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Cross-Modal Priming Evidence for Phonology-to-Orthography Activation in Visual Word Recognition

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Subjects were asked to indicate which item of a word/nonword pair was a word. On critical trials the nonword was a pseudohomophone of the word. RTs of dyslexics were shorter in blocks of trials in which a congruent auditory prime was simultaneously presented with the visual stimuli. RTs of normal readers were longer for high frequency words when there was auditory priming. This provides evidence that phonology can activate orthographic representations; the size and direction of the effect of auditory priming on visual lexical decision appear to be a function of the relative speeds with which sight and hearing activate orthography. © 1999 Academic Press

INTRODUCTION

Models of visual word recognition assume three domains of representation: orthography, phonology, and semantics. The type of representation (lexical/sublexical, symbolic/subsymbolic) within each domain and the importance and direction of activation between these domains are major distinguishing features of the different models. Several models (Coltheart, Curtis, Atkins, & Haller, 1991; Seidenberg & McClelland, 1989; Lukatela & Turvey, 1994a, 1994b; Plaut, McClelland, Seidenberg, & Patterson, 1996; Van Orden, Pennington, & Stone, 1990; see also Jacobs & Grainger, 1994, for an overview of 15 models), hypothesize that not only do orthographic representations activate phonological representations for word pronunciation, but also that phonological representations directly activate and/or constrain orthographic representations through feedback. The reasons, either empirical or theoretical, for the inclusion of phonological feedback in the models are

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rarely stated. Most investigations into the role of phonology in reading have been directed at its involvement in accessing the meaning of written words (Jared & Seidenberg, 1991; Lukatela & Turvey 1994a, 1994b; Van Orden, 1987) with the effect of phonology on orthographic processing itself remaining unclear. An exception to this is the recent work of Stone, Vanhoy, and Van Orden (1997) who found that words which had pronunciation bodies with more than one possible spelling (e.g., heap, deep) were identified as words more slowly than were those with only one possible spelling (e.g., probe, globe).

Other researchers have purposefully not included direct retrograde activation of orthography by phonology in their theoretical models. Ellis and Young's model (1988), which is based on selective impairments in brain lesioned subjects, only admits to phonological activation of the orthographic lexicon via the semantic system. Similarly, Monsell (1985), after having carried out experiments in cross-modal priming, concluded that the phonology of a word does not activate its orthography.

In Monsell's (1985) experiments subjects first performed a sentence completion task in which they either saw, heard, pronounced, or blindly wrote target words. They then performed a lexical decision task which included the target words. Monsell found that there was facilitation only for the target words which had previously been seen. These findings differ from those of Kirsner and Smith (1974) and more recently McKone and Dennis (1997) who have found that auditory primes can facilitate visual lexical decision. While the difference in findings may be explained in terms of the difference in the prime-stimulus SOA, evidence of auditory priming in visual lexical decision is not necessarily evidence that phonology can activate orthography. If the nonwords in the task have a nonword phonology (e.g., heek), then it is possible for subjects to base their response on the phonology or perhaps the meaningfulness of the stimuli. Facilitation from an auditory prime in that case could result from the activation of either the phonology or the meaning of the word without activating orthography.

It would appear then that the role of phonology in orthographic activation is still an open question that can be asked at various levels of intensity: does it happen at all? If so, is it an obligatory process in visual word recognition, and if it is, does it confirm, constrain or disperse orthographic activation? In the experiments reported here we take a second look at auditory priming and ask: can a simultaneous auditory input influence a lexical decision which must be made on the basis of orthography alone? In order to encourage an ''orthographic only'' decision, the task was in the form of a forced choice between a word and a nonword homophonic to it (e.g., height/hite). The presence of pseudohomophones in the task renders the use of orthography-to-phonology transcoding disadvantageous to the subject as processing the nonwords in this manner results in lexical phonology. In order to assess the contribution that congruent phonology might confer on visual lexical decision, the task was performed under two conditions: with and without auditory input. In the ‘‘with audio’’ condition, the subject heard a digitized recording of the word whose onset was almost simultaneous (visual-to-auditory SOA = 16 ms) with the visual word/nonword pair. In the ‘‘no audio’’ condition the subject performed the task without exposure to an auditory input.

An interesting type of reader to examine in a task of visual lexical decision is the surface dyslexic. Surface dyslexia (SD) in its purest form is characterized by a frequency related deficit in reading exception words (Marshall & Newcombe, 1973; Saffran & Marin, 1980; Shallice & Warrington, 1975). Exception words, especially of low frequency, are typically read by these readers in a ‘‘regular’’ fashion (i.e., ‘‘BEAR’’ read as ‘‘beer’’). The existence of such a type of reader greatly contributes to the argument for dual processes for reading: one that deals with whole lexical representations and another that uses rules to associate sublexical graphemic units to phonemes (Coltheart et al., 1991). It would be this latter process which is responsible for the ‘‘regularization’’ of exception words by surface dyslexics due to damage to the lexical route. Plaut et al. (1996), however, point out that reported cases of SD frequently have major semantic impairments. They show that within a single orthography to phonology route, the strengthening by semantics of exceptional grapheme-phoneme correspondences during learning and the subsequent withdrawal of this semantic support can also explain their error pattern.

The pure form of SD described above is relatively rare. In general, subjects classified as surface dyslexics do not have such a specific error pattern: while being particularly impaired in reading exception words, they not only make regularization errors but also make mistakes on regular words and on nonwords, and do not have any obvious semantic impairment. In the first experiment we report here three surface dyslexics of this less ‘‘pure’’ type served as subjects. The hope was that their frequency dependent error pattern as well as their slow reaction times would reveal effects of auditory input that are not readily apparent in the normal, efficient reader. In the second experiment, which is a slightly modified version of the first, normal readers served as subjects.

CASE REPORTS AND EVALUATIONS OF READING DEFICITS

IH. The subject, IH, a right-handed English-speaking male, is a former life insurance representative with a college degree who suffered a subarachnoid hemorrhage in 1983 causing a left temporo-occipital hematoma. He presented with a right-homonymous hemianopia, anomia, and reading and spelling difficulties. IH has been previously described in Bowers, Arguin, and Bub (1996). The tests and experiments reported here were conducted between June and December 1995 when he was 56 years old.

IH’s reading deficits conform to the pattern of letter-by-letter surface dyslexia (Friedman & Hadley, 1992). His latency in reading single words ranges from 290 ms to 9900 ms and he displays a pronounced word length effect such that reaction time increases by approximately 500 ms for each additional letter. For words with frequencies of more than 50 per million his error rate in naming is 60% for exception words and 16% for regular words. Errors on exception words are regularizations 57% of the time (e.g., none read <known>). He also makes ‘‘visual’’ type errors on both words and nonwords (food read <foot>, stew read <slew>).

IH’s spelling was evaluated by asking him to orally spell four-letter words for which a semantic context was provided. He made 135 errors on 237 words (57%). His responses were almost exclusively phonetically correct. Some typical examples are: dare > *dair,* curl > *kerl,* and herd > *hurd.*

JF. The subject JF is a right-handed French-speaking female with six years of education. She was living autonomously at the time of the testing reported here at which time she was 73 years of age and had a one- to two-year history of speech problems. A neurological examination by Dr. H. Chertkow (Jewish General Hospital, Montreal) suggested a diagnostic of primary progressive aphasia. Dr. Chertkow noted one year later that her condition appeared to be stable. Her speech disorder consists predominately of speech apraxia and speech hesitancy. She has trouble planning any verbal output, is unable to repeat words, and has a marked word finding difficulty. Attempts at spontaneous communication typically break down after the first two or three words of a sentence. Comprehension, however, appears normal and she has no difficulty with visual spatial function or visual memory and no obvious frontal lobe dysfunction. A brain SPECT showed marked impairment in cerebral blood flow to the left perisylvian area. A CT scan showed no evidence of an acute lesion in this area.

An evaluation of JF’s single word reading displayed a profile of surface dyslexia. On words with a frequency of 25 or more per million, she made no error on regular words but had an error rate of 23% for exception words. For words of very low frequency (1–10 per million) her error rate increased to 13% for regular words and to 43% for exception words. Her errors consisted mostly of regularizations (e.g., GARS read <gare>) although she also made ‘‘visual’’ type errors on both regular and exception words, and nonwords (SUIF read <suisse>; PAVOLE read <pervole>). In a task of visual lexical decision she rejected 28% of low frequency words and accepted 26% of nonwords. Her reading comprehension for text was normal and one year after testing she still enjoyed reading novels.

JF was able to correctly write to dictation only eight out of twenty common words. Her writing difficulties mirrored her speech disorder: she either was unable to begin to write the word, or began with the correct letter and stopped after she had made a mistake on the second or third letter.

EL. The subject, EL, is a right-handed bilingual (English/French) 22-year-old female who received all her formal education in English. She has a global IQ of 113 as measured by WAIS (VIQ:106; PIQ:120). EL had marked difficulties learning to read and write as a child with no other language or attentional problems. In particular she would invert the order of letters. Although she reads regularly in both English and French she finds it laborious and must frequently use context to disambiguate words that she realizes she has misread. She has no history of neurological risk factors.

EL's reading deficits are similar to those of developmental surface dyslexia (Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Temple, 1984a, 1984b). Her error rate in single word reading is 30% for exception words and 10% for regular words. Errors on exception words are regularizations 67% of the time (e.g., BREAK read <breek>). She also makes ''visual'' type errors on both words and nonwords (e.g., MOST read <mast>, FACT read <fake> and GINK read <gint>). Her latency in reading single words ranges from 597 ms to 781 ms and she displays a word length effect such that her response latencies increase by approximately 42 ms with each one letter increase in word length.

EL was errorless in writing to dictation very high frequency (>175 per million) regular words and had an 11% error rate for exception words from the same frequency range. She had error rates of 25% and 27% writing, respectively, regular and exception words of low frequency (1–75 per million). Typical examples of her errors are: full > *ful,* stir > *stur,* rode > *wrode* and wore > *woar.*

EXPERIMENT 1

In the first experiment a forced-choice visual lexical decision task was used to investigate the effect of a congruent auditory input on visual word recognition. IH, JF, and EL served as subjects. On each trial the subject was asked to identify which of two visual stimuli was a word. On critical trials the nonword was homophonic to the word (e.g., height/hite). The task was done under two conditions: without auditory input (''no audio'') and with auditory input (''with audio''). On ''with audio'' trials the subject heard a digitized recording of the visual word (e.g., the subject heard the word <HEIGHT> when choosing between height and hite).

Method

English Stimuli (for IH and EL)

The stimulus set consisted of 300 word/nonword pairs, of which 100 pairs were of a regular word and a nonword homophonic to it (e.g., same/saim), 100 were of an irregular word and a nonword homophonic to it (e.g., height/hite), and 100 orthographic-control pairs consisting of a regular word and a nonword derived from it but not homophonic to it (e.g., seek/heek). The control pairs were included to provide an indication of whether the subject's difficulties arose primarily from visual or othographic aspects of the stimuli.

Twenty words of each type of pair were selected from each of five word frequency ranges: 1–20, 21–50, 51–100, 101–200, and more than 200 per million (Francis & Kucera, 1982). Each frequency subgroup was made of an approximately equal number of four-, five-, and six-letter words.

The word/nonword pairs were randomly distributed into six blocks of 50 trials. Each block was presented once with accompanying auditory input (‘‘with audio’’ condition) and once without an auditory input (‘‘no audio’’ condition). Blocks with vs without auditory input alternated and the order of presentation of the blocks was such that half of the stimuli were first seen with the auditory input and half were first seen without auditory input. The subjects did not encounter the same orthographic stimuli twice in the same weekly session.

French Stimuli (for JF)

The stimulus set consisted of 132 word/nonword pairs of which 43 pairs were of a regular word and a nonword homophonic to it (e.g., servir/cervire), 44 were of an irregular word and a nonword homophonic to it (e.g., écho/équo), and 45 orthographic-control pairs consisting of a regular word and a nonword derived from it but not homophonic to it (e.g., noir/toir). Within each group of pair-types there was an approximately equal number of words which were from each of four frequency ranges: 1–20, 21–50, 51–150, and greater than 150 occurrences per million (Content, Mousty, & Radeau, 1990). Mean word length within each frequency range was equivalent (mean: 4.8, range: 3–7 letters). Word length was not formally included as a factor because previous tests had shown it did not abnormally affect JF’s reading performance and because it was not possible to find enough words with irregular grapheme-phoneme correspondences for each word length and frequency range.

The stimulus set was randomly distributed into two blocks of 66 word/nonword pairs and the order of presentation of blocks in ‘‘with audio’’ and ‘‘no audio’’ conditions was counterbalanced.

Procedure

The visual stimuli appeared in lowercase Geneva 24-point print on a Macintosh computer monitor. The subjects positioned themselves so that they could view and respond to the stimuli comfortably.

On each trial a fixation point appeared in the middle of the screen for 1020 ms followed 595 ms later by a word/nonword pair with one item displayed 2 cm above the fixation location and the other 2 cm below. The position of the word was randomly assigned. In blocks of trials with auditory input (‘‘with audio’’ condition) a digitized recording of the word was generated by the computer 16 ms after the visual stimuli appeared. The visual stimuli remained on screen until the subject responded. The experimenter initiated the next trial when the subject was ready. Subjects were asked to indicate which of the two stimuli was the word. IH and EL responded by pressing the multiplication key and the enter key on the numerical pad of the computer keyboard to indicate the ‘‘upper’’ and ‘‘lower’’ items respectively. JF did not wish to use the keyboard so she indicated her response by touching the visual stimulus directly on the screen and the experimenter pressed the appropriate key when she touched the screen. The program Psychlab (Bub & Gum, 1995) controlled stimuli exposure and recorded the subjects’ responses and response latencies.

RESULTS AND ANALYSIS

Subject IH

Error rates for subject IH are given in Table 1. IH made significantly less errors on the control trials (seek/heek; error rate: 5%) than on critical trials (goes/goze; error rate: 19%) [$\chi^2 = 19.64$, $p < 0.001$]. On critical trials (word/pseudohomophone pairs) he made significantly more errors with irregular words than with regular words [$\chi^2 = 6.23$, $p < 0.05$]. Presentation

TABLE 1
Error Rates for IH on Visual Lexical Decision, with and without Auditory Input

Stimuli	Without audio (%)	With audio (%)	Significance
All	15	13	n.s.
Control	9	1	$\chi^2 = 6.7, p < .01$
Critical			
All	18	19	n.s.
Regular	17	11	n.s.
Irregular	19	26	n.s.

Note. With audio, regular (11%) vs irregular (26%): $\chi^2 = 7.46, p < .01$. Control (5%) vs critical (19%): $\chi^2 = 19.64, p < 0.001$.

of the auditory input had no significant effect on error rates globally [$\chi^2 = .74$, n.s.] but it did reduce his error rates on control trials [$\chi^2 = 6.7, p < 0.01$].

An analysis of the subject's RT distributions showed that no response latency was more than three standard deviations above or below the mean per condition. A two-way ANOVA with auditory condition (with/without audio) and trial type (control/critical) as factors was carried out on IH's correct RTs. Only the regular words of the critical trials were included in this analysis to provide a more appropriate comparison with the control trials which consisted only of regular word targets. The analysis revealed a main effect of auditory condition [$F(1, 356) = 38.4, p < .0001$]. There was no effect of trial type [$F(1, 356) < 1$] and no interaction between auditory condition and trial type [$F(1, 356) < 1$]. IH's response latency on correct trials with audio was 3748 ms and 6329 ms without audio, a facilitation of 2581 ms.

Because IH's error rate on control trials was lower than on critical trials, we assumed that IH's difficulties were not primarily visual and analyzed critical trials separately. On critical trials, because of the presence of a pseudohomophone as distractor, a response could not be made on the basis of phonology alone but required specific whole-word orthographic knowledge.

IH's correct RTs on critical trials with and without an auditory input as a function of frequency are plotted in Fig. 1. Analysis of lexical decision times with factors of auditory condition (with/without audio), word length (4, 5, or 6 letters), stimulus type (regular/irregular word) and frequency revealed main effects of auditory condition [$F(1, 269) = 35.6, p < .0001$] and word length [$F(2, 269) = 7.7, p < .001$] as well as a significant auditory condition × word length interaction [$F(2, 269) = 7.0, p < .01$]. No other factor or interaction had a significant effect on the subject's performance. IH's mean RT without auditory input was 6871 ms, and with auditory input was 4115 ms, a facilitation of 2756 ms.

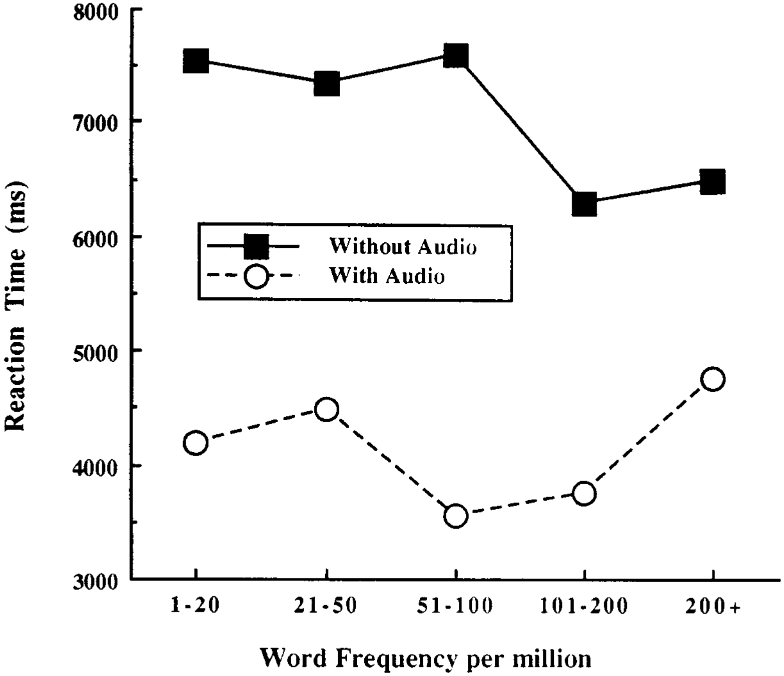

FIG. 1. IH's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

Figure 2 plots the auditory condition × word length interaction. Simple effect analysis showed that whereas there was a significant effect of word length in the ''no audio'' condition [$F(2, 269) = 14.3$, $p < .001$], there was none with an auditory input [$F(2, 269) < 1$].

Subject JF

Error rates for subject JF are shown in Table 2. JF had an overall error rate of 12%. This rate did not vary with trial type (critical vs. control) [$\chi^2 = .03$, n.s.] and was not influenced by auditory condition (with or without auditory input) [$\chi^2 = .33$, n.s.].

A distribution analysis showed that no RT was more than three standard deviations above or below the mean per condition. A two-way ANOVA with auditory condition (with/without audio) and trial type (control/critical) as factors was carried out on JF's correct RTs. As for IH, only the regular words of the critical trials were included in this analysis. The analysis revealed a main effect of auditory condition [$F(1, 152) = 6.1$, n.s.]. JF's response latency on correct trials with audio was 3752 ms and 4708 ms without audio, a facilitation of 956 ms. The effect of stimulus type (control/critical) was

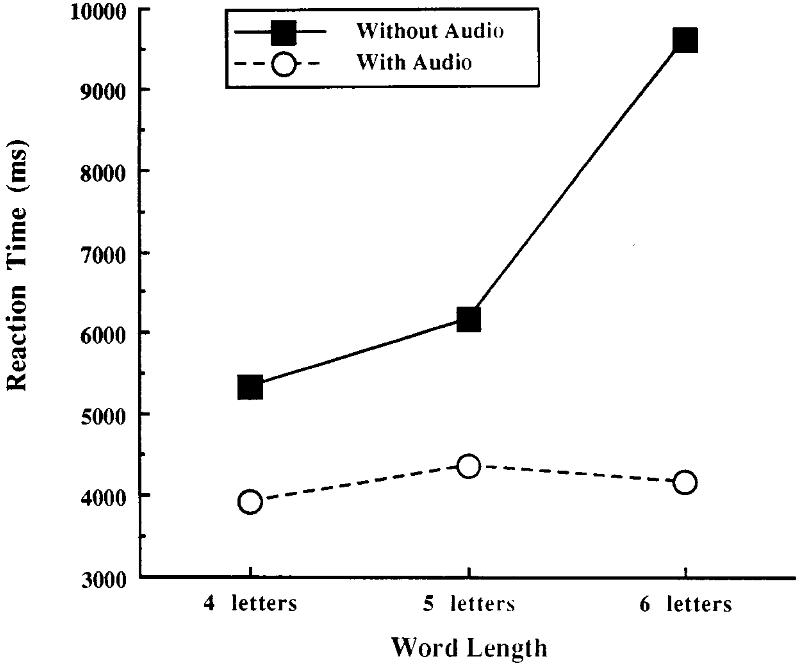

FIG. 2. IH's mean latency in the visual lexical decision task with and without auditory input as a function of word length.

not significant [$F(1, 152) = 2.4$, $p = .12$], nor was the interaction between auditory condition and trial type [$F(1, 152) < 1$].

Although the effect of stimulus type (control/critical) was not significant ($p = .12$), it is worth mentioning that JF's mean RT's were slower on the control trials than on the critical trials (control trials 4520 ms, critical trials

TABLE 2
Error Rates for JF on Visual Lexical Decision, with and without Auditory Input

Stimuli	Without audio (%)	With audio (%)	Significance
All	13	11	n.s.
Control	13	11	n.s.
Critical			
All	13	10	n.s.
Regular	14	7	n.s.
Irregular	11	14	n.s.

Note. Control (12%) vs critical (11%): n.s.

3931 ms). In lexical decision, when the phonology of a nonword is not that of a word as in the control trials, normal readers find it easier to discard the item than when the nonword is homophonic to a word (Pring, 1981). JF's slower responding to nonhomophonic nonwords may indicate that some visual characteristic of the nonword foils was causing her more difficulty on control trials than on critical trials. One difference between the control and critical trials which had not been controlled for is the orthographic distance between the word and the nonword. Whereas all the nonwords on control trials were formed by changing one letter of the target word (e.g., seek/heek), most of the nonwords on critical trials involved several letter changes because the goal was to form a pseudohomophone (e.g., motion/moshun). This orthographic proximity may have caused JF more difficulty. Since there was no hint of a trial type × auditory condition interaction ($p = .85$), however, we can reasonably assume that the facilitation produced by the auditory input was not simply to restore a degraded visual representation.

JF's correct reaction times on critical trials with and without an auditory input as a function of frequency are graphed in Fig. 3. Analysis of lexical decision times on critical trials with factors of condition (with/without audio), stimulus type (regular/irregular word) and frequency revealed a main

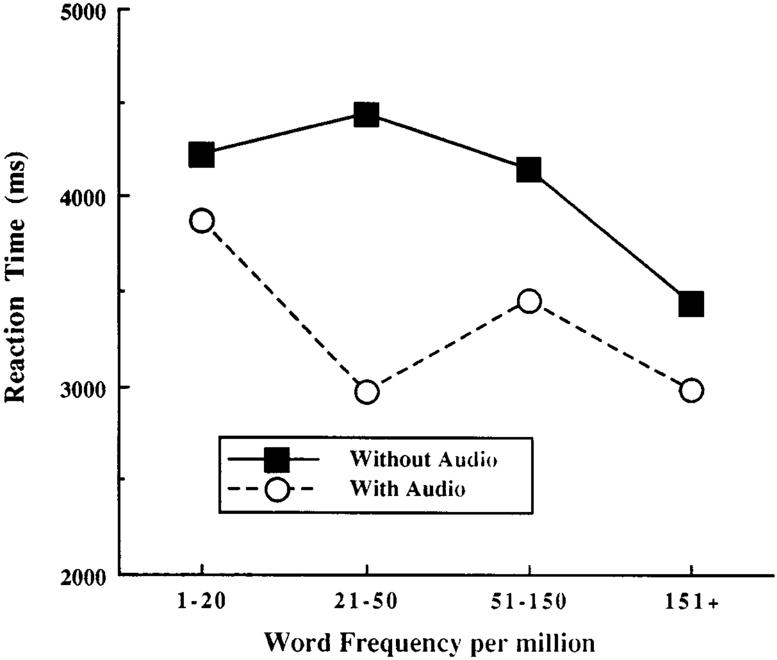

FIG. 3. JF's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

effect of auditory condition [$F(1, 138) = 7.1$, $p < .01$]. JF's mean RT was 4027 ms without auditory input, and 3304 ms with auditory input, a facilitation of 723 ms. A main effect of stimulus type approached significance [$F(1, 138) = 3.3$, $p = .07$]. JF's mean RT was faster for irregular (3456 ms) than regular (3943 ms) words. No other factor or interaction had a significant effect on the subject's performance.

Patient EL

Error rates for subject EL are given in Table 3. EL had an overall error rate of 6%. This rate did not vary significantly across word/nonword pair types and was not influenced by auditory condition (i.e., with or without auditory input).

A distribution analysis of the subject's RT's showed that none was more than three standard deviations above or below the mean per condition. A two-way ANOVA with auditory condition (with/without audio) and trial type (control/critical) as factors carried out on EL's correct RTs. As for IH and JF only the regular word trials of the critical trials were included in this analysis. It revealed a main effect of auditory condition [$F(1, 369) = 20.4$, $p < .0001$]. There was no effect of trial type [$F(1, 369) < 1$] and there was no interaction between auditory condition and trial type [$F(1, 369) < 1$]. EL's response latency on correct trials with audio was 895 ms and 1241 ms without audio, a facilitation of 346 ms.

EL's correct RTs on critical trials with and without an auditory input as a function of frequency are plotted in Fig. 4. Analysis of correct lexical decision times with factors of condition (with/without audio), word length (4, 5, or 6 letters), stimulus type (regular/irregular word) and frequency revealed significant main effects of auditory condition [$F(1, 314) = 11.0$, $p < .001$] and of frequency [$F(4, 314) = 16.9$, $p < .0001$], two-way interactions of auditory condition × frequency [$F(4, 314) = 3.4$, $p < .01$], of auditory condition × regularity [$F(1, 314) = 4.0$, $p < .05$] and of word length ×

TABLE 3
Error Rates for EL on Visual Lexical Decision, with and without Auditory Input

Stimuli	Without audio (%)	With audio (%)	Significance
All	7	5	n.s.
Control	5	5	n.s.
Critical			
All	9	5	n.s.
Regular	12	5	n.s.
Irregular	5	4	n.s.

Note. Control (5%) vs critical (7%): n.s.

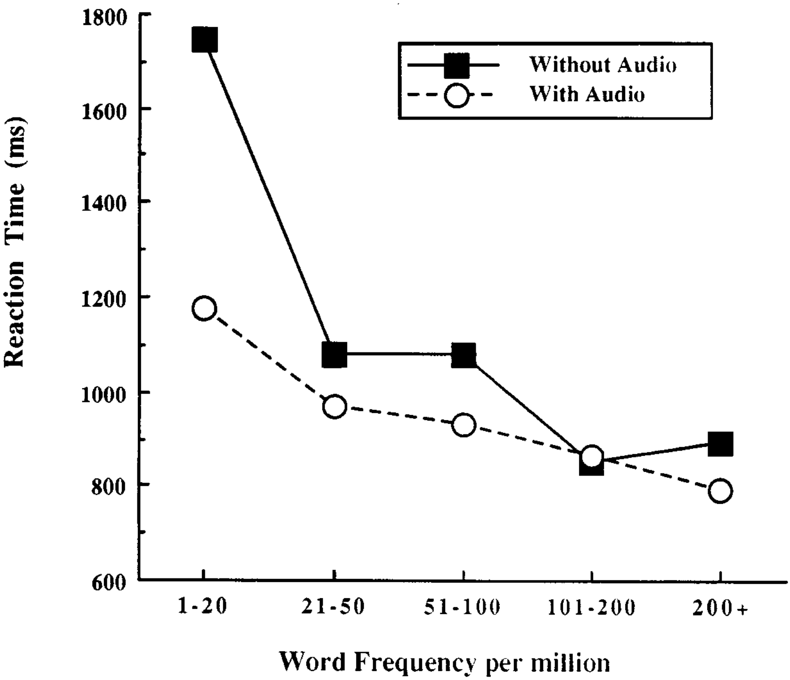

FIG. 4. EL's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

frequency [$F(8, 314) = 2.1, p < .05$], and a three-way interaction of auditory condition × regularity × frequency [$F(4, 314) = 3.4, p = .01$].

Simple effect analysis of the word length × frequency interaction showed that there was a main effect of word length only in the lowest frequency range (1–20) [$F(2, 314) = 6.6, p < .05$]. Latencies at this frequency range were 1130 ms for four-letter words, 1552 ms for five-letter words and 1706 ms for six-letter words.

The analysis of the simple effects for the auditory condition × frequency interaction revealed that auditory condition had a significant effect only on words from the lowest frequency range (i.e., 1–20) [$F(1, 314) = 22.7, p < .01$]. At this frequency EL's mean RT was 1748 ms without auditory input, and 1177 ms with auditory input, a facilitation of 571 ms.

Simple effect analysis of the auditory condition × regularity interaction showed that whereas auditory condition had a significant effect on regular words [$F(1, 314) = 13.6, p < .01$], it had none on irregular words [$F(1, 314) = .83$]. EL's response latency to regular words in the ''no audio'' condition was 1204 ms and 912 ms with audio, a facilitation of 292 ms.

For the lowest frequency range, simple effect analysis of the three-way interaction of auditory condition × regularity × frequency only showed a main effect of auditory condition on regular words [$F(1, 314) = 34.9$, $p < .001$]. The subject's response latency for regular words was 2092 ms without an auditory input and 1018 ms with an auditory input, a facilitation of 1074 ms. There were no other effects at other frequency ranges.

DISCUSSION

Because IH made less errors on control trials than on critical trials, we can conclude that his difficulties were not primarily visual and that he was able to use grapheme-phoneme conversion to reject nonwords which were not pseudohomophones. For JF and EL, error rates were the same on control and critical trials.

The phonology of the nonword foils on control trials was never that of a word and so we had expected that these nonwords would be easier for the subjects to reject (Pring, 1981). None of the three dyslexics, however, were faster on the control trials than on the critical trials. This would suggest that they were not primarily using grapheme-phoneme conversion in the task. Rather, it seems they were basing their decision on the orthography of the stimuli.

The main result of Experiment 1 is that an auditory input facilitated three surface dyslexics in a task of visual lexical decision. Since the auditory input was congruent to both the word and the nonword on critical trials, its effect on lexical decision performance must lie at the orthographic processing stage. This result supports the inclusion of some type of orthographic activation by phonology in reading models. While the results do not reveal whether this activation is direct or indirect (e.g., mediated by semantics), the orthographic activation is orthographically specific in that it can reduce the time to distinguish between a word and nonword which had the same phonology.

Providing a congruent auditory input to the subjects appears to have facilitated them by exempting them from bottom-up factors which usually cause them difficulty. Effects of regularity, word length, and frequency, if present in the silent condition, were either reduced or eliminated when auditory input had a significant effect. The most spectacular example of this is the absence of a word length effect for IH (a letter-by-letter reader) when an auditory input was provided whereas this effect was quite large without an auditory input. Similarly, EL displayed no regularity effect in the ''with audio'' condition and also a greatly reduced frequency effect in this condition.

The amount of facilitation produced by phonology was greatest (2756 ms) for the patient with the longest RTs (IH). The dyslexic with the shortest RTs, EL, exhibited the least facilitation from the auditory input (571 ms for low frequency words). Overall a congruent auditory input did not increase accuracy and did not appear to influence response latencies which were less than one second. This raises the question of whether normal readers would be susceptible to the influence of a congruent auditory input in performing visual lexical decisions, considering that such subjects are typically capable of responding in much less than one second.

EXPERIMENT 2

In order to better understand normal word recognition processes, the effect of a congruent auditory input on visual lexical decision was assessed with normal readers. Because there was no reason to believe that the subjects would have difficulty with the visual analysis of the stimuli and in order to encourage an orthographic analysis of the stimuli, only homophonic nonwords were used as foils in this experiment.

Subjects

The twelve subjects, seven men and five women, were introductory level psychology students at the University of Victoria who received course credit for participation in the experiment. All had 20/20 or corrected vision. Their ages ranged from 18 to 24 with a mean of 20.8 years. One subject was left-handed and all others were right-handed.

Stimuli

The parameters for the stimulus set were the same as for IH and EL except that there were no ‘‘control’’ trials (i.e., trials with nonwords heterophonic to the target word).

Procedure

The 200 word/nonword pairs were randomly divided into two lists. All of the subjects were administered both lists under both conditions: with and without auditory input. The order of presentation of lists under each condition was varied so that half of the subjects saw the lists in the order: list 1/with audio, list 2/no audio, list 1/no audio, list 2/with audio; and the other half saw them in the order: list 2/no audio, list 1/with audio, list 2/with audio, list 1/no audio. The subjects completed the entire experiment in one session. Event order and timing were the same as for Experiment 1.

Subjects responded by a key press as described for IH. They took a five minute pause after completing the first two blocks.

Results

The mean error rate for the normal subjects was 5.3% and ranged from 2.3% to 10%. Most errors (63%) were on words from the lowest frequency range. There was no speed-accuracy trade-off, as the correlation between mean correct RT's and error rates across conditions was of $+.63$ was significant ($p < .0001$].

Both a subjects' and items' analysis of the logarithms of correct RTs with factors of auditory condition (with/without audio), word length (4, 5, or 6 letters), stimulus type (regular/irregular word) and frequency (1–20, 21–50, 51–100, 101–200, 200+) revealed a significant effect of frequency [$F_S(1, 11) = 55.8$, $p < .001$, $F_i(4, 169) = 24.8$, $p < .001$]. There was a main effect of auditory condition in the items' analysis whereas this effect was only marginally significant in the subjects' analysis [$F_i(1, 169) = 9.2$, $p < .01$, $F_S(1, 11) = 3.8$, $p = .07$]. There was a significant interaction between auditory condition and word frequency in the subjects' but not the items' analysis [$F_S(4, 44) = 2.8$, $p < .05$, $F_i(4, 169) = 1.8$, n.s.]. This interaction is plotted in Fig. 5. A simple effects analysis of the frequency by auditory condition interaction for subjects showed that response latencies to words from the highest frequency range were longer by approximately 45 ms with an auditory input than without [$F_S(1, 11) = 15.8$, $p < .05$], but there was no effect of auditory condition on words of lower frequency. A post hoc items' analysis of the effect of audio condition for each frequency range using Tukey's honest significant difference method showed significantly longer RT's (p <

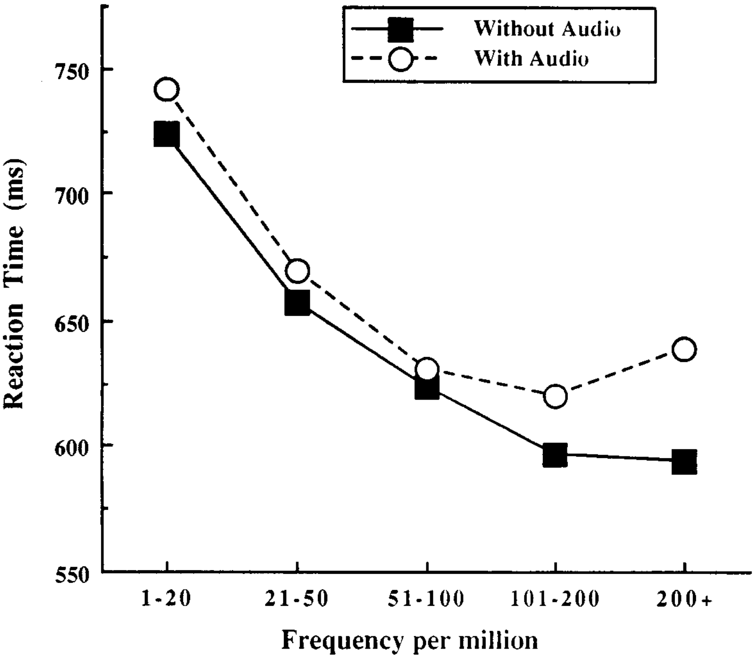

FIG. 5. Normal readers' mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

.05) with an auditory input than without, for words from the highest frequency range. Similar analyses performed for other word frequencies showed no effect of auditory condition.

Other interactions which were significant for subjects but not for items were: regularity × frequency [$F_S(4, 44) = 4.6$, $p < .01$]; word length × frequency [$F_S(8, 88) = 7.2$, $p < .001$]; auditory condition × regularity × word length [$F_S(2, 22) = 4.2$, $p < .05$], auditory condition × word length × frequency [$F_S(8, 88) = 3.6$, $p < .01$]; regularity × word length × frequency [$F_S(8, 88) = 3.6$, $p < .001$]; auditory condition × regularity × word length × frequency [$F_S(8, 88) = 2.4$, $p < .05$]. An examination of these interactions revealed that they consisted of small differences between irregular and regular words and words of different word lengths which changed direction from one frequency to the next, rendering them uninterpretable.

DISCUSSION

When there was a congruent auditory input accompanying visual word/pseudohomophone pairs for lexical decision, normal readers exhibited an inhibitory effect for high frequency words. No significant effect of auditory input, either facilitatory or inhibitory, was observed at other frequencies. These results cannot be explained by a general effect of interference since the effect of the auditory input was specific to one range of word frequencies. Because the nonword foils were homophonic to the target words, subjects were obliged to base their responses on the orthography of the stimuli. Any factor, then, which modulated performance, be it facilitatory or inhibitory, must have been acting on the state of orthographic representations. Therefore, while the effect of auditory input was in the opposite direction (i.e., inhibitory) for normal readers as it was for dyslexics (Experiment 1), the results argue in favor of orthographic activation by phonology.

GENERAL DISCUSSION

In the two experiments reported here, we have provided evidence that the phonology of a word, when supplied by an incident auditory input, can activate its orthographic representation. In the first experiment, this was shown by the facilitation that three dyslexic subjects experienced in a task of visual lexical decision when they heard a digitized recording of the target word at the same time as they viewed the stimuli. In the second experiment, phonological activation of orthography was manifested by the inhibitory effect that normal readers showed selectively for high frequency visual words when they heard the digitized recording. Because the experiments took the form of a forced choice between a word and a pseudohomophonic foil, subjects could not base their lexical decision on phonology alone and therefore an interpretation of the effect of the auditory prime cannot be not limited to one of activation of the phonological representation.

TABLE 4
Comparison of Dyslexic and Normal Readers' Reaction Time (ms) in the Task of Visual Lexical Decision

Subject	Without audio	With audio	Auditory effect	
IH	6871	4115	2756 ms	facilitation
JF	4027	3304	723 ms	facilitation
EL, low frequency words	1748	1177	571 ms	facilitation
EL, high frequency words	891	795	96 ms	n.s.
NOR, low frequency words	724	742	−18 ms	n.s.
NOR, high frequency words	594	639	−45 ms	inhibition

Note. NOR: normal readers.

The size of the effect varied among the dyslexic readers and it was in the opposite direction as that of the normal readers. Table 4 presents a comparison of the response latencies for the three dyslexics and the average for the twelve normal subjects. For EL and for the normal readers, RTs for the lowest and highest word frequency ranges are given. All three dyslexic subjects were facilitated by a congruent auditory input. The size of the facilitation was a direct function of the subject's response latency in the ‘‘no audio’’ condition, so that the slowest responder, IH (RT = 6871 ms in the ‘‘no audio’’ condition) was facilitated by 2756 ms and the fastest responder, EL, displayed a facilitatory effect of 571 ms for low frequency words (RT = 1748 ms in the ‘‘no audio’’ condition) but none for the words from the highest word frequency range, to which she responded the most quickly (RT = 891 ms) in the ‘‘no audio’’ condition. The correlation between reading speed (RTs in the ‘‘no audio’’ condition) and effect size for the data reported in this table is $r = +.96$, $p < .001$.

That the effect of auditory priming on the three dyslexics reported here is related to the slowness of their reading rather than their deviant reading patterns is further borne out by EL's reading profile. Although EL manifests single word reading deficits associated with surface dyslexia (i.e., regularizations of exception words) for words of almost all frequencies, she only benefited from auditory priming in this task for visual words to which she responded the slowest. It would appear that when a reader is abnormally slow (RT > 1000 ms) in the task of visual lexical decision, an auditory input can activate its corresponding orthographic representation fast enough to facilitate visual recognition.

In the ‘‘no audio’’ condition, the normal subjects displayed response latencies which varied as a function of word frequency, ranging from a mean of 724 ms for words from the lowest frequency range to 594 ms for words from the highest frequency range. Normal readers appear to visually activate orthographic representations from the highest frequency range too quickly to benefit from auditory activation in this task. In fact, normal readers display an inhibitory auditory effect for decisions made on words from this range. It would appear, then, that the direction (i.e., facilitatory or inhibitory) of the effect of an auditory input is a function of the relative speeds of activation by the different modalities. This would predict that normal readers should be facilitated by an auditory input if it is supplied sufficiently in advance of visual presentation.

One explanation that can be advanced for the inhibitory effect of a congruent auditory input in normal readers is that the orthographic representation which is activated by the auditory input is initially not very distinct and resolves over time; this activation is only beneficial to visual word recognition after resolution. If visual activation arrives when the state of the orthographic representation is not yet clearly defined there will be inhibition.

To conclude, there is evidence that phonology, when supplied by a simultaneous auditory input, can activate whole-word orthography. Its effect on visual word recognition as measured by lexical decision performance will depend on the speed with which visual activation of orthography takes place. If visual recognition is abnormally slow ($>$1000 ms), there will be facilitation, whereas when visual recognition is extremely fast as it is for normal readers for very frequent words, then there will be inhibition.

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