The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t716100704

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First published on: 27 May 2010

To cite this Article Orfanidou, Eleni , Davis, Matthew H. , Ford, Michael A. and Marslen-Wilson, William D.(2011) 'Perceptual and response components in repetition priming of spoken words and pseudowords', The Quarterly Journal of Experimental Psychology, 64: 1, 96 — 121, First published on: 27 May 2010 (iFirst)

To link to this Article: DOI: 10.1080/17470211003743794

URL: http://dx.doi.org/10.1080/17470211003743794

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2011, 64 (1), 96–121

Psychology Press
Taylor & Francis Group

Perceptual and response components in repetition priming of spoken words and pseudowords

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Two experiments explored repetition priming effects for spoken words and pseudowords in order to investigate abstractionist and episodic accounts of spoken word recognition and repetition priming. In Experiment 1, lexical decisions were made on spoken words and pseudowords with half of the items presented twice (~12 intervening items). Half of all repetitions were spoken in a "different voice" from the first presentations. Experiment 2 used the same procedure but with stimuli embedded in noise to slow responses. Results showed greater priming for words than for pseudowords and no effect of voice change in both normal and effortful processing conditions. Additional analyses showed that for slower participants, priming is more equivalent for words and pseudowords, suggesting episodic stimulus–response associations that suppress familiarity-based mechanisms that ordinarily enhance word priming. By relating behavioural priming to the time-course of pseudoword identification we showed that under normal listening conditions (Experiment 1) priming reflects facilitation of both perceptual and decision components, whereas in effortful listening conditions (Experiment 2) priming effects primarily reflect enhanced decision/response generation processes. Both stimulus–response associations and enhanced processing of sensory input seem to be voice independent, providing novel evidence concerning the degree of perceptual abstraction in the recognition of spoken words and pseudowords.

Keywords: Repetition priming; Episodic/abstractionist accounts; Response learning; Deviation point; Pseudowords.

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The research was funded by Medical Research Council (MRC) funding of the Cognition and Brain Sciences Unit (U.1055.04.013.1.1) and by an A.G. Leventis Foundation and a Cambridge European Trust research bursary to Eleni Orfanidou. Preliminary results of Experiment 1 were presented at the January 2006 meeting of the Experimental Psychology Society.

http://www.psypress.com/qjep
DOI:10.1080/17470211003743794

Spoken word recognition requires the identification of a highly variable sensory input, reflecting differences in the age, sex, dialect, speaking rate, and so forth of the speaker. For lexical access to take place this variable input must make contact with stored memory representations of familiar spoken words (the mental lexicon). This process involves matching of perceptual features extracted from the stimulus to these stored lexical representations. Two questions emerge: How does the recognition of spoken words proceed in the face of such variability? And how much of this variability is encoded in the memory representations of spoken words?

In answer to these critical questions, two broad classes of account of spoken word recognition have been developed. Abstractionist theories propose that words are stored in the form of abstract phonological representations (Luce & Pisoni, 1998; Norris, 1994) that discard the specific details of speech, whereas episodic theories posit exemplar-based representations that encode stimulus-specific information, such as characteristics of the talker's voice along with the other perceptual properties of spoken words (Goldinger, 1996, 1998). The repetition priming paradigm has played a prominent role in investigating the representations that underlie spoken word recognition. Repetition priming for words produces a decrease in response times and/or an increase in the accuracy of responses, reflecting an increase in the ease with which participants can extract sufficient information from the speech stream to recognize familiar words. By assessing whether these increases in processing efficiency are specific to the repetition of previously encountered episodic representations, or general for stimuli that share underlying abstract lexical representations, researchers have been able to address the question of whether the perceptual representations that support spoken word representations are abstract or episodic.

The perceptual component in priming: Abstractionist and episodic representations

Two critical behavioural effects have been used in evaluating abstractionist and episodic theories: effects of lexical status (word or pseudoword) and of speaker's voice on repetition priming. A key prediction for abstractionist accounts is that, since spoken word recognition depends on abstract preexisting representations of the phonological form and meaning of words, long-term repetition priming should only be observed where abstract, long-term representations exist. That is, repetition priming should be observed for familiar words, but not for unfamiliar pseudowords (Tenpenny, 1995). In contrast, episodic accounts propose that recognition of spoken words results from newly formed episodic representations. Therefore, long-term priming could occur even for unfamiliar lexical items, without preexisting representations (i.e., pseudowords). In other words, unless a single presentation is sufficient to create a lexical entry, the abstractionist view predicts that we should be able to find differences in repetition priming for words and pseudowords (Tenpenny, 1995). It should be noted that priming effects may be contaminated by explicit memory—that is, explicit recall of earlier occasions when the current stimulus was encountered previously (Henson, 2001). Thus, priming might involve explicit memory (also often referred to as "episodic" processes) yet these memory representations might still be based on abstract phonological representations. In the present work, however, we focus on the specific prediction of episodic accounts of lexical representation (cf. Goldinger, 1996, 1998) that acoustic details of spoken words are critical for supporting lexical processing and repetition priming. It is in this latter sense that the terms "episodic" and "episodic accounts" of priming are used throughout this paper.

A number of repetition priming experiments have tested priming for both words and pseudowords. Some studies using the lexical decision task have failed to yield any evidence of pseudoword priming (Brown & Carr, 1993; Duchek & Neely, 1989; Ratcliff, Hockley, & McKoon, 1985), though more recent demonstrations of priming have been reported (e.g., Bowers, 1996; McKone & Dennis 2000; Mimura, Verfaellie, & Milberg, 1997). Robust repetition priming effects for pseudowords has been obtained with other tasks such as perceptual identification (e.g., Feustel, Shiffrin, & Salasoo, 1983; Rueckl, 1990) and naming (Brown & Carr, 1993). The observation that priming extends to pseudowords that have no preexisting representation provides evidence that priming for both pseudowords and words in word identification tasks is the product of new memory representations. However, it has been suggested that pseudoword priming is not incompatible with abstractionist theories (Bowers, 2000). In this view, pronounceable and phonologically legal pseudowords consist of portions of familiar words (e.g., morphemic and syllabic components), and thus priming can be mediated by the preexisting sublexical representations that pseudowords share with real words (Dorfman, 1994; Humphreys, Besner, & Quinlan, 1988).

Predictions derived from abstractionist and episodic theories with regard to effects of the speaker's voice are, however, more straightforward. According to abstractionist accounts, word recognition involves access to phonological form representations that exclude voice information (e.g., Jackson & Morton, 1984; Luce & Pisoni, 1998; Norris, 1994). If repetition priming effects are supported by phonological form information, then voice changes between the first and second presentations of an item should not affect the magnitude of repetition priming. Abstractionist theories do not deny that specific perceptual information is stored in memory elsewhere, rather their main claim is that this information is not necessary for word recognition and therefore should not influence primed lexical decision (Bowers & Kouider, 2003). In contrast, in the episodic framework words are identified through the formation of new, episodic representations that preserve much of their physical detail (Goldinger, 1996, 1998). Word recognition involves a comparison between multiple memorized acoustic patterns, each of which reflects a previous processing episode, and the pattern elicited by the current acoustic signal. Repetition priming effects are explained on the basis of greater accessibility of recent episodes that are similar to the current items. Thus, episodic accounts predict attenuation of priming following changes in the surface form of items between repetitions and more facilitation when the details of a prior occurrence are repeated.

In spite of these clear predictions, voice effects on auditory priming studies are rather inconsistent. Effects of voice change have been observed for the fragment completion task and for identification of low-pass filtered or noise-embedded stimuli in some studies (e.g., Church & Schacter, 1994; Schacter & Church, 1992, Experiment 3; see Goldinger, 1996; Sheffert, 1998) but not in others (Gonzalez & McLennan, 2007, Experiment 1; Jackson & Morton, 1984; Schacter & Church, 1992, Experiment 5; see Pilotti, Bergman, Gallo, Sommers, & Roediger, 2000, for voice effects in identification but not in stem/fragment completion). In the lexical decision task, specificity effects emerged only when the lexical decision task was made more difficult by introducing pseudowords that were very word-like (Gonzalez & McLennan, 2007, Experiment 2; McLennan & Luce, 2005), while equivalent and robust priming for both same and different voice repetitions of high-frequency words was reported by Luce and Lyons (1998).

As shown by this review, research using pseudoword priming and voice manipulations provides evidence that both detailed episodic traces and abstract representations support repetition priming and recognition of spoken words. This evidence has thus led to the proposal of hybrid accounts of priming and spoken word recognition in which both abstract and episodic coding play a role (Goldinger, 2007; Luce, McLennan, & Charles-Luce, 2003; Pisoni & Levi, 2007). For example, a hybrid model developed by Luce and colleagues (2003) proposes that abstract representations dominate during initial contact between the sensory input and lexical representations when identification is easy and effortless. Only when identification is slowed (as for low-frequency or perceptually degraded items) do more voice-specific episodic codes come into play. The success or failure of this hybrid model will depend on precisely specifying what other manipulations alter the relative influence of abstract and episodic representations in word recognition and priming.

In the present paper, we therefore present two experiments that explore the influence of lexicality (word vs. pseudoword presentation) and voice (same- vs. different-voice stimulus repetition) on repetition priming of spoken items. One goal of this work is to specify in more detail those conditions that give rise to abstract and episodic influences on repetition priming for spoken materials. With this in mind, we report two experiments that include the same stimuli and task in two different stimulus presentation conditions. We assessed priming effects both for normal clearly spoken stimuli (Experiment 1) and when recognition is slower and more effortful (Experiment 2) by embedding spoken stimuli in background noise. This permits a test of the prediction made by hybrid abstract/episodic accounts that voice effects on priming are slow acting and hence of greater magnitude when identification is slowed (e.g., Luce et al., 2003).

The decision/response component in repetition priming

In developing a hybrid account of the mechanisms involved in spoken word recognition and priming we also consider additional nonperceptual processes that might contribute to the priming effect. Specifically, we explore the possibility that a significant contribution to repetition priming comes not from modifications to underlying perceptual representations, but rather to decision processes that are facilitated for repeated presentations. This possibility reflects the fact that many repetition priming studies involve the execution of the same task during both study and test phases. This introduces the possibility that learned stimulus–response associations can give rise to response facilitation (by an abstract account), or that a representation of the chosen behavioural response to a stimulus is primed. To the extent that these response-based priming processes contribute to priming, then, these might similarly be abstract and/or episodic in nature.

Evidence that learned stimulus–response associations can influence repetition priming has come from a number of sources. For instance, behavioural studies have shown that repetition priming effects for familiar stimuli are often restricted to the task performed on the stimulus on its initial presentation (e.g., Durso & Johnson, 1979; Logan, 1990; though see also Scarborough, Gerard, & Cortese, 1979; Valentine, Moore, Flude, Young, & Ellis, 1993). In the neuroimaging literature, functional magnetic resonance imaging (fMRI) studies have identified brain areas that show a neural repetition suppression effect that is closely correlated with behavioural priming. A number of findings suggest that frontal response changes in areas associated with decision processes and response generation predict the magnitude of task-specific repetition priming (Bunzeck, Scütze, & Düzel, 2006; Dobbins, Schnyer, Verfaellie, & Schacter, 2004; Macotta & Buckner, 2004; Orfanidou, Marslen-Wilson, & Davis, 2006; Wagner, Koutstaal, Maril, Schacter, & Buckner, 2000). Those imaging studies that use different tasks for first and second presentations tend to highlight more posterior regions involved in perceptual processing (Gagnepain et al., 2008; Horner & Henson, 2008). Neuropsychological studies have similarly shown that prefrontal lesions can impact on behavioural and neural repetition priming for written words and nonwords (Swick, 1998). Here we report two additional behavioural analyses to compare the magnitude of repetition priming for different participants and different stimulus items with the aim of providing behavioural evidence concerning perceptual and response contributions to repetition priming of spoken words and pseudowords.

One important issue in assessing decision-based priming effects in lexical decision tasks, however, is that participants must indicate that words are familiar (a YES response) while pseudowords require that participants indicate that an item is unfamiliar (a NO response). This may produce different priming effects for words and pseudowords since there is a potential conflict between experimentally induced familiarity with the pseudoword stimuli (due to repeated presentation) and the requirement to make a NO response. Consistent with this proposal, recent studies of visual word recognition (Wagenmakers et al., 2004a; Wagenmakers, Zeelenberg, Steyvers, Shiffrin, & Raaijmakers, 2004b; Zeelenberg, Wagenmakers, & Shiffrin, 2004) have suggested that the activation of an episodic trace containing both perceptual information and stimulus–response associations is the most plausible mechanism for facilitatory pseudoword priming in the lexical decision task. A crucial feature is that this episodic-based priming is slow acting, while familiarity of an item, resulting in inhibition for pseudowords in lexical decision, can be assessed very quickly. Thus, these studies observe differences between fast- and slow-responding participants in the relative magnitude of word and pseudoword priming observed, reflecting differential dependence on (fast abstract) perceptual familiarity and (slow episodic) response-learning processes in supporting priming for these different classes of stimulus. The relative contribution of these two mechanisms to lexical decision performance may be affected by a number of factors such as the study task, the frequency of the word and pseudoword stimuli, and so on (Zeelenberg et al., 2004), which could explain the inconsistent pseudoword priming effects in the lexical decision task (facilitation, e.g., Logan, 1990; McKone, 1995; null effects, e.g., Brown & Carr, 1993; inhibition, e.g., Bowers, 1994; McKoon & Ratcliff, 1979). The opposing processes account of pseudoword priming in lexical decision also explains why inhibitory or null effects are not usually obtained with other word recognition tasks, where there is no conflict between the familiarity with the pseudoword and the correct response (Wagenmakers et al., 2004b). However, similar effects have not been tested in the auditory domain in which the influence of voice changes can provide additional evidence for the involvement of episodic representations in priming.

To further assess whether priming reflects facilitation of decision or response generation processes rather than the ease of perceptual processing we also report a novel analysis to relate the magnitude of repetition priming for individual items to the time-course of perceptual processing of speech. Existing evidence has shown that pseudoword responses in the lexical decision task are closely tied to the time-point in the spoken stimulus at which pseudowords can be distinguished from all other familiar words in the lexicon (uniqueness/deviation points, cf. Marslen-Wilson, 1984). Decision processes to indicate that an item is a pseudoword can only be initiated once sufficient spoken input has been perceived. We might therefore predict that repetition-induced changes to decision processes would only affect processes that occur after the deviation point, producing equivalent priming effect for early- and late-deviating pseudowords. In contrast, repetition-priming effects that modify the time-course of perceptual processing may interact with deviation point. There is additional opportunity for stimulus repetition to influence response times for items that have a later deviation point and for which perceptual processing is extended in time. Should repetition priming effects differ in magnitude for items with early and late deviation points this would provide novel evidence to separate perceptual and response-based contributions to repetition priming. The rationale and analysis method used are explained in more detail after presentation of the two experiments and the results of conventional, factorial analysis.

EXPERIMENT 1

Method

Participants

A total of 24 native English speakers between the ages of 18 and 40 years participated in this study. All volunteers had normal hearing and normal or corrected-to-normal eyesight and reported no language problems. Each gave informed consent after the experimental procedure was explained.

Stimuli

The stimulus set consisted of 240 low-frequency words (nouns, monosyllabic and bisyllabic, 1 to 100 occurrences per million; see Appendix, Table A1) and 240 word-like pseudowords, divided into eight lists matched on a number of variables (length, number of phonemes, number of syllables, frequency, bigram/trigram frequency, uniqueness point/deviation point, imageability;

see Appendix, Table A2). An analysis of variance, in which list was entered as the fixed factor and each of these variables as the dependent measure, revealed no significant differences between the lists (Fs < 1). The pseudowords respected the phonotactic rules of the English language and were made by changing one or two phonemes of words with COBUILD frequency of 1 to 100 occurrences per million that were not used in the final experimental lists. We included pseudowords with an average bigram frequency of 89 and an average trigram frequency of 1,192. The stimuli in Lists A–D were treated as the test items and were presented twice, while those of Lists E–H were used as fillers and were presented only once. The stimuli were recorded by both a male and a female native English speaker at a sampling rate of 44.1 kHz and were edited into separate files for playback using Cool Edit software. The recorded stimuli were checked by a phonetician for any differences in pronunciation between the two speakers to avoid confounds between phonetic variation and potential voice effects on priming.

Experimental design

The experimental design included 120 test words and 120 test pseudowords each of which were presented twice, as well as 120 filler words and 120 pseudowords to disguise stimulus repetition. Half of all repetitions were in the "different voice" from the first presentations. This configuration resulted in 480 test trials and 240 filler trials, 720 trials overall, which were split into three sessions of 240 trials each. Each session lasted about 12 minutes, and participants had 2,500 ms in which to respond before the program moved on to the next item, while the intertrial interval was 1,500 ms. To control for item-specific effects, the four groups of test items were pseudorandomly assigned to same voice and different voice repetitions for different volunteers, creating a four-experimental-lists experiment, and participants were randomly assigned to one of these lists. Repetitions occurred after approximately 12 intervening items (30-s delay between first and second presentations).

Procedure

Each session started with a practice block, followed by the three blocks of the experiment proper. Each trial consisted of the auditory presentation of a word to which participants made a lexical decision. The stimuli were presented auditorily over headphones using DMDX software (Forster & Forster, 2003). Participants were advised that they were to decide as quickly and as accurately as possible whether what they heard was a real word or not. They were also advised that the words would be spoken in two different voices, one male and one female, but they should not let this affect their judgement and that they should attend to what was said, not the voice that said it. Accuracy and reaction times (with millisecond accuracy, measured from word onset) were recorded. A two-button response box was used, and participants were instructed to keep their fingers on the buttons at all times to encourage quick responding. The "yes" response key was always pressed with the dominant hand and the "no" response with the nondominant hand.

Results

Mean response times from word onset (RTs) and error rates (ERs) were calculated for each participant and each item in each condition. All incorrect responses were excluded from the RT analyses. Data from 1 participant were removed from data analyses as accuracy and decision latencies were two standard deviations above the mean. One pseudoword was associated with disproportionate numbers of errors (above 33%) and was excluded from the analysis. Three outlying data points (latencies less than 200 ms from word onset) were excluded from the RT analysis. Due to an error in the design, four pseudowords in Condition 3 were not included. Analyses of variance by participants (F_1) and items (F_2) were performed on the remaining data. Response times were inverse-transformed to reduce the effects of outliers (Ratcliff, 1993). The significance level adopted in the present study is .05.

The means of the error rates and mean correct reaction times across participants were 6% and

Table 1. *Mean RTs and error rates in Experiment 1*

	Presentation 1 collapsed		*Presentation 2 same voice*		*Presentation 2 different voice*	
Lexicality	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*
Words	895	7.74	809	4.86	811	4.72
Pseudowords	949	5.03	907	4.58	917	6.81

Note: RT = response time, in ms. Error rates in percentages.

838 ms for words and 5% and 924 ms for pseudowords. Table 1 displays means of the RTs for correct responses and error rates to words and pseudowords in each condition for first and second presentations.

The data were collapsed over the first presentation of each speaker for the purposes of analysis. Main effects and interactions involving the speaker factor are not of interest per se since they may merely reflect differential intelligibility of the two individuals chosen to record the materials.[1] In the following analyses we focus on differences in the magnitude of responses on second presentation as a function of whether the same or different speaker produced a particular word as on first presentation. We included lexicality (2 levels, words/pseudowords) and presentation (3 levels, first presentation collapsed over voice/second presentations in the same voice/second presentation in a different voice) as factors of interest. Speaker (2 levels, female/male) and version (4 levels) were included as variables to account for variation in performance across experimental lists or between voices but effects are not reported as they are of no theoretical interest. Words were recognized faster than pseudowords, main effect of lexicality, $F_1(1, 20) = 93.4$, $p < .001$, $F_2(1, 114) = 59.6$, $p < .001$, min $F'(1, 92) = 36.4$, $p < .001$, and there was a difference between presentations, reflecting slower responses for first presentations, main effect of presentation $F_1(2, 40) = 96.6$, $p < .001$, $F_2(2, 228) = 89.5$, $p < .001$, min $F'(2, 144) = 46.4$, $p < .001$. We observed a two-way interaction of lexicality and presentation, $F_1(2, 40) = 27.7$, $p < .001$, $F_2(2, 228) = 30.2$, $p < .001$, min $F'(2, 128) = 14.4$, $p < .001$, suggesting differential repetition priming of words and pseudowords. To investigate the effects of the same voice versus different voice repetition additional analyses were performed in each condition separately comparing first presentation with second presentation in the same voice and second presentation in the different voice. These analyses showed that there was significant repetition priming in all cases, both for words and for pseudowords (all ps $< .001$; see Figure 1).

The same analysis was run for the error rates. There was no difference in accuracy between words and pseudowords, $F_1 < 1$, $F_2(1, 114) = 2.8$, $p = .093$, min $F'(1, 34) = 0.7$, $p = .419$, but a difference in accuracy between presentations, $F_1(2, 40) = 6.2$, $p = .005$, $F_2(2, 228) = 7.0$, $p < .001$, min $F'(1, 125) = 3.3$, $p = .041$. We observed a two-way interaction of lexicality and presentation, $F_1(2, 40) = 3.9$, $p = .029$, $F_2(2, 228) = 5.6$, $p = .004$, min $F'(2, 106) = 2.3$, $p = .105$, again suggesting differential priming for words and pseudowords. Separate analyses for the pseudowords only showed no main effect of presentation, $F_1(2, 40) = 2.1$, $p = .140$, $F_2 < 1$, min $F'(2, 268) = 0.3$, $p = .738$. Analyses in each condition separately comparing first presentation with second presentation in the same voice and second presentation in the different voice showed that there was significant repetition priming in all cases for words (all ps $< .05$).

To compare the magnitude of priming directly for words and pseudowords in the same and different repetition conditions (same vs. different voice, irrespective of speaker's gender) an analysis of variance (ANOVA) was performed on the priming scores with lexicality (2 levels, words/pseudowords) and voice (2 levels same/different). RTs to the second occurrence were subtracted from RTs to

[1] In general, male recordings were more intelligible than female recordings, producing faster responses that were more pronounced for words than for pseudowords. Given the absence of significant interactions between speaker and presentation, no interesting effects are lost by ignoring these effects.

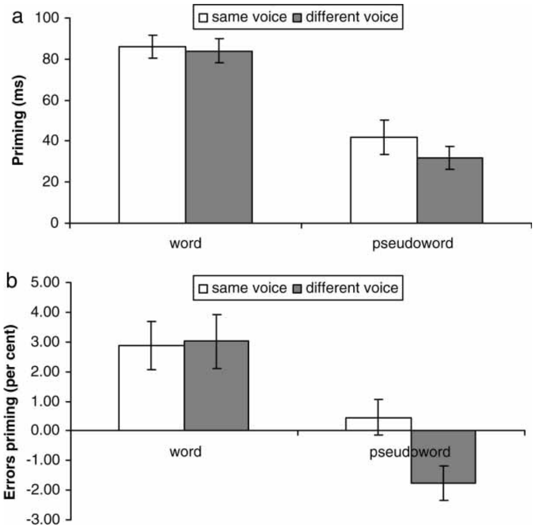

Figure 1. *(a) Priming effects (response times, RTs) and (b) errors (percentages) for words and pseudowords in the same and different voice conditions in Experiment 1. Error bars represent one standard error.*

the first, so that a positive value indicates repetition priming. As shown in Figure 1a, priming for words differs significantly from priming for pseudowords—lexicality, $F_1(1, 20) = 40.8$, $p < .001$, $F_2(1, 119) = 63.2$, $p < .001$, min $F'(1, 51) = 24.8$, $p < .001$—although as described previously, analyses on simple RTs showed that there was significant priming for pseudowords. Same and different voice repetitions produced roughly equivalent amounts of priming, consistent with previous findings (Luce & Lyons, 1998). Although there was a numerical reduction of 10 ms in priming for pseudowords when a voice change was involved compared to when the voice remained the same, this was not significant, with no main effect of voice, $F_1(1, 20) = 2.4$, $p = .137$, $F_2(1, 119) = 2.1$, $p = .147$, min $F'(1, 75) = 1.1$, $p = .293$, and no lexicality by voice interaction (F_1, $F_2 < 1$). Analyses of priming scores in separate conditions showed no differences in priming due to the voice change between repetitions (i.e., same vs. different voice priming in all conditions $p > .05$). The average repetition effects are plotted in Figure 1 as a function of voice (same/different) and lexicality (word/pseudoword).

The analysis on the priming scores for the error data again showed more priming for words than for pseudowords, $F_1(1, 20) = 19.1$, $p < .001$, $F_2(1, 119) = 8.0$, $p = .005$, min $F'(1, 117) = 5.6$, $p = .019$, more priming for same than for different voice repetitions by participants only, $F_1(1, 20) = 7.1$, $p = .014$, $F_2 < 1$, min $F'(1, 125) = 0.2$, $p = .66$, but no significant lexicality by voice interaction, $F_1(1, 20) = 3.2$, $p = .090$, $F_2 < 1$, min $F'(1, 138) = 0.4$, $p = .541$, indicating no differences between word and pseudoword priming in the effects of the voice change (see Figure 1b).

Discussion

Analyses showed a greater magnitude of repetition priming for words than for pseudowords. Although facilitation effects for the pseudowords were reduced, they were still statistically significant in RT data. Furthermore, changing the voice of words and pseudowords had no significant effect on the magnitude of response time priming for pseudowords and only a marginal effect on the accuracy of lexical decision responses. Although a number of behavioural studies using other tasks have reported effects of voice change on the magnitude of priming (e.g., McLennan & Luce, 2005), the present results are in line with previous studies that found little or no effects of voice change on auditory lexical decision (Gonzalez & McLennan, 2007, Experiments 1 and 2; Luce & Lyons, 1998; McLennan & Luce, 2005).

The lack of a robust effect of changing the physical form of the stimuli between repetitions suggests that the representation being contacted is at a more abstract level than an episodic trace consisting of all physical properties of the stimulus items. However, since a repetition priming effect was observed for pseudowords as well as words, and a difference between same and different voice repetitions was found in the error data for pseudowords, results also present a problem for theories that posit that abstract lexical representations are uniquely responsible for repetition priming effects for spoken stimuli. Thus, these results are consistent with hybrid abstract/episodic accounts reviewed previously.

One motivation for these hybrid accounts is the finding that voice changes modulate priming in lexical decision only when the task was made more difficult by including very word-like pseudowords (McLennan & Luce, 2005) or low-frequency bisyllabic words (McLennan, Luce, & Charles-Luce, 2003). Based on their findings, Luce et al. (2003) proposed a time-course hypothesis, by which specificity effects emerge in task situations where the stimuli require longer processing times either because they are perceptually degraded or because they are highly infrequent. In their resulting hybrid model, when identification is easy and fast, abstract codes dominate spoken word recognition or at least dominate the initial contact of the sensory input with lexical representations. More specifically, episodic sensory codes only come into play when longer processing time is available. This hypothesis was tested in Experiment 2 by increasing the difficulty of auditory lexical decisions. We used the same materials and design as those in Experiment 1 but added background noise to the stimuli.

EXPERIMENT 2

In this study we repeated the first experiment with background noise added to all speech stimuli. To ensure equivalent masking of speech information throughout each item we used a form of signal-correlated background noise (Schroeder, 1968) with the same spectrum and amplitude envelope as those for the original speech. In order to find the appropriate signal to noise ratio for the main experiment a series of pilot studies were run varying the degree of distortion and recording response times and error rates. The goal was to find a level of noise that gave around 10% errors and mean RT around 1,000 ms, a level of performance at which participants found the task substantially more difficult than when the stimuli were clear speech but could still perform the task with reasonable accuracy. Data from the pilot studies suggested that +4dB signal to noise ratio would produce the appropriate level of difficulty for the participants.

Method

Participants

A total of 25 native English speakers between the ages of 18 and 40 years participated in this study. All volunteers had normal hearing and normal or corrected-to-normal eyesight and reported no language problems. Each gave informed consent after the experimental procedure was explained.

Materials

The stimuli used were those of Experiment 1. For this experiment a script in the Praat speech manipulation software (Boersma & Weenink, 2007) was used to add signal-correlated, speech-spectrum noise to the recordings. This signal-correlated noise was added to the original recordings at a signal to noise ratio of +4 dB, and the resulting speech file was then attenuated to ensure that overall level matched the original recording. Examples of the original and distorted recordings can be obtained from the authors.

Procedure

The procedure was the same as the one used in Experiment 1. Participants were informed that the words would be noisy and that it might be difficult to comprehend what they heard, but that they should do the best they could.

Results

Mean RTs and ERs were calculated for each participant and each item as before and subjected to the same statistical analysis as that for Experiment 1. The means of the error rates and mean correct reaction times across subjects were 10% and 986 ms for words and 8% and 1,110 ms for pseudowords. As expected, the addition of noise made the experiment more difficult, hence the increase of the RTs and ERs. Thus, this manipulation has achieved the desired goal of increasing the difficulty and hence response times in the lexical decision task. Table 2 displays means of the RTs for correct responses and ERs to words and pseudowords in each condition for first and second presentations.

Table 2. *Mean RTs and error rates in Experiment 2*

	Presentation 1 collapsed		*Presentation 2 same voice*		*Presentation 2 different voice*	
Lexicality	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*
Words	1,042	11.5	953	10.1	962	8.89
Pseudowords	1,144	8.68	1,095	7.43	1,093	8.89

Note: RT = response time, in ms. Error rates in percentages.

Following the same procedure as that in Experiment 1, data were collapsed over the first presentation of each speaker for the purpose of analysis. Words were identified faster than pseudowords, $F_1(1, 21) = 80.1, p < .001, F_2(1, 91) = 75.2, p < .001$, min $F'(1, 71) = 38.8, p < .001$, and there was a difference between presentations, possibly reflecting the fact that first presentations were slower than second presentations, $F_1(2, 42) = 58.2, p < .001, F_2(2, 182) = 67.5, p < .001$, min $F'(2, 124) = 31.3, p < .001$. We again observed the critical two-way interaction of lexicality and presentation, $F_1(2, 42) = 11.9, p < .001, F_2(2, 182) = 3.2, p = .041$, min $F'(2, 200) = 3.0, p = .050$, suggesting greater priming for words than for pseudowords. Similar to Experiment 1, analyses of the separate conditions comparing first presentation with second presentation in the same voice and second presentation in the different voice showed significant repetition priming in all cases, both for words and for pseudowords (all ps $< .05$ in participants and items analyses; see Figure 2a).

The same analysis run on the error rates indicated a tendency for pseudowords to be identified more accurately than words, which was significant by participants, $F_1(1, 21) = 12.5, p = .002, F_2(1, 119) = 2, p = .161$, min $F'(1, 140) = 1.7, p = .191$, and there was a difference in accuracy between presentations, $F_1(2, 42) = 3.6, p = .035, F_2(2, 238) = 5.7, p = .004$, min $F'(2, 104) = 2.2, p = .115$, and a significant two-way interaction of lexicality and presentation, $F_1(2, 42) = 4.5, p = .018, F_2(2, 238) = 3.8, p = .023$, min $F'(2, 161) = 2.1, p = .131$, suggesting differential priming for words and pseudowords.

To compare directly the magnitude of priming for words and pseudowords in the same and different repetition conditions (same vs. different voice, irrespective of gender) an ANOVA was performed on the priming scores for the RTs. In line with the previous analysis, a main effect of lexicality, $F_1(1, 21) = 21.1, p < .001, F_1(1, 110) = 35.5, p < .001$, min $F'(1, 50) = 13.2, p < .001$, was found, with priming effects being more pronounced for words than for pseudowords, although in separate analysis of the pseudoword data priming for pseudowords was significant as well: presentation, $F_1(2, 42) = 15.6, p < .001, F_2(2, 200) = 9.4, p < .001$, min $F'(2, 106) = 9.4, p < .001$. We did not find an effect of voice change, either as a main effect, $F_1(1, 21) = 2.5, p = .128, F_2(1, 110) = 2.4, p = .127$, min $F'(1, 73) = 1.2, p = .272$, or as an interaction: lexicality by voice, $F_1 < 1, F_2(1, 110) = 2.2, p = .145$, min $F'(1, 32) = 0.4, p = .513$ (Figure 2).

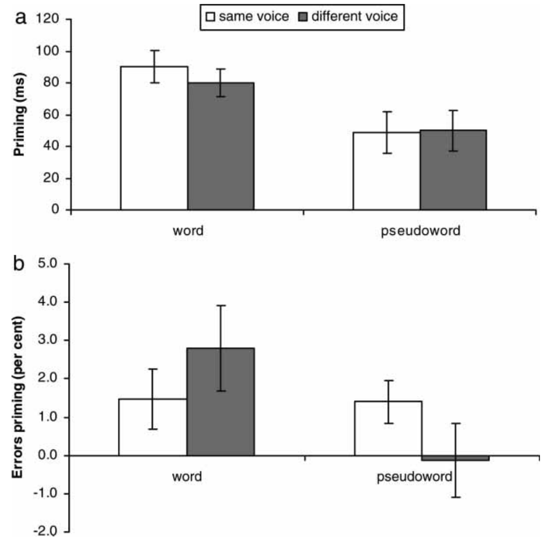

Figure 2. *(a) Priming effects (response times, RTs) and (b) errors (percentages) for words and pseudowords in the same and different voice conditions in Experiment 2. Error bars represent one standard error.*

The analysis of the priming scores for the error rates showed a difference between word and pseudoword priming, $F_1(1, 21) = 2.3, p = .141, F_2(1, 119) = 12.1, p < .001$, min $F'(1, 30) = 1.9, p = .174$, no difference between same and different voice repetitions ($F_1, F_2 < 1$), and a lexicality by voice interaction that was significant by participants and marginal by items, $F_1(1, 21) = 7.0$, $p = .018$, $F_2(1, 119) = 3.2$, $p = .075$, min $F'(1, 116) = 2.2$, $p = .141$, which suggests that there were differences between word and pseudoword priming on the effects of the voice change. Inspection of Figure 2b suggests that for words, there was more priming for different voice repetitions than for same-voice repetitions, while for pseudowords the reverse was true (the predicted effect of voice changes). However, assessment of simple effects comparing voice effects on error rate priming for words and pseudowords separately showed that neither of these differences in priming due to voice change was significant for between repetitions for either words, $t_1(24) = -1.5$, $p = .135$, $t_2(119) = 1.3$, $p = .198$, or pseudowords, $t_1(24) = 1.6$, $p = .111$, $t_2(119) = -1.3$, $p = .213$.

Comparison between experiments

In order to increase statistical power to detect effects of voice change on priming, we combined the results of Experiment 1 and Experiment 2 into a single analysis. In this analysis, we included three factors of interest: lexicality (2 levels, words/pseudowords), presentation (3 levels, first presentation/second presentation same voice/second presentation different voice), and experiment (1–clear speech, 2–noisy speech). We included version as a dummy factor to absorb additional variance. As expected, words were recognized faster than pseudowords—main effect of lexicality, $F_1(1, 41) = 146.5$, $p < .001$, $F_2(1, 110) = 64.2$, $p < .001$, min $F'(1, 150) = 44.63$, $p < .001$—second presentations were faster than first presentations—main effect of presentation, $F_1(2, 82) = 158.0$, $p < .001$, $F_2(2, 220) = 155$, $p < .001$, min $F'(2, 241) = 78.2$, $p < .001$—and this priming effect was more pronounced for words than for pseudowords—two-way interaction of lexicality and presentation, $F_1(2, 82) = 15.7$, $p < .001$, $F_2(2, 220) = 2.6$, $p = .074$, min $F'(2, 278) = 2.2$, $p = .109$. There was a main effect of experiment showing slowed responses due to speech degradation (responses in Experiment 2 were on average 141 ms slower), $F_1(1, 41) = 15.2$, $p < .001$, $F_2(1, 110) = 1{,}296$, $p < .001$, min $F'(1, 42) = 15$, $p < .001$, and a lexicality by experiment interaction, $F_1(1, 41) = 5$, $p = .031$, $F_2(1, 110) = 119$, $p < .001$, min $F'(1, 44) = 4.8$, $p = .034$, since lexicality effects were more pronounced with degraded speech. However, there was no significant experiment by presentation interaction, $F_1 < 1$, $F_2(2, 220) = 1.2$, $p = .313$, min $F'(2, 142) = 0.3$, $p = .737$, suggesting that priming effects were largely unmodified by degradation. The same analysis was performed on the error rates. There was a main effect of experiment, with increased error rates in Experiment 2, $F_1(1, 41) = 27.5$, $p < .001$, $F_2(1, 119) = 43.6$, $p < .001$, min $F'(1, 96) = 16.9$, $p < .001$, and a lexicality by experiment interaction, $F_1(1, 41) = 7.9$, $p < .007$, $F_2 < 1$, min $F'(1, 136) = 0.6$, $p = .452$, again due to the bigger difference between words and pseudowords in error rates in Experiment 2 than in Experiment 1. Once more, there was no significant experiment by presentation interaction (F_1, $F_2 < 1$), suggesting that there were no differences between the experiments in the overall magnitude or pattern of priming effects observed.

To directly compare the priming effects, we compared the priming scores for same and different voice repetitions of words and pseudowords in each experiment and entered these values into an ANOVA. In the RTs there was a main effect of lexicality, $F_1(1, 41) = 59.2$, $p < .001$, $F_2(1, 110) = 72.6$, $p < .001$, min $F'(1, 108) = 32.6$, $p < .001$, with greater priming for words, no effect of experiment, $F_1 < 1$, $F_2(1, 110) = 1.4$, $p = .232$, min $F'(1, 85) = 0.5$, $p = .504$, either as a main effect or as an interaction with voice changes (experiment by voice, F_1, $F_2 > 1$). However, in the items analysis experiment did interact with lexicality, $F_1 < 1$, $F_2(1, 110) = 11.4$, $p < .001$, min $F'(1, 48) = 0.9$, $p = .355$, reflecting greater overall priming for pseudowords in Experiment 2 than in Experiment 1. This pattern confirms that despite the overall slowing of responses in Experiment 2, there were no major differences in priming effects between experiments. In the errors analysis, there was no main effect of lexicality, $F_1 < 1$, $F_2(1, 110) = 1.9$, $p = .176$, min $F'(1, 52) = 0.2$, $p = .639$, but an interaction between experiment and lexicality, $F_1(1, 41) = 5.8$, $p < .021$, F_2

< 1, min $F'(1, 131) = 0.3$, $p = .584$, reflecting greater overall priming for pseudowords in Experiment 2 than in Experiment 1. There was a main effect of experiment, $F_1 < 1$, $F_2(1, 119) = 43.6$, $p < .001$, min $F'(1, 41) = 0.03$, $p = .872$, but no interaction between experiment and voice (F_1, $F_2 < 1$).

Discussion

In Experiment 2 we manipulated the ease of lexical decision by adding signal-correlated noise to test the hypothesis put forward by McLennan and Luce (2005) that specificity effects in lexical decision become apparent when the task is made more difficult by adding background noise or pseudowords that are word-like (see Appendix B for the list of pseudowords used). Although response times were significantly increased in Experiment 2 compared to Experiment 1, which should have allowed greater time for episodic codes to influence processing, voice changes between first and second presentations did not have any significant effect on the amount of repetition priming for either words or pseudowords. Numerical trends towards priming effect differences between same and different voice repetitions only emerged in ANOVA on the errors that showed a lexicality by voice interaction but no differences between same and different voice repetitions for words and pseudowords in subsequent pairwise comparisons. Furthermore, combining data across experiments failed to show reliable voice effects on priming, nor any apparent change in the magnitude of voice effects when responses were slowed.

Taken together the results from Experiment 1 and Experiment 2 show that repetition priming for words and pseudowords is largely insensitive to changes in the physical form of the stimuli between repetitions. Yet, in both experiments reliable repetition priming (on response times, if not on error rates) was observed for pseudowords. This pattern of results suggests the involvement of episodic, newly acquired representations for pseudowords (given the presence of priming), and yet these representations are sufficiently abstract as to be shared over same- and different-voice repetitions. In particular, in light of the apparent support in the literature for both the abstractionist and episodic theories, it is therefore plausible to assume that priming reflects residual activation in preexisting abstract representations under some circumstances and the influence of new episodic memory traces under other circumstances. However, a successful hybrid model will need to make more specific predictions concerning the situations under which episodic influences are observed.

With regard to the specific time-course prediction generated by McLennan and Luce (2005), data from Experiment 2 showed that even under slow processing conditions, voice-specific episodic codes did not sufficiently influence processing to produce voice effects on repetition priming. This could be either because episodic codes are not slow acting or because they do not contain voice-specific information.

In the analyses presented so far, we have treated word and pseudoword priming equally. However, there may be different processes and representations involved in producing what appear to be quite similar word and pseudoword priming effects. It is interesting in that respect that priming effects for words were positive and facilitatory throughout, whereas priming effects for pseudowords were positive in response times and negative or absent in error rates. To shed more light on these findings we performed two additional analyses on the data with the aim to identify differences between word and pseudoword priming and to characterize the processes and representations involved in different stages during recognition and priming of words and pseudowords in lexical decision.

As reviewed at the outset, in the present study, response learning is a plausible mechanism for generating priming effects for pseudowords in particular since stimulus–response associations could still apply even if no preexisting representation of a pseudoword exists. To test this proposal, we performed two additional analyses on response times and priming effects for pseudowords to investigate whether the speeding of responses for second presentations can be attributed to facilitation in decision processes.

RESPONSE COMPONENTS IN REPETITION PRIMING

Fast versus slow processing

In this first analysis we compare priming effects for slow and fast participants. According to the account of pseudoword priming by Wagenmakers, Zeelenberg, and colleagues (Wagenmakers et al., 2004b; Zeelenberg et al., 2004), slow participants would show more pseudoword priming than fast participants because the former rely on a slow-acting episodic trace containing a stimulus–response association, while the latter rely more on a fast-acting familiarity-based process, which produces less priming for pseudowords than for words. This analysis allows us to examine whether retrieval of this episodic trace is hindered by the voice change. In addition, this priming profile should be even more evident in Experiment 2, where the processing is slowed down by the addition of noise.

In Experiment 1, 12 participants with RTs between 735–867 ms were included in the fast participants category, and 12 participants with RTs between 870 and 1,097 ms were included in the slow participants category. This categorization was based on a median split of participants based on their grand-mean RT (median RT = 868 ms). An ANOVA was run on the priming scores with lexicality (2 levels, word/pseudoword) and voice (2 levels, same/different) as within-participants factor and version (4 levels) and speed of participant (2 levels, fast/slow) as between-participants factors. Since the only change between this analysis and the factorial analyses reported previously is the additional factor speed of participant, we focus our attention on main effects and interactions that involve this factor. The results showed a main effect of speed of participant, $F_1(1, 16) = 5.2$, $p = .037$, $F_2(1, 119) = 26.9$, $p < .001$, min $F'(1, 23) = 4.4$, $p = .872$, and, critically, an interaction between speed of participant and lexicality, $F_1(1, 16) = 5.2$, $p = .037$, $F_2(1, 119) = 9.2$, $p = .003$, min $F'(1, 41) = 0.03$, $p = .048$, reflecting the fact that slow participants show more equivalent priming for words and pseudowords (see lexicality effect column in Table 3). There was no effect of the voice change, either as a main effect or as an interaction with speed of participant (all ps > .05), suggesting that slow and fast participants were affected in the same way by same and different voice repetitions. The analysis on the errors produced by slow and fast participants showed an effect of speed of participant only in the items analysis, $F_1(1, 16) = 3.0$, $p = .100$, $F_2(1, 119) = 4.4$, $p = .039$, min $F'(1, 43) = 1.8$, $p = .188$, but no interaction with lexicality (F_1, $F_2 < 1$) or voice (F_1, $F_2 < 1$), showing that fast and slow participants were equally affected by voice changes.

The same analysis was run in Experiment 2. A total of 12 participants with RTs between 754 and 1,002 ms were included in the fast participants category, and 13 participants with RTs between 1,024 and 1,296 ms were included in the slow participants category (median = 1,023 ms). In Experiment 2 the interaction between lexicality and speed of participant on the magnitude of priming was even more robust than that in Experiment 1, $F_1(1, 17) = 22.0$, $p < .001$, $F_2(1, 117) = 28.6$, $p < .001$, min $F'(1, 49) = 12.4$, $p < .001$; see Table 3). This fits nicely with the fact that responses were (overall) slower in Experiment 2 than in Experiment 1—further increasing this change in the priming profile. The analysis on the errors produced by slow and fast participants showed a main effect of speed of participant by items only, $F_1(1, 17) = 1.3$, $p = .274$, $F_2(1, 119) = 9.8$, $p = .002$, min $F'(1, 22) = 1.1$, $p = .001$, no interaction between speed of participant and lexicality, $F_1(1, 17) = 2.1$, $p = .295$, $F_2 < 1$, min $F'(1, 120) = 0.5$, $p = .472$, but an interaction between speed of participant and voice by participants only, $F_1(1, 17) = 6.6$, $p = .020$, $F_2 < 1$, min $F'(1, 121) = 0.1$, $p = .805$. This interaction reflects the fact that fast participants show more priming for different voice repetitions (an average of 2.88 for words and pseudowords) than do slow participants, who show

Table 3. *Priming effects for fast and slow participants in Experiments 1 and 2*

			Priming		*Lexicality effect*	
	Participant	*Lexicality*	*RT*	*ER*	*RT*	*ER*
Experiment 1	Fast				55	4.17
		Word	90	4.24		
		Pseudoword	35	0.07		
	Slow				40	3.06
		Word	78	1.67		
		Pseudoword	38	−1.39		
Experiment 2	Fast				63	2.69
		Word	106	3.65		
		Pseudoword	43	0.96		
	Slow				7	0.21
		Word	64	0.49		
		Pseudoword	57	0.28		

Note: The lexicality effect represents word minus pseudoword priming.

considerably less priming for different voice repetitions (an average of −0.35 for words and pseudowords) than do fast participants. This is the only indication of an effect of the voice change in this analysis and fits well with the hypothesis that the priming effects displayed by slow participants are based on an episodic trace, the retrieval of which seems to be hindered by the voice change.

Discussion

Consistent with the proposal by Wagenmakers and colleagues (e.g., Wagenmakers et al., 2004b), we observed differences between fast and slow participants in their use of familiarity-based and response-learning processes. However, contrary to our predictions, we did not find that slow participants show more pseudoword priming than fast participants; in Experiment 1 there is a 3-ms increase (35 ms to 38 ms for fast vs. slow participants), and in Experiment 2 there is a 14-ms increase in pseudoword priming (43 ms to 57 ms for fast vs. slow participants). At the same time changes in word priming for fast versus slow participants are numerically larger (12 ms for Experiment 1, and 43 ms for Experiment 2). A tentative explanation of these results is that fast participants use both familiarity and episodic stimulus−response associations and hence produce strong word priming. Slow participants use only stimulus−response associations and thus produce more similar amounts of priming for words and pseudowords. This would not be so consistent with abstract, familiarity-based processes being faster than episodic processes as proposed by Wagenmakers and colleagues, but rather that episodic processes suppress familiarity-based priming effects when participants take more time to respond. This is even more pronounced under the slower processing conditions of Experiment 2, where slow participants produced numerically similar amounts of priming for words and pseudowords (64 ms and 57 ms, respectively, though word priming was still larger than pseudoword priming), $F_1(1, 8) = 40.9$, $p < .001$, $F_2(1, 119) = 1.9$, $p = .175$, min $F'(1, 126) = 1.8$, $p = .180$. Only in the analyses of the errors in Experiment 2 was there a difference between participants in terms of the effect of voice changes on priming. This appears to suggest that episodic stimulus−response priming more so than familiarity-based priming uses perceptually detailed representations. These detailed representations under certain circumstances (e.g., degraded input) seem to encode specific acoustic details of productions of the stimuli. This result is in line with the time-course hypothesis, where slow processing involves detailed episodic representations. However, this pattern was not observed for the reaction time data and was not statistically very robust, and thus we refrain from drawing strong conclusions based solely on this finding.

The results of this analysis indicate that word priming is mediated mainly through familiarity-based processes, which facilitate responses to second presentation. In contrast, the process of retrieving episodic information is more critical in supporting pseudoword priming, and when relied upon by participants (as for the slow participants in Experiment 2) leads to reduced priming effects for words. At least under normal processing conditions, this episodic information does not contain detailed perceptual information (e.g., voice of presentation) but perhaps higher order information related to the interpretation of the stimulus as a word or a pseudoword. Thus, whilst results are to some extent consistent with the time-course hypothesis put forward by McLennan and colleagues (McLennan & Luce, 2005), which predicts that episodic codes will influence processing when response times are longer, we find that the familiarity-based mechanism and the episodic mechanism do not consistently rely on detailed information concerning the voice used for presentation in judging whether items are words or pseudowords. Our results suggest, however, that in the lexical decision task, where there is a conflict between familiarity and the NO response, these episodic codes can operate equally with preexisting lexical representations (for words) and for items that are initially unfamiliar (i.e., for pseudowords). In the next set of analyses we further examine the nature of the priming effects supported by episodic stimulus–response associations for pseudowords.

ENHANCED PERCEPTUAL OR DECISION PROCESSES IN PSEUDOWORD PRIMING

One established method for enhancing perceptual influences on visual repetition priming in both behavioural (Grainger & Segui, 1990; Warrington & Weiskrantz, 1968) and functional imaging experiments (Eger, Henson, Driver, & Dolan, 2007; James, Humphrey, Gati, Menon, & Goodale, 2002) uses progressive demasking of stimuli. In this method, stimuli are initially displayed in an unrecognizable form such as when masked with noise, or presented too briefly for identification. Over the course of several seconds, the stimulus is gradually revealed using longer presentation durations or reduced visual noise. Such a method allows an otherwise static visual stimulus to unfold over time, thereby increasing the influence of perceptual identification processes on repetition priming effects.

One critical property of spoken language is that in natural presentation conditions it similarly unfolds over time. The perceptual system is initially provided with a relatively indistinct or uninformative input (the initial segments of a spoken word), which is gradually refined and enhanced by the presentation of subsequent segments over the course of the duration of a spoken word. Accounts of spoken word recognition starting from the Cohort model (Marslen-Wilson & Welsh, 1978) and later localist (McClelland & Elman, 1986; Norris, 1994) and distributed (Gaskell & Marslen-Wilson, 1997) connectionist models have all incorporated mechanisms by which lexical activation and selection respond progressively to incoming information in the speech signal. Although recent evidence would suggest that additional processing time (over and above the duration of the speech signal) is required for successful identification (Dahan & Gaskell, 2007; Zwitserlood & Shriefers, 1995), it remains the case that all current, large-scale models of spoken word recognition incorporate (explicitly or implicitly) mechanisms for accessing lexical representations based on ongoing, sequential information in the speech signal.

The sequential nature of speech perception therefore permits a novel test of whether repetition priming effects arise from increased efficiency of perceptual processes that track the speech signal (such that participants can respond based on reduced amounts of sensory input), or whether the same amount of sensory information is required for identification, but postperceptual decision processes operate more rapidly. We can potentially distinguish these two possible mechanisms of repetition priming by analyses in which response latencies for first and second presentations of spoken stimuli are related to the time at which critical perceptual information appears in the speech signal—the uniqueness point of words and deviation point of pseudowords (see Marslen-Wilson, 1984, for discussion). In the present analysis we focus our attention on the relationship between deviation point and pseudoword response latencies for two reasons: first because the influence of learned stimulus–response associations on priming is clearer for pseudowords, and second because the influence of uniqueness point on word responses is weaker both in our data and in previous data.[2]

One important determinant of response times to pseudowords in lexical decision is the delay from sequence onset until the offset of the phoneme at which the pseudoword deviates from any existent word (henceforth referred to as the deviation point). In Marslen-Wilson (1984) it is shown that lexical decision times are well predicted by a linear function, such that response times are delayed by a fixed amount from this deviation point (see Figure 3 for an illustration). If repetition priming reflects facilitation in decision processes, one might expect that this fixed delay from deviation point to response would be reduced in the second presentation of a pseudoword, therefore changing the intercept, but not the slope of the line relating the delay between deviation point and reaction times as shown in Figure 3a. However, if stimulus processing is made faster and more efficient on the second presentation, then it might be the case that less sensory input is required to distinguish a pseudoword from similar existing words. That is, the delay between stimulus onset and deviation point would reduce for second presentations. Since this reduction would probably be proportional to magnitude of this delay (and hence the amount of time required for perceptual processing), then stimulus repetition should have a greater impact on responses to late than on responses to early deviating pseudowords (see Figure 3b). Hence, the hallmark of enhanced perceptual processing of pseudowords would be a change not to the intercept but to the slope of the line relating the delay until deviation point to lexical decision response time. That is, we would predict enhanced repetition priming for pseudowords that required more extensive stimulus-driven processing (i.e., pseudowords with a later deviation point) and hence a reduction in the steepness of the slope that relates deviation point to response times, as is illustrated in Figure 3. Of course, it might well be that repetition priming reflects enhancement of both perceptual and response components, in which case we would predict changes in both the slope and the intercept for second presentations.

Before moving on to the details of this analysis, we should remark that notwithstanding the considerable evidence for sequential processing of spoken language, there is evidence that pseudoword decisions can be driven by information after the deviation point. For example, Taft and Hambly (1986) found that reaction times to long pseudowords were longer than those to short pseudowords, even though both kinds of pseudowords had their deviation point at the same distance from onset. Goodman and Huttenlocker (1988) used pseudowords with early and late deviation points and found that reaction times measured from the deviation points were longer for early than for late deviation points. According to Goodman and Huttenlocker (1988), the strong deviation point effect (close to 100%) found by Marslen-Wilson (1984) may reflect the use in the items with early deviation points of pseudowords with phonotactically illegal onsets that could be detected without consulting the lexicon. Although we acknowledge

[2] A similar analysis was performed on the word data, relating the reaction time to words with the delay from sequence onset until the offset of the phoneme at which the word becomes uniquely distinguishable from any other existing word in the language, the uniqueness point (UP). A trained phonetician marked the uniqueness point for each word in the male and the female voice. We calculated for each participant on a trial-by-trial basis the slope and intercept of the line relating the delay until the UP to the reaction time for first and second presentations separately. Unlike the pseudoword data, the analysis showed that UP is not a strong predictor of lexical decision latencies for both experiments. Given this nonsignificant correlation with UP we did not proceed to analyses looking at how the effect of UP changes with repetition.

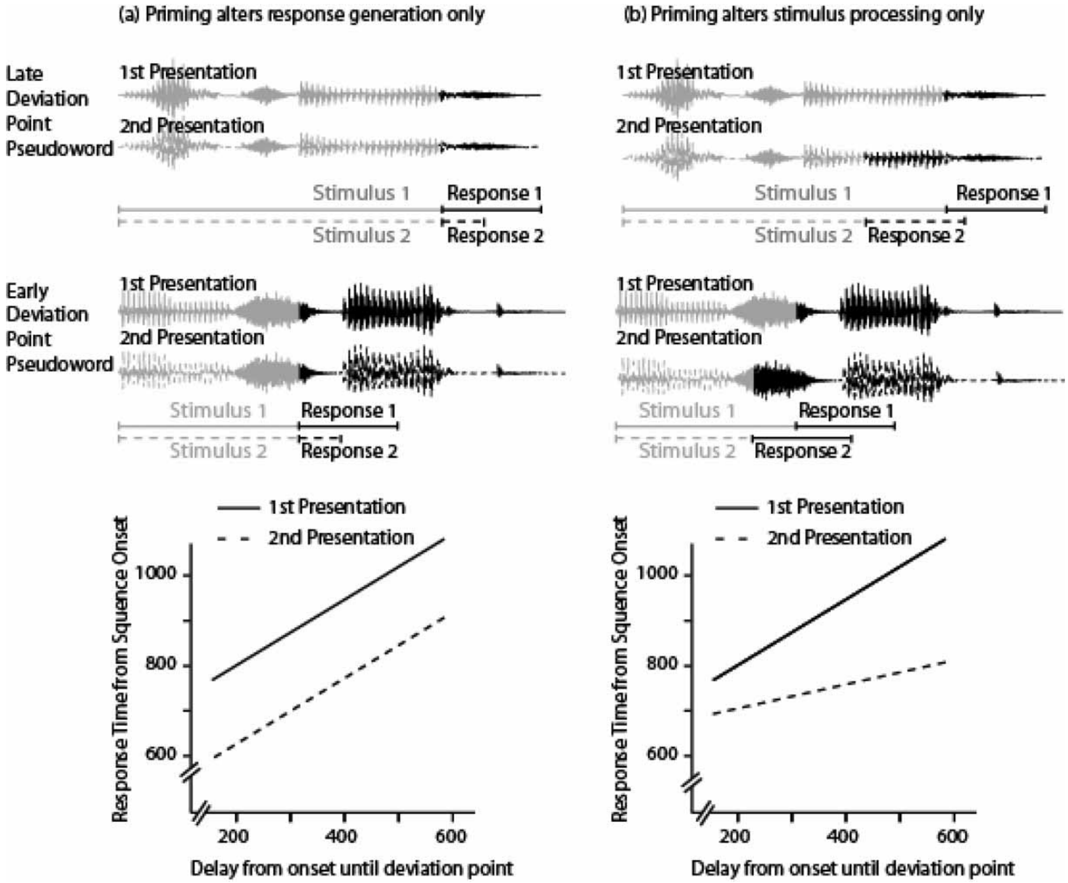

Figure 3. *Illustration of how deviation point correlations can be used to separate stimulus and response components of pseudoword priming. The portion of the speech waveform prior to the point at which the pseudoword deviates from familiar spoken words is shown in grey; the postdeviation point is shown in black. Pseudoword responses are initiated once sufficient postdeviation information has been processed. If priming reflects only response-based mechanisms (Panel a), deviation points are unaltered for second presentations, and equivalent response priming would be predicted for both early- and late-deviating pseudowords. This is shown in the time-line of stimulus and response components and by a change in the intercept (but not the slope) of the line relating deviation points and response times for first and second presentations. Panel b depicts equivalent predictions if repetition priming derives from enhanced stimulus processing. In this case, there is a reduction in the deviation point for second presentations of pseudowords that is proportional to the amount of perceptual processing required (i.e., the initial deviation point). Since there is a greater change in the deviation point for second presentations of late-deviating pseudowords, we would predict increased behavioural repetition priming for these items. Thus, the change in the slope relating deviation point and response time for second presentations (Panel b) provides a diagnostic for inferring that repetition priming arises from enhanced stimulus processing. Of course, priming may reflect the operation of both stimulus and response-based mechanisms, in which case we would predict changes to both the slope and the intercept.*

these criticisms, in the present research we use pseudowords that are all phonotactically legal sequences. Furthermore, interpretation of an analysis that examines the relationship between response times and deviation points for first and second presentations separately does not depend on deviation point being the only predictor, or an entirely accurate predictor of pseudoword response times. Indeed, improved efficiency of perceptual processing on second presentation could only come about if perceptual processing to some extent continues after the physical deviation point.

For this analysis, a trained phonetician marked the deviation point for each pseudoword in the male and the female voice. The average duration of the recordings (collapsed for male and female voice) was 594 ms ($SD = 120$ ms). The average of the deviation point for all recordings was 395 ms ($SD = 117$ ms). To ensure consistency with previous factorial analyses that used inversed transformed response times, deviation points (in ms) were inverse transformed as well. In this way, the same positive correlation between deviation points and response times would be predicted as for untransformed data, though the precise slope estimates would differ. To ensure that reported slope estimates are interpretable, we therefore report and graph slope estimates from analyses conducted on untransformed response times and deviation point values.

To determine whether the delay until the deviation point is a predictor of reaction times for pseudowords in lexical decision, we followed the "individual regression equations" procedure described in Lorch and Myers (1990). We calculated for each participant on an item-by-item basis the slope and intercept of the best fitting linear regression line relating the delay until the deviation point to response times for first and second presentations of pseudowords. Each of the resulting values (regression coefficients) thus represents for a particular participant the relation between lexical decision response times and deviation points.

We preferred this method instead of computing the mean response time for each item averaged over all participants and then assessing the relationship between deviation point and these item mean response times because this method ignores a critical source of variance, since it eliminates any between-subject variance (i.e., the reverse of the "language as fixed effects fallacy" documented by Clark, 1973). Lorch and Myers (1990) argue convincingly that this conventional regression analysis is inappropriate for repeated measures because it is prone to Type I error and inflates the estimate of the variance accounted for by the predictor variable. In this work we follow the recommendations of Lorch and Myers (1990) and conduct a regression analysis on the response times for each participant and obtain an estimate of the parameter predicting these response times on the basis of deviation point for each participant. These parameters are then entered into a repeated measures ANOVA to compare the slope for first and second presentation. The mean and standard error of these parameters are depicted in Figure 4.

A t test confirmed that the slope values were significantly greater than zero: slope of first presentation, $t_1(23) = 9.7$, $p < .001$; slope of second presentation, $t_1(23) = 3.7$, $p < .001$. The steepness of the slope relating the delay until the deviation point to reaction times was altered by repetition as shown by the significant difference between the slope of the first presentation (0.4) and the slope of the second presentation (0.2), $t_1(23) = 2.8$, $p < .009$ (Figure 4). In addition, the delay between deviation point and response time was significantly reduced for second presentations, as demonstrated by the significant difference between the intercept of first presentation (retransformed harmonic means, 1,077 ms) and the intercept of second presentation (968 ms), $t_1(23) = -2.9$, $p < .009$. These harmonic means represent the latency of responses to an item with the average deviation point of 395 ms for

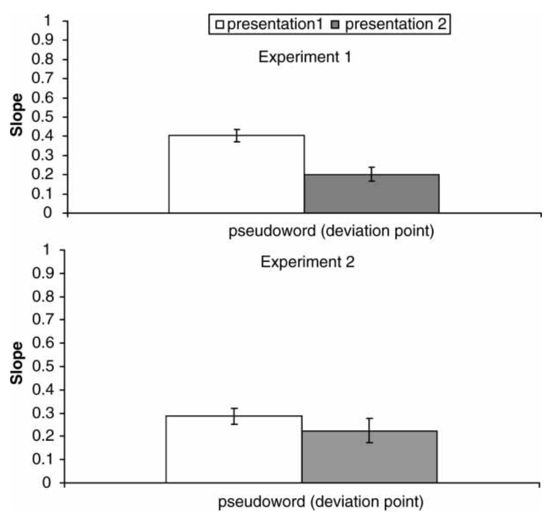

Figure 4. *Mean slope values for pseudowords for first and second presentations in Experiment 1 and Experiment 2. Error bars represent one standard error.*

which there is a priming effect of 109 ms. For an item with a deviation point two standard deviations earlier/later than the mean, we would therefore predict a priming effect of 104 ms and 114 ms, respectively. This effect of deviation point on the magnitude of repetition priming reflects enhanced perceptual processing of the pseudowords on second presentations. Not all of the repetition priming effect can be shown to arise from decision processes that are initiated after the deviation point is reached (as depicted in Figure 3b).

The same analysis was performed on the data from Experiment 2 to investigate whether the same relationship between deviation point and reaction times applies in a situation in which perceptual processing is made more difficult by degrading the speech input with background noise. As the addition of noise to the speech files used in Experiment 1 does not change the duration of the speech signal, we used the same measurements of deviation points for the pseudowords as those used in Experiment 1. However, we anticipate that reducing the quality of the speech input would further slow RTs and provide less opportunity for enhanced perceptual processes to produce repetition priming. Following the same procedure as that in Experiment 1, we calculated for each participant on a item-by-item basis the slope and intercept of the line relating the delay until the deviation point to the reaction time for first and second presentations separately. In line with results from Experiment 1, a *t* test confirmed that the slope values were greater than zero: slope of first presentation, $t(24) = 7.2$, $p < .001$; slope of second presentation, $t(23) = 6.8$, $p < .001$. In contrast to Experiment 1, the steepness of the slope relating the delay until the deviation point to reaction times was not altered by repetition, as shown by the lack of a significant difference between slope of first presentation and slope of second presentation, $t(23) = -0.231$, $p > .05$ (see Figure 4). In contrast, the delay between deviation point and response time was significantly reduced for second presentations, which is demonstrated by the significant difference between intercept of first presentation (1,218 ms) and intercept of second presentation (1,163 ms), $t(23) = -2.7$, $p < .012$, consistent with Experiment 1 and the priming effect observed in the factorial analysis.

Comparison between experiments

Given the difference between Experiment 1 and Experiment 2 in the effects of repetition on the slope and intercept relating pseudoword response times to deviation points, we conducted a comparison between the two experiments for the pseudoword data. In these analyses we compared separately the slope and intercept values for first and second presentations in each experiment—that is, presentation (2 levels, slope of first presentation/slope of second presentation and intercept of first presentation/intercept of second presentation) was the within-participants factor, and experiment (Experiment 1 clear speech, Experiment 2 noise) was the between-participants factor. The ANOVA on the slope values showed no main effect of experiment, $F_1(1, 41) = 1.4$, $p = .237$, indicating no overall differences between the slope values relating reaction times and deviation points in the two experiments. However, there was a main effect of presentation, $F_1(1, 41) = 12.6$, $p < .001$, which was qualified by a significant interaction between presentation and experiment, $F_1(1, 41) = 14$, $p < .001$. This interaction reflects the fact that slope values were reduced for second presentations of pseudowords in Experiment 1 but not in Experiment 2.

The comparison of the intercept values showed a significant main effect of experiment, $F_1(1, 41) = 16.7$, $p < .001$, reflecting the slower responses obtained in Experiment 2 than Experiment 1 and a main effect of presentation, $F_1(1, 41) = 64.2$, $p < .001$, with intercept values being reduced for second presentations. In addition, there was a presentation by experiment interaction, $F_1(1, 41) = 12.7$, $p < .001$, with the effect of presentation on the intercept values being bigger in Experiment 1 than in Experiment 2.

Discussion

The results of the above analyses indicate that the second presentation of pseudowords in Experiment

1 speeded up the processing of the pseudoword until the deviation point, and thus pseudoword priming in this experimental setting can be explained by enhanced perceptual processing of a recently encountered pseudoword. For the perceptually degraded pseudowords in Experiment 2, second presentations speeded up the decision process after the deviation point was reached but did not result in enhanced perceptual processing. Thus, priming in this experimental setting can be interpreted in terms of enhanced decision processes or stimulus–response associations rather than as a result of improved processing until the deviation point is reached.

GENERAL DISCUSSION

Primed identification of spoken words has featured prominently in psycholinguistic research to probe the extent to which spoken word recognition and repetition priming draw upon long-term/abstract or episodic/perceptually specific lexical representations. An underlying assumption in this research is that the priming effects occur at the stage of perceptual processing during lexical access. However, the validity of this assumption has been challenged by behavioural (e.g., Logan, 1990; Valentine et al., 1993; Zeelenberg et al., 2004) and recent neuroimaging findings (Dobbins et al., 2004; Orfanidou et al., 2006), which have emphasized the idea of repetition-induced facilitation of decision/response processes.

In the present research the abstractness/specificity of the representations mediating spoken word recognition and priming was examined in two auditory priming experiments using the lexical decision task. For both words and pseudowords we compared priming effects using the same or different voice repetitions using clear speech (Experiment 1) and speech distorted with background noise (Experiment 2). In both experiments we found that both word and pseudoword priming were observed irrespective of voice changes and that voice changes failed to modulate the magnitude of priming. In both experiments, we observed greater priming effects for words than for pseudowords, though this lexicality effect was reduced for slower participants, particularly in Experiment 2. We interpret this finding as suggesting that pseudoword priming is primarily mediated by episodic stimulus–response associations, especially in the slow processing conditions of Experiment 2. In Experiment 1, however, a regression analysis relating reaction times to the deviation point for pseudowords showed that repetition speeded up both perceptual processing until the deviation point and decision processing after the deviation point was reached. This was not the case for pseudowords in distorted speech. We return to this point later.

Voice effects on priming

Regarding the absence of voice effects an overview of the literature on the effects of specificity shows that specificity effects in auditory priming are difficult to obtain. A series of experiments by Gonzalez and McLennan (2007) demonstrate the degree to which specificity effects are sensitive to the exact experimental conditions, such as the type of task performed at test and study phases. In their study, specificity effects were obtained in lexical decision only when stimuli were presented to the left ear, and they were weaker when participants performed a different task in the study and test phase than when lexical decision was performed in both phases. In the present experiments items were presented to both ears and hence both hemispheres. If the voice-specific right hemisphere has a significant influence on recognition processes under normal, binaural listening conditions then these voice-specific effects should have been observed in the present studies.

Although in the two experiments reported here we included manipulations that could maximize the possibility of obtaining specificity effects (low-frequency words, word-like pseudowords, McLennan & Luce, 2005; distorted speech, e.g., Sheffert, 1998), voice changes between repetitions produced only a small, nonsignificant reduction of the priming and then only in error rates. In addition, the effects of the voice change were not entirely clear and consistent, as in Experiment 2 we found more priming in the error rates for words repeated in a different than in the error rates for words repeated in a same voice. Due to the sensitivity of the voice effects to experimental manipulations the literature is characterized by discrepancies. For example, Schacter and Church (1992) reported voice effects in an auditory stem completion task (Experiment 3) but Gonzalez and McLennan (2007) did not replicate this result using the same task. Furthermore, McLennan and Luce (2005, Experiment 1) did find voice effects with lexical decision, unlike Luce and Lyons (1998) and the present studies. Another manipulation, the number of talkers, has not always produced consistent results as other studies have found large voice effects using only two different voices as in the present research (e.g., Gonzalez & McLennan, 2007; McLennan & Luce, 2005, Experiment 2B) while nonsignificant effects of voice change on priming have been reported with presentation of multiple talker-specific tokens (Schacter & Church, 1992, Experiment 5).

The data showed comparable amounts of priming for same and different voice repetitions, pointing towards abstract, voice-independent representations and favouring abstractionist accounts of the priming effects. However, in agreement with episodic accounts, priming effects extended to pseudowords as well, although these were significantly reduced compared to word priming. Pseudoword priming is not predicted on abstractionist theories, but the small effect of voice change on pseudoword priming only in the error rates in Experiment 1 cannot easily be explained within an episodic account, where priming is based on the perceptual overlap between prime and target.

Thus, the repetition effect for pseudowords that lack a preexisting memory representation, coupled with the voice change results, points towards a compromise position in which both the modification of preexisting representations and newly acquired representations can contribute to the priming effects. Real word priming can benefit from both components (Henson, 2003), whereas for pseudowords, recent behavioural evidence has suggested that these two mechanisms can produce conflicting effects on lexical decision responses (episodic facilitation and familiarity-based inhibition, Wagenmakers et al., 2004b; Zeelenberg et al., 2004). The traditional abstractionist/episodic approach to priming in spoken word recognition seems increasingly inadequate to describe the complexity of these processes. In contrast, hybrid models containing abstract representations and episodic traces are better suited to accommodate these diverse findings (e.g., Goldinger, 2007).

Perceptual and decision components of priming

One novel contribution of the present studies was to use information on the time-course of pseudoword processing as a diagnostic for exploring the influence of stimulus and response-based priming on word recognition. In the context of a lexical decision, the task of rejecting a pseudoword can only be achieved once sufficient evidence has accumulated in the speech signal to rule out existing, familiar words in the language. Our results show that for repeated presentations of pseudowords, repetition priming is of a greater magnitude for pseudowords that have a late divergence point. This finding is consistent with perceptual processing of the input being enhanced by repeated presentation; items with later deviation points can benefit more from enhanced perceptual processing.

Thus, these behavioural results suggest that repetition priming effects on pseudoword processing do (to some extent) reflect enhanced perceptual processing, at least for items presented as clear speech. We note with interest that presentation of distorted speech does not lead to the same enhancement of perceptual processing due to repetition—despite the obvious challenge to perception that is created by this acoustic degradation. In these situations, although we observe robust repetition priming for pseudowords this effect appears to be entirely determined by enhanced response generation processes (cf. Dobbins et al., 2004; Orfanidou et al., 2006) that are equivalent for early- and late-deviating pseudowords. Evidence for a greater involvement of response learning in Experiment 2 is also suggested by the analysis of fast and slow participants. This comparison shows that under slow processing conditions (especially in Experiment 2) episodic-based retrieval of stimulus–response associations dominates processing leading to equivalent priming for words and pseudowords. This may also explain why fMRI studies of auditory priming, where the noisy environment of the scanner does not provide optimal perceptual processing conditions, found that behavioural priming correlated with neural priming in areas associated with decision processes/response generation (Maccotta & Buckner, 2004; Orfanidou et al., 2006) rather than areas involved in lexical processing.

In any case, enhanced decision processes/response generation can constitute only one component of the priming effects, since an account purely in terms of response learning would predict the same amounts of priming for words and pseudowords. The observation of significantly more behavioural priming for words than for pseudowords indicates that the processing during the second presentation is facilitated in the presence of a preexistent representation. This preexistent representation does not encode specific perceptual attributes of the spoken word as demonstrated by the lack of an effect of voice change on the word priming. Pseudoword priming could be mediated by episodic traces of stimulus–response associations, which are abstract enough to tolerate changes in the surface phonological form of the pseudowords. Thus, the absence of consistent voice effects on the behavioural priming, even when the task is made harder by introducing white noise, and thus there is ample time for slow-acting episodic codes to come into play (see time-course hypothesis, McLennan & Luce, 2005), suggests that even if priming during spoken word recognition is partially based on associations between stimuli and responses, these associations are abstract enough to be voice independent.

It seems that although the effects observed with repetition priming and lexical decision reflect to some extent decision processes and stimulus–response associations, they still remain a useful tool in examining the nature of lexical stored representation. By comparing priming between word/pseudoword pairs in different tasks, where a discrete decision stage and the confounds it brings into the performance are removed (e.g., identification tasks, word completion), one could gather more convincing evidence about the involvement of lexical representations or decision processes in primed lexical decision. In this research we took a first step in considering the nature of the component processes involved in performing the lexical decision task and how these are affected by repetition. We believe that this possibility needs to be examined by future research that will consider the specific component processes that benefit from repetition in each task.

Original manuscript received 29 April 2009
Accepted revision received 12 February 2010
First published online 27 May 2010

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APPENDIX

Stimuli

Table A1. *Words*

Group A	*Group B*	*Group C*	*Group D*	*Group E*	*Group F*	*Group G*	*Group H*
knee	zoo	earl	oak	fee	toy	ash	guy
badge	dame	booth	bush	ant	beak	beef	barn
beard	doll	chin	cave	dirt	gem	bone	calf
elm	fog	cone	elf	gown	hoof	harp	card
herb	goat	goal	gin	haze	porch	keg	gang
latch	king	hen	lad	lane	rung	moss	lung
meal	kite	noose	shawl	rib	tomb	shark	noun
moth	lard	pope	thief	van	verse	thorn	pouch
rat	rug	pup	vine	vase	weed	wig	verb
rogue	wick	wheat	whiff	wharf	wing	wool	web
cult	blade	cliff	frill	bench	chrome	mule	brass
glove	blouse	pint	rust	broom	corpse	prop	mast
spade	crumb	ranch	tweed	plum	frog	sleeve	pest
speck	filth	scab	shrub	truce	span	spool	snail
wolf	tune	troop	silk	wand	vest	stub	spark
chapel	axle	bubble	atom	autumn	fable	diet	basin
heaven	camel	cable	buckle	bible	hero	maple	bison
kitten	lesson	cotton	chisel	channel	hurdle	polo	fellow
nozzle	noodle	nickel	daisy	mutton	movie	title	honey
shovel	organ	poet	devil	orchid	muzzle	tunnel	petal
towel	whistle	python	hockey	poison	vessel	willow	turtle
bristle	apron	carpet	cabin	bishop	bourbon	garlic	balloon
panic	barrel	harpoon	canal	furnace	column	hermit	cedar
ribbon	satchel	herring	lemon	pencil	gravel	palace	flora
sardine	havoc	linen	soccer	pudding	nephew	saloon	gallon
wallet	pimple	margin	spire	tortoise	rabbit	tennis	monkey
basket	mountain	dungeon	mattress	canteen	cuisine	biscuit	crystal
spirit	piston	mackerel	reptile	fountain	helmet	blossom	harvest
tunic	planet	stomach	victim	lantern	insect	sultan	human
siren	squirrel	velvet	sapphire	magnet	walrus	volume	tulip

Table A2. *Pseudowords*

Group A	*Group B*	*Group C*	*Group D*	*Group E*	*Group F*	*Group G*	*Group H*
gow	sodge	caust	pung	drow	carse	thod	geal
kiar	ludge	nopple	crett	hamp	vorks	slub	sleach
kighness	sperrea	geck	crishine	umple	matten	rilla	ballan
triscal	shirr	kise	nortle	fascinch	provail	relmick	spinza
looth	zarse	smeal	stashy	bipe	crow	fip	vert
frup	plish	zomith	iln	kerrow	croot	cupe	pisk
cardom	relat	sar	gattle	silloom	tencil	casten	wreckle
stuneck	jilten	cogue	pessm	puzz	feam	turb	scaider
phato	gra	purps	yease	roin	taid	freeb	mewk
provel	stall	rockle	tibe	briff	gossy	joydle	berrye
kime	berrit	dack	cloom	monet	vitar	wartine	rossup
vorce	purg	swuad	ingle	scuzzm	blackarp	neckrel	nar
biot	mooth	nummal	prosig	jung	rin	poth	seash
brayple	paiddle	correr	bline	wiom	grutch	blike	boist
poy	thermen	pud	mokey	munken	blample	radick	solease
tooge	dige	pite	racquor	ind	sarve	koth	cumic
decket	peash	kiffen	nug	spig	breck	freeve	margy
ush	pog	rappig	scole	madea	seedle	arrtit	bagma
dobe	werve	rart	susstle	yetteaze	caston	craless	despip
harby	teego	gicial	cotim	broy	fown	rup	rotch
calip	oxaim	circue	dade	stipe	drib	stabe	brooth
cousket	glanic	oap	jerrow	gillar	shattel	sightle	mennea
cong	harsh	tove	sarak	sorb	rorn	insipped	mactar
rost	gloth	flip	garl	lomb	plass	troke	torn
twiant	ellish	morate	tarve	royer	coer	passon	pottle
rarn	ribe	hybrack	doopy	houlor	pallif	magnark	testam
karden	prief	spope	blarmer	ter	fud	sorn	lem
humim	kollow	antle	pantern	sharf	corch	tarf	kank
pla	onswark	raptole	shorm	panch	tiddle	nifle	adome
treak	fackle	rudd	jettuce	feinten	wobing	parair	cullic