF: high-frequency words, LF: low-frequency words, NW1: "one letter replaced" nonwords, NW2: "two letters replaced" nonwords. The digit 2 in brackets indicates the second presentation.

observed. More specifically, "one letter replaced" nonwords were responded to less accurately on their second presentation than on their first presentation, $F(1, 28) = 43.1$, $MSE = 66$, $p < .001$. Nonwords differing in two letters from any existing word (i.e., "two-letters replaced nonwords") were also responded to less accurately on their second presentation than on their first presentation, thus showing an inhibitory repetition priming effect, $F(1, 28) = 12.2$, $MSE = 35$, $p < .01$. The response latencies for both "one letter replaced" nonwords and "two

TABLE 4
Mean reaction times[a] for first and second presentations in Experiment 3 as a function of target word status and deadline

	Deadline[a]											
	350		*400*		*450*		*500*		*550*		*600*	
Target	*Pres. 1*	*Pres. 2*	*Pres. 1*	*Pres. 2*	*Pres. 1*	*Pres. 2*	*Pres. 1*	*Pres. 2*	*Pres. 1*	*Pres. 2*	*Pres. 1*	*Pres. 2*
HF	363	364	411	409	455	449	494	488	533	528	579	576
LF	366	363	416	412	462	460	500	501	545	541	595	584
NW1	367	364	417	417	463	464	504	500	546	544	586	587
NW2	365	368	417	420	462	462	501	500	536	537	579	582

Note: HF: high-frequency words. LF: low-frequency words. NW1: "one letter replaced" nonwords. NW2: "two letters replaced" nonwords. Pres. = presentation.
[a] In ms.

letters replaced" nonwords were not affected by prior presentation, $F(1, 28) = 2.3$, $MSE = 66$, $p > .10$, and $F(1, 28) = 1.4$, $MSE = 93$, $p > .20$, respectively.

As in the previous experiments, facilitatory effects of repetition priming were observed for both HF stimuli and LF stimuli. More specifically, both HF words and LF words were responded to more accurately on their second presentation than on their first presentation, $F(1, 28) = 26.3$, $MSE = 71$, $p < .001$, and $F(1, 28) = 101.2$, $MSE = 149$, $p < .001$, respectively. HF words and LF words were also classified correctly faster on their second presentation than on their first presentation, $F(1, 28) = 18.1$, $MSE = 63$, $p < .001$, and $F(1, 28) = 14.2$, $MSE = 79$, $p < .01$, respectively.

Discussion

The main result of Experiment 3 is that nonword stimuli were responded to less accurately on their second presentation than on their first presentation. Thus, using a speeded-response procedure with variable short deadlines, inhibitory nonword repetition priming can be reliably obtained. In contrast to the nonword stimuli, word stimuli showed positive effects of repetition priming. As pointed out to us by an anonymous reviewer, the support for a two-process account of nonword repetition priming would have been even stronger if nonword repetition priming reversed as a function of processing time (i.e., inhibitory nonword repetition priming at short deadlines and facilitatory nonword repetition priming at longer deadlines). Experiment 3 did not reliably demonstrate such an interaction with respect to probability of correct classification for "one letter replaced" nonwords and "two letters replaced" nonwords, $F(1, 28) = 1.5$, $MSE = 68$, $p > .2$, and $F(1, 28) = 1.00$, respectively. The absence of this interaction might be due, at least in part, to the inclusion of many relatively short deadlines that effectively discourage the use of a time-intensive episodic process. Regardless, the main result from Experiment 3 is a clear inhibitory effect of nonword repetition priming when variable short deadlines are used. This finding strongly suggests that a process of global familiarity can influence lexical decisions for repeated nonwords. More specific accounts of inhibitory nonword repetition priming are discussed in the next section.

GENERAL DISCUSSION

In three experiments, we systematically studied the effects of prior presentations on performance for word and nonword stimuli in lexical decision. The focus of these experiments was to demonstrate that two opposing processes influence lexical decision performance for nonwords. First, retrieval of episodic information (e.g., "GREACH is a nonword") can facilitate performance for nonwords repeatedly presented in lexical decision (Logan, 1988, 1990). Second, an increased sense of familiarity can harm performance for repeated nonwords (e.g., Bodner & Masson, 1997). To influence the balance between the facilitatory episodic retrieval process and the inhibitory familiarity process we manipulated speed-stress. Increasing speed-stress should decreasing the role of the facilitatory episodic retrieval process and consequently enhance the role of the inhibitory familiarity process (e.g., Balota & Chumbley, 1984; Yonelinas, 2002). In complete agreement with this hypothesis, we found that a gradual increase in speed-stress from Experiment 1 to Experiment 3 reversed the effect of nonword repetition priming: With low speed-stress (i.e., Experiment 1), previous presentation increased performance for nonwords, but with high speed-stress (i.e., Experiment 3), previous presentation decreased performance for nonwords. In Experiment 2, even four previous presentations did not affect performance for nonword stimuli. In contrast to nonword stimuli, the qualitative pattern of results for *word* stimuli was unaffected by speed-stress: In all three experiments, previous presentation facilitated performance for words. This facilitatory repetition priming effect was more pronounced for LF words than for HF words (cf. Scarborough et al., 1977; Wagenmakers, Zeelenberg, & Raaijmakers, 2000).[4]

In a study by Smith and Oscar-Berman (1990) additional evidence for the existence of two opposing processes in nonword repetition priming was obtained. Smith and Oscar-Berman (1990, Exp. 1) used a dual-task paradigm to reduce the contribution of episodic memory to lexical decision performance. Word stimuli showed reliable facilitatory repetition priming effects in both the single-task condition and the dual-task condition. For nonword stimuli in the single-task condition, performance was substantially facilitated by a previous presentation. However, this facilitatory nonword repetition priming effect was eliminated in the dual-task setting. In another experiment, Smith and Oscar-Berman (1990, Exp. 2) found that in a regular, respond-when-ready lexical decision task, both control participants and amnesic participants performed better for repeated words than for nonrepeated words (i.e., facilitatory repetition priming for words). However, control participants performed better for repeated nonwords than for novel nonwords, but amnesic participants showed just the opposite pattern: Amnesiacs performed worse for repeated nonwords than for novel nonwords. We believe this result supports the notion that repetition priming for nonwords in lexical decision is the net result of (1) an inhibitory familiarity process, operative in both amnesiacs and control participants, and (2) a facilitatory episodic process that is dysfunctional in amnesiacs but that is able to support performance for repeated nonwords in control participants.

Alternative explanations for facilitatory nonword repetition priming

Throughout this paper, we have assumed that an increase in performance for repeated nonwords in lexical decision is due to the retrieval of specific episodic information. This assertion is consistent with the results reported here (cf. Experiment 1) and with the results of Smith and Oscar-Berman (1990, Exp. 2) mentioned above. Also, a theoretical explanation of facilitatory nonword repetition priming in terms of the retrieval of episodic information is provided by Logan's instance theory (e.g., Logan, 2002).

However, Dorfman (1994) has contradicted the claim that facilitatory nonword repetition priming is necessarily due to the use of episodic information. Dorfman pointed out that nonwords used in standard lexical decision experiments usually bear a close resemblance to real words and that repeated nonwords might therefore show a performance benefit due to the

[4] Up to now, we focused on the effects that are of primary interest for the present argument and hence omitted the statistical results on the attenuation of the word frequency effect for repeated words. In all three experiments, repetition priming was larger for LF words than for HF words with respect to both accuracy and response latency, all *p*s smaller than or equal to .01. The one exception was the lack of an attenuation of the word frequency effect for repeated words with respect to response latencies in Experiment 3, $F < 1$.

activation of preexisting abstract sublexical codes (see Dorfman, 1994, p. 1121). That is, any comparison process between a presented nonword and various word representations in memory could arguably be facilitated when it involves sublexical codes that have already been activated by prior exposure. We do not believe this explanation can provide a complete account of facilitatory nonword repetition priming. As mentioned in the Introduction, facilitatory nonword priming in lexical decision is usually found only when the study task requires participants to make lexical decisions (e.g., Tenpenny, 1995). Additional and specific evidence for this assumption is provided by Logan (1990, Exp. 3 and 4). If facilitatory nonword repetition priming was solely mediated by the activation of abstract sublexical codes, facilitatory priming effects would be expected to occur regardless of the nature of the study task. It seems implausible to us that a study task such as lexical decision would lead to activation of specific sublexical codes that would not be activated by other word recognition tasks such as naming, pronunciation decision (e.g., Logan, 1990), or recognition memory (e.g., McKoon & Ratcliff, 1979). In addition, facilitatory priming for nonwords is also found for nonwords that are random letter strings (e.g., Bowers, 1994; Stark & McClelland, 2000).

Another alternative explanation was proposed by Bowers (2000), who argues that facilitatory repetition priming for nonwords is due to perceptual learning, possibly mediated by specific brain regions in the right hemisphere (for a comparison between word and nonword repetition priming using the perceptual identification task, see Bowers, 1996). In good agreement with this hypothesis, several studies in perceptual identification have found that prior study leads to more efficient processing, an effect that is particularly pronounced for low frequency stimuli (e.g., Bowers, 1999; Wagenmakers et al., 2000; Zeelenberg, Wagenmakers, & Raaijmakers, 2002). Bowers' (2000) account is in some respects similar to the episodic explanation that we propose here, since in both accounts the benefit of a prior study episode is mediated by the construction of a novel memory trace. We believe that the fact that facilitatory repetition priming for nonwords in lexical decision occurs only when the study task is also lexical decision strongly suggest that prior exposure to a nonword stimulus results in the storage of not only perceptual information but also of higher order information related to the interpretation given to the nonword stimulus. We would further like to point out that in tasks such as lexical decision or perceptual identification, the activation of the higher order episodic information might be outside awareness (cf. Logan, 1988), and depend at least in part on a match between lower order perceptual information contained in the newly constructed episodic memory trace and the presented stimulus. In sum, we believe the activation-of-episodic-/perceptual-information account provides the most plausible explanation of facilitatory nonword repetition priming in lexical decision.

Models for nonword repetition priming in lexical decision

Most models of lexical decision have not been applied to nonword repetition priming. Two of the most recently developed models for lexical decision, the multiple read-out model (MROM; Grainger & Jacobs, 1996) and the dual route cascaded model (DRC; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) have not been applied to repetition priming in general. The parallel distributed model (PDP) proposed by Plaut (1997) does specifically address how repeated exposure of words affects classification accuracy in lexical decision. In Plaut's PDP model, exposure to a particular word strengthens the association between the orthographic activation and the corresponding semantic activation. The word–nonword decision is based on the semantic pattern of activation, which is less random for words than it is for nonwords. One might hypothesize that this model would predict inhibitory nonword repetition priming, since the distributed network can only distinguish words from nonwords through familiarity or frequency of previous exposure. On the other hand, one might argue that isolated presentation of nonwords does not, as a rule, lead to associations with any semantic properties. Hence, the Plaut model might theoretically also predict a null effect of priming for nonwords. It is not easily seen how PDP models can accommodate facilitatory nonword repetition priming except through some major restructuring.

In contrast, Logan's instance theory (e.g., Logan, 2002) can readily explain facilitatory nonword repetition priming, because instance theory is based on the premise that the interpretation given to individual episodes (e.g., "GREACH is a nonword") is available to the decision process. However, instance theory has no explicit mechanism to explain the inhibitory nonword repetition effects as observed in Experiment 3.

The findings reported here are perhaps best explained by a dual-process model such as that proposed by Balota and Chumbley (1984; also Balota & Spieler, 1999). Under conditions of high speed-stress, the participant can only complete the first stage of familiarity assessment, and hence the model predicts inhibitory nonword repetition. As the allotted time for stimulus processing increases, so does the probability that the participant will enter a second stage of processing, which involves a more elaborate analysis. The specific kind of elaborate analysis that is involved in the second stage of processing has not been rigorously defined. However, if one is willing to assume that the hypothesized analysis entails retrieval of episodic information, the model can explain the facilitatory nonword repetition priming effect under conditions in which the participant has ample time to respond (cf. Experiment 1).

In conclusion, we have shown that nonword repetition priming can be systematically manipulated by speed-stress. The observed results are consistent with a dual-process model for lexical decision (e.g., Balota & Chumbley, 1984; Balota & Spieler, 1999) in which an early stage of processing is based on global familiarity, and a subsequent stage involves a more elaborate analysis.

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