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Activation of visual orthography by auditory phonology in dyslexic and normal readers

par

Christine Whatmough

Département de psychologie

Faculté des arts et des sciences

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présentée par:

Christine Whatmough

a été évaluée par un jury composé des personnes suivantes:

Yves Joanette
Isabelle Peretz
Martin Arguin
Howard Chertkow
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ABSTRACT

This thesis provides evidence that auditory phonology can rapidly activate orthographic representations both directly and by semantic mediation and that this activation is lexical (i.e. word to word).

The experimental format used is cross-modal priming in the context of visual lexical decision (auditory prime, visual target) and requires a forced choice between a word and a pseudohomophone of the target word (e.g. height, hite). This feature ensured that subjects based their responses on the orthography and not the phonology of the stimuli and permits in turn that the effects of auditory priming be interpreted as implicating orthographic activation.

The first article shows that while surface dyslexics are facilitated by simultaneous auditory priming (e.g. auditory = HEIGHT, visual = height, hite), normal readers demonstrate an inhibitory effect specific to high frequency words. It is concluded that phonology can facilitate the activation of orthographic representations, but that the size and direction of the auditory priming effect are a function of the relative speeds by which sight and hearing activate orthography. The second article shows that the facilitatory effect of auditory priming goes beyond an alerting effect produced by auditory stimulation and is dependent on a holistic lexical match between phonology and orthography (i.e. word to word). This raises the possibility that the priming effect is semantically mediated. Article three shows that while auditory priming can be semantically mediated, not all effects can be accommodated by the assumption of phonology-to-semantics-to-orthography activation. It is therefore argued that direct phonology-to-orthography activation also takes place. The final chapter describes an

experiment in which normal subjects demonstrate both facilitatory and inhibitory effects to cross-modal priming. The results indicate that the auditory activation of orthography is also lexically based in normal readers and that it can be automatic.

Besides informing about processes involved in normal reading, the experiments provide indications about the possible functional loci of impairment in the dyslexic subjects.

RÉSUMÉ

Plusieurs chercheurs (Coltheart, Patterson, & Leahy, 1994; Plaut, McClelland, Seidenberg & Patterson, 1996; Stone, Vanhoy & Van Orden, 1997; Van Orden, 1987; Ziegler, Montant & Jacobs, 1997) avancent l'hypothèse que l'activation rétroactive de l'orthographe par la phonologie est intrinsèque aux processus de lecture et de reconnaissance visuelle des mots. D'autres (Clarke & Morton, 1983; Monsell, 1985; Ellis and Young, 1988; Rugg, Doyle & Melan, 1993), par contre, qui ont examiné les interactions entre la phonologie auditive et le lexique orthographique sont généralement arrivés à la conclusion que la phonologie d'un mot entendu n'active pas les représentations orthographiques impliquées dans la lecture. Cette thèse fournit une démonstration expérimentale que la phonologie peut activer l'orthographe et elle indique quelques propriétés de cette activation. En particulier elle suggère que la phonologie auditive peut faciliter la reconnaissance d'un mot visuel, que l'activation intermodale est lexicale, c'est-à-dire un mot phonologique entier active un mot orthographique entier, et que cette activation peut être directe ainsi que par entremise sémantique.

Le format expérimental utilisé dans cette recherche implique l'emploi de l'amorçage intermodal dans une tâche de décision lexicale visuelle (amorce auditive, cible visuelle). Ce format a déjà été utilisé par d'autres chercheurs pour examiner la question des interactions entre la phonologie et l'orthographe. Cependant, dans ces études, la tâche pouvait être accomplie sur la base de la phonologie des items et, de ce fait, rendait l'interprétation de l'effet de l'amorce ambiguë: est-ce que l'amorce facilite uniquement un traitement phonologique, ou, est-ce qu'elle active aussi l'orthographe? Dans la recherche rapportée ici cette difficulté d'interprétation a été contournée en

demandant aux sujets de faire un choix forcé entre la cible (un mot) et un pseudohomonyme de la cible. Par exemple le sujet devait indiquer si *hanche* ou *henche* était le vrai mot. De cette façon, le sujet devait baser ses décisions sur l'orthographe et non la phonologie des stimuli. Il a été ainsi possible de s'assurer que toute modulation des temps de réponse par amorce auditive indique une activation de l'orthographe par l'input phonologique.

Les trois articles qui font le corps de la thèse rapportent principalement des expériences menées auprès de sujets ayant un profil de dyslexie de surface. L'intérêt de tester ces sujets dans ce paradigme se rapporte à leur utilisation apparente de la conversion graphème-phonème en lecture (par opposition à une conversion lexicale). Ainsi en lecture de mots isolés les dyslexiques de surface commettent beaucoup plus d'erreurs sur des mots ayant des correspondances graphèmes-phonèmes irrégulières qu'aux mots dit "réguliers" et leur réponse à ces mots est le plus souvent une régularisation. Par exemple le mot *gars* serait lu *gare*. De plus, ce mode de traitement orthographique limite leur compréhension de mots imprimés. Ainsi ils ne comprennent pas les mots qu'ils lisent mal et font beaucoup d'erreurs dans la compréhension des homonymes (par exemple: ballet vs balai) parce que ces mots ont la même prononciation. L'ensemble de ces caractéristiques suggère que ces sujets ont subi une perte de la représentation lexicale orthographique des mots.

Le premier article de la thèse démontre que trois dyslexiques de surface, IH, JF et EL, sont plus rapides à faire des décisions lexicales visuelles lorsqu'ils entendent simultanément un enregistrement auditif (l'amorce) du mot cible que lorsqu'ils font la tâche sans amorçage. Ces sujets sont tous anormalement lents à faire la tâche et la taille de l'effet de l'amorçage est en corrélation linéaire avec le temps de réponse individuel sans amorçage. Dans une deuxième expérience menée auprès de lecteurs normaux, l'amorçage n'entraîne pas de facilitation mais plutôt un effet inhibiteur qui se limite aux mots de fréquence lexicale élevée. L'ensemble des résultats indique que la phonologie peut activer les représentations orthographiques, mais que la taille et la direction de l'effet de l'amorçage auditif sont fonction des vitesses relatives par lesquelles les deux modalités (la vision et l'audition) activent l'orthographe.

Les expériences du deuxième article démontrent que l'effet facilitateur de l'amorçage auditif va au-delà d'un effet d'alerte qui résulte d'une stimulation auditive. De plus, elles indiquent qu'une correspondance orthographique partielle entre l'amorce et la cible est insuffisante pour produire l'effet d'amorçage, qui ne se manifeste qu'avec une correspondance lexicale complète (c.-à-d., même mot). Une explication possible de ce résultat est que la mise en correspondance entre l'amorce auditive et la cible visuelle ne se fait pas par un appariement direct de phonologie à orthographe, mais plutôt que le système sémantique agit comme médiateur de cette correspondance.

Le troisième article examine le rôle de la sémantique dans l'activation de l'orthographe par la phonologie. La première expérience indique que les patients IH et JF peuvent être facilités par une amorce auditive qui a un lien sémantique avec le mot cible. Par exemple, le mot auditif ROUGE facilite le choix forcé entre *sang* et *sant*. La taille de l'effet d'amorçage sémantique est aussi grande que celle de l'effet d'amorçage mot à mot (p. ex., auditif = HANCHE, visuel = hanche, henche) dans les expériences précédentes. Cependant, pour les deux sujets, l'effet n'est pas présent dans les deux blocs d'essais comme il l'était pour l'amorçage mot à mot. Une deuxième expérience menée auprès de IH démontre que l'effet de l'amorçage mot à mot est modulé par la "force" sémantique des stimuli. Toutefois tous les effets d'amorçage auditif ne peuvent être interpretés comme étant entremis par la sémantique et il est proposé que de l'activation directe de la phonologie vers l'orthographe est aussi présente.

Le dernier chapitre de la thèse rapporte brièvement une expérience qui examine l'évolution temporelle de l'activation orthographique résultant de la présentation d'une amorce auditive chez des sujets normaux. Cette expérience démontre que les sujets normaux peuvent être facilités par de l'amorçage auditif lorsque la présentation de l'amorce débute au moins 225ms avant la présentation de la cible visuelle. De plus, dans le contexte de cette expérience l'activation orthographique par l'amorce semble être automatique et non sujette à des stratégies de la part des participants. L'effet inhibiteur d'une amorce dont l'orthographe est voisin de la cible signale que comme pour les dyslexiques, l'activation entre les domaines a une base lexicale pour les lecteurs normaux.

En plus des conclusions qui se rapportent aux interactions entre la phonologie et l'orthographe, la discussion de chaque article cherche à mieux situer les troubles fonctionnels des sujets dyslexiques participant aux expériences.

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List of Abbreviations

CT: computed tomography

GPC: grapheme-phoneme conversion

RT: reaction time

SD: surface dyslexia

SDs: surface dyslexics

SOA: stimulus onset asynchrony

SPECT: single-photon emission computed tomography

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It is the glory of God to conceal a thing:

but the honour of kings is to search out a matter.

Proverbs 25:2

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To my family

Chapter One

Reading: Three Representational Domains

READING: THREE REPRESENTATIONAL DOMAINS

From the orthographic code of a printed word, the normal reader has the capacity both to derive meaning and produce an intended pronunciation. Reading, then, can be considered to involve a system of at least three representational domains: orthography, or the spelling of a word, phonology (pronunciation) and semantics (meaning). Reading skills are usually acquired after an individual has the capacity to comprehend and produce speech. Because of this, reading is frequently conceived of as a kind of graft by which orthography is inserted into an existent linguistic system in which semantics and phonology already freely interact.

Although there is a very obvious feedforward aspect to reading, with the whole motivation of reading being that orthography should activate phonological and/or semantic representations, a subject of research has been to examine whether, via feedback mechanisms, phonology and semantics can activate the orthographic representations of words during reading performance. This thesis focusses on the question of whether phonology can directly activate orthography. It seeks to provide evidence that incidental auditory phonology can rapidly activate whole word orthographic representations in both normal readers and subjects suffering from acquired surface dyslexia. This activation is shown to be facilitatory to the visual recognition of words under certain conditions. The experimental technique used for this purpose is that of cross-modal priming in conjunction with visual lexical decision (auditory prime, visual target). Results show that phonological as well as semantic representations which are contacted with the presentation of an auditory word can activate the orthographic representations which are involved in visual word recognition.

Four main sections follow in this introductory chapter. In the first section, a review of the literature pertinent to the subject of phonology-to-orthography activation in reading is presented. A particular emphasis is placed on research using cross-modal priming and on the ambiguities in the interpretation of the results from these studies. The second section outlines two reading theories and their proposals concerning the locus of deficit in surface dyslexia. The third section considers the theoretical implications of using cross-modal priming to infer on to processes involved in reading and visual word recognition. Here the main question asked is: is phonology modality specific? Also considered is the question of whether the visual lexical decision task implicates the reading lexicon. The final section outlines the motivation for the research in each of the three articles which make up the thesis, and provides a summary of their main results.

EVIDENCE OF PHONOLOGY-TO-ORTHOGRAPHY ACTIVATION

Phonological Feedback as an Integral Part of Visual Word Recognition

The question of whether phonology can activate orthography stands somewhat in contrast with a strong postition taken by some researchers who hold that not only is phonology-to-orthography activation a possibility but that feedback to orthography from phonology is an integral and necessary part of the visual recognition of words. According to them, phonology, once activated by incoming orthographic activation, exerts a top-down influence on the visual recognition of printed words. Evidence put forth to support this position comes from a variety of experimental tasks: semantic classification, whole word report of masked stimuli, visual lexical decision, and naming (Coltheart, Patterson, & Leahy, 1994; Lukatela & Turvey, 1991, 1994a, 1994b; Perfetti, Bell & Delaney, 1988; Stone, Vanhoy & Van Orden, 1997; Van Orden, 1987;

Ziegler, Montant & Jacobs, 1997). While all these experiments show that phonological information is recruited very early in these tasks, only those in which phonology appears to actually influence visual word recognition will be reviewed here.

Inconsistencies in the feedforward mappings of orthography to phonology (e.g., *int* is pronounced /ɪnt/ in *mint*, but, /aɪnt/ in *pint*) have been frequent subjects of investigation in reading research. Stone, Vanhoy & Van Orden (1997), however, have recently shown that feedback inconsistency from phonology to orthography (e.g., /ip/ is spelled *eap* in *heap* and *eep* in *deep*) also influences the speed with which subjects process words. Their results show that subjects are slower to respond in a task of visual lexical decision to words which have a pronunciation body which can be spelled in more than one way than to words which have unique body spellings (e.g., / ip/ as in HEAP and DEEP vs /ob/ as in PROBE and GLOBE). The generality of this effect has been demonstrated by Ziegler et al. (1997) who looked at sublexical inconsistencies smaller than the word body in the French language. They also show that both feedforward and feedback consistency exert an influence not only on visual lexical decision tasks but also in single word naming. These findings suggest that phonology-to-orthography activation is implicated in visual processing of words.

Coltheart et al. (1994) also provide evidence that phonology plays a role in visual word recognition. They compared the reaction times (RTs) of subjects in rejecting three types of nonwords in a task of visual lexical decision. They found that relative to matched nonwords (e.g., foat), pseudohomophones (e.g., koat) were slower to reject only if they were also orthographically close to their respective base word, so that *koat* but not *phocks* slowed correct NO responses. This indicates that, in the context of this experiment, visual lexical decisions made on pseudohomophones involved the convergent activity of phonology and orthography.

The object of this thesis is to provide evidence that phonology can directly activate orthography and, further, to show that it can facilitate the recognition of printed words. Although the thesis cannot arbitrate the question of automatic phonological feedback in reading, it does provide indications concerning the basic nature of phonology-to-orthography activation which will ultimately have to be taken into account in theories which propose that phonology has a top-down influence on visual word recogntion.

Auditory Phonology As An Incidental Activator Of Orthographic Activation

In the research reviewed above, the central issue was whether there is automatic feedback of phonology onto orthography in visual word recognition and, to do this, researchers examined the influence of sublexical phonology-to-orthography correspondences in words and nonwords. Some researchers have looked at a broader question concerning the interactions between phonology and orthography which is, can phonology, as provided by incident auditory input, activate orthographic representations? Intuitively it is not obvious what the answer should be because there does not appear to be any real necessity for the spoken word to rapidly access orthographic representations.

The avenue which has been taken to study this question is cross-modal priming in which an auditory prime is presented in the context of an orthographic task performed on a printed visual input. The reasoning behind the use of priming is that if the presentation of an auditory prime has any influence on the speed with which a subject perceives or recognises a visual target, it can be concluded that the prime accesses a form of internal representation which is common with the target. In this context, the effect of a prime is generally conceived of as either lowering the activation threshold to the representations it accesses, or producing a sustained level of activation of these representations. Both conceptions are approximately equivalent.

When there is some reason to believe that there is an overlap between the representations contacted by the prime and the target, and the response to the primed stimulus is faster than the response to an "unprimed" stimulus (i.e., neutral prime or control condition) the prime is usually said to have a facilitatory effect on RTs. The term 'facilitatory' is used loosely because unless it can be confirmed that the unprimed condition is completely neutral, this RT difference may in fact reflect a facilitatory effect but it may also be a function of an inhibitory influence of the unprimed condition or a combination of facilitation and inhibition. However, whatever the direction of the effect, the fact that there is a RT difference under the two conditions indicates that there is some level of commonality in the representations that are contacted by the auditory prime and the visual target.

Dijkstra, Fraunfelder, & Schreuder (1993) studied the priming effect of the bimodal presentation of graphemes (visual) and phonemes (auditory) on the recognition of a target phoneme or grapheme. In the task subjects monitored simultaneously for a visual letter target (A or U) and an auditory vowel target (/a/ or /u/). The targets could be presented either singly or bimodally (i.e., together). Dijkstra et al., (1993) found that in bimodal presentations subjects were faster to respond when the target set consisted of nominally congruent stimuli (e.g., visual target = A, auditory target = a) than when it was not (e.g., visual target = U, auditory target = a). This facilitatory effect was present even when the visual target preceded the auditory target by 100 ms. They did not find that incongruent target sets (i.e., visual target = U, auditory target = a) faired any worse than neutral target sets (i.e., visual target = *, auditory target = a) indicating that intermodal activation in this paradigm did not exert an inhibitory effect.

Dijkstra et al. (1993) hold that their experiments support the concept that sublexical phonology (phonemes) can activate sublexical orthographic representations (graphemes).

Dijkstra et al. (1993) make two important assumptions which are critical to their conclusion. The first is that in the bimodal presentations, when the visual stimulus preceded the auditory stimulus by 100 ms, the subjects were responding to the visual stimulus. This assumption is justified by the fact that RTs to single presentations in auditory and visual mode are equivalent, so that subjects would most likely be responding to the visual stimulus when it appeared 100 ms before the auditory stimulus. The second assumption, which is problematic, assumes that subjects are not mentally converting all visual stimuli into a phonological code **in order to respond.** If subjects were in fact recoding, the facilitation experienced on bimodal presentations would not neccessarily indicate phonology was activating orthography but rather that the auditory vowel primed the phonological product of the recoding process.

Experiments which investigate whole word cross-modal priming have produced contradictory results regarding the possible facilitation of visual word recognition by auditory priming. The time delay between the prime and the target appears to be the factor which is critical in explaining these discrepant observations. When the auditory stimulus is encountered in a pretest block of trials, often it does not facilitate visual recognition of the stimulus in a subsequent block of trials (Clarke & Morton, 1983; Monsell, 1985). This stands in contrast with the strong facilitation of within modality priming (i.e visual to visual) observed in a similar context. On the other hand, if the prime precedes the target by a shorter interval (<10 secs), a facilitatory effect can be found for both within and across modality priming (Kirsner & Smith, 1974; McKone, 1997).

Thus, Clarke & Morton (1983), who used the pretest priming design, found no transfer from auditory to visual modality. In a treatment phase subjects read aloud printed words, hand written words or definitions to words, or, they repeated auditorily presented words. In the recognition phase a mean duration threshold was established which was the time required to visually recognize the words from the various treatments and control words not previously encountered. Subjects recognised words they had previously encountered visually at lower thresholds than they did control words. Curiously, however, words which the subjects had heard and repeated were not recognised faster than control words. Similarly, Monsell (1985) found that while seeing a word in a block of priming trials facilitated its recognition in a subsequent visual lexical decision task, neither articulating nor hearing the word in the priming block did. In both of these studies within modality priming was shown to be more than a priming of surface features of the stimuli and referred to more abstract (perhaps orthographic) properties of the words. So, Clarke and Morton (1983) found that handwritten words could prime typed words and Monsell (1985) found that words in uppercase letters could prime words in printed in lower case letters.

As noted above, when the prime/target stimulus onset asynchrony (SOA) is fairly short it is possible to obtain reliable cross-modality priming effects. In these experiments the subjects made lexical decisions to auditory and visual stimuli presented in pseudorandom order. Stimuli were repeated within blocks at targeted item lags. Using this method Kirsner & Smith (1974) and more recently McKone & Dennis (1997) have found that cross-modal priming (auditory to visual) can facilitate lexical decisions with up to 15 trials intervening between the auditory prime and the visual target. The size of the effect, however, was found to be smaller than visual to visual priming and diminished more rapidly over time.

As with the Dijkstra et al. (1993) experiments, however, a problem arises when one wishes to explain these results as indicating that phonology activates orthography. This is because all of the nonwords in these experiments had a nonword phonology, and subjects could have been basing their "visual" lexical decisions on the phonology, or the semantics of the stimuli. That is, subjects may have been implicitly or explicitly testing whether an item sounded like a word, or meant something. If that were the case the auditory prime could be exerting its facilitatory effect within phonology and under such a possibility, it is not necessary to conclude that phonology can activate orthography. Indeed this is what is concluded by Rugg, Doyle & Melan (1993) in their study in which they compare the event related potentials of visual words which are auditorily primed with those visually primed. In their experiment subjects responded to nonwords in a list which was a pseudorandom mix of auditory and visual words and nonwords. Rugg et al. (1993) found that both types of primed words (visual prime-visual target and auditory prime-visual target) demonstrated a positive shift relative to words which were not primed. However, the positive shift associated to auditorily primed words onset 100 ms later than the shift associated to visually primed words. The authors maintain that the priming effect was taking place within phonology for the auditory prime-visual target words and the later repetition effect results from the extra time required for orthography to generate a phonological representation. They discount the possibility that cross-modal priming involves the semantic system in this experimental paradigm because they have found similar effects for pronouceable nonwords which have no meaning. However, as they mention this does not mean that auditory words cannot under different conditions prime visual stimuli by semantic mediation. Indeed, cross-modal semantic priming has been abundantly demonstrated (Marslen-Wilson, 1987; Swinney, 1979; Swinney, Onifer, Prather & Hirshkoitz, 1979; Holcomb & Anderson, 1993).

There are then three possibilities which prevent interpreting cross-modal effects as providing conclusive evidence that phonology directly activates orthography. First, if the task can be performed by recoding the visual stimuli into a phonological form and basing the lexical decision on the phonology of the stimulus, then the auditory prime can be interpreted as priming the phonological lexicon and not activating orthography. Secondly, it is possible that the subjects are making semantically based decisions. That is, they may be deciding whether the visual stimuli are meaningful in which case words would be accepted, nonwords rejected. In this case phonology would be priming semantic representations which would be the basis for the facilitatory priming effect on visual lexical decision performance. Finally, it is possible that, while the subjects are basing their decisions on the orthography of the visual stimuli, the auditory prime is not directly activating orthography but rather is activating a semantic representation which in turn activates the orthographic representation. In which case phonology could be said to activate orthography by semantic mediation, a position which is maintained by Ellis and Young (1988). In the research reported in this thesis the first question has been dealt with by using stimuli which must be processed ultimately on the basis of their orthography. This feature of the task is explained in the section which immediately follows . The second and third possibility of interpretation have been addressed by studying surface dyslexics who, as will be shown, do not directly associate printed words with their meaning or vice versa.

Cross-Modal Priming Effects: Constraining their Interpretation

In tasks of visual lexical decision normal readers are slower to reject nonwords which are homophones to real words (pseudohomophones) such as BRANE, than they are to reject nonwords such as ROLT which do not sound like words (Rubenstein, Lewis & Rubenstein, 1971). This "pseudohomophone effect" has been interpreted as indicating that subjects automatically recode visual stimuli into a phonological form in reading.

In 1981, however, McQuade questioned the automaticity of this recoding and demonstrated that the subjects' reliance on a phonological code can be manipulated by varying the proportion of pseudohomophones in the task. She found that in a task of lexical decision, when a high proportion of the nonwords (86%) did not sound like words, subjects responded 40 ms slower to the few pseudohomophones present in the list than to control nonwords. However, when a high proportion of the nonwords were pseudohomophones (again 86%) the "pseudohomophone effect" disappeared, suggesting that the use of phonology in this task was under the strategic control of the subjects and that subjects could block out the participation of phonology in a task if it generally slowed the decision making process. In this present thesis, except in Experiment 1 of the first article (Whatmough, Arguin & Bub, in press) all the nonwords used in the task of lexical decision are pseudohomophones. There is, however, an important motivational difference in using pseudohomophones in the present series of experiments. Here pseudohomophones are used not to prohibit phonological recoding but to ensure that even if subjects do recode the stimuli, their lexical decisions are still based on the orthography of the stimuli. This then allows us to interpret auditory priming effects as evidence that phonology is activating orthography.

The experimental format used then in the thesis is one of forced choice lexical decision in which subjects are asked to choose between a word and a nonword. On critical trials the nonword is a pseudohomophone so that it cannot be distinguished on the basis of phonological recoding. If, for the purposes of investigating orthographic activation, the use of pseudohomophones is important in testing normal readers, it is imperative in testing the surface dyslexic subjects. This is because surface dyslexics appear, as will be described later, to rely heavily on phonology to access meaning and tend to base visual lexical decisions on the phonology of the stimuli and not the orthography.

The precautionary measures taken to prevent phonologically based descisions does not remove the possibility that a normal subject might be basing his or her decision on the meaningfulness of the visual stimuli. That is, confronted with the visual stimuli *brain* and *brane*, a subject might ask, not, does this item sound like a word? but, does this item mean something? Any priming produced by an auditory word could in this case be priming this decision process within semantics. That is, hearing "BRAIN" could activate the meaning of *brain* which makes the decision easier and faster than simply seeing *brain* without priming. The thesis seeks to show that priming is facilitating an orthographic process and that phonology is activating orthography. To avoid a semantic facilitation interpretation, the priming effect is shown to be present in surface dyslexics who do not appear to use semantic-orthographic associations to recognize words.

CONSTRAINING INTERPRETATIONS OF CROSS-MODAL PRIMING: SURFACE DYSLEXIA

Surface dyslexia is a term which is applied to a particular pattern of reading deficit which may manifest itself as a developmental problem or be acquired after some kind of brain damage. The basic reading symptom in surface dyslexia is a disproportionate number of errors made on words which have irregular grapheme-phoneme correspondences in the presence of good nonword reading. Typically the erroneous responses to these irregular words are responses which are plausible at a sublexical level. For example, the word deaf might be read by a surface dyslexic as /dif/. Bub, Cancelliere & Kertesz (1985), also show that in one case of surface dyslexia which was particularly pure, accuracy to irregular words declined monotonically with word frequency.

Within the category of surface dyslexia it has become useful to distinguish two types (Shallice, Warrington & McCarthy, 1983). In pure surface dyslexia (Type I SD) a clear dissociation exists between preserved non-word and regular word reading and impaired reading of irregular words. A survey of these cases (Bub et al.,1985; McCarthy and Warrington, 1986; Parkin, 1993; Warrington, 1975) reveals further that in all recorded cases there is also a severe semantic deficit. In Type II cases, on the other hand, the dissociation is less clear with a certain percentage of errors being made also on low frequency regular words and nonwords. Errors on regular words and nonwords and on some of the exception words, appear "visual" (e.g. INSECT->insist, NIECE->nice) although the SDs can identify the letters of the words which they misread (see Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Humphreys & Evett, 1985; Marshall & Newcombe, 1973). Type II cases do not have the severe overall comprehension deficits of the Type II SDs. They do, however, have difficulty understanding some of the words they read because they (although see Howard & Franklin, 1987, and Kay and Patterson, 1986, for exceptions) derive the meaning of printed words from their pronunciation of them. This manifests itself in several ways. First of all, printed homophones (e.g., sale, sail) are confused with one another as they cannot be distinguished by their phonology. Secondly, irregular words frequently cannot be understood (e.g., break -> /brik/) or are misunderstood (e.g., bear understood to mean beer).

Dual-route and Connectionist Interpretations of Surface Dyslexia

Interpretations of reading disability can be said to have a symbiotic relationship with functional reading models in that explanations of the various disorders are tied to theory, and reading theories derive a certain credibility from being able to encompass these disorders. There are two major approaches in reading theories. Over the years, as each has been adapted to account for more of the information which we have about reading and dyslexia, their predictions concerning any particular paradigm have become less and less distinguishable and both approaches are quite successful in explanation. According to one theory, called the dual-route model (Coltheart, Curtis, Atkins & Haller, 1991; Paap & Noel, 1991), the orthography of printed stimuli is mapped onto phonology both as an orthographic whole and at a sublexical level from graphemes to phonemes. The whole word one-to-one mapping which is said to take place between the orthographic and phonologial lexicon is held to be frequency dependent, with high frequency words being processed more quickly than low frequency words and associations between orthography and phonology are said to take place bidirectionally. The sublexical route, often called the grapheme-phoneme conversion (GPC) route (although not everyone agrees it is based on graphemes and phonemes) is said to acquire rules about the regularities between graphemes and phonemes. While the phonemes do not feedback to graphemes, they do feed forward to the phonological lexicon and in this way sublexical phonology can partially activate whole-word lexical representations. Critical differences between the routes make that only the lexical route can give the correct pronunciation of irregular words and only the sublexical route can read nonwords. Both routes are assumed to operate simultaneously but at different speeds. Because the sublexical route is rule-bound it regularises the pronunciation of irregular words and a normal reader will be slowed in responding to these words because different responses will be produced by the two routes within the same time frame and more time is required in order to arbitrate between the two responses.

Within the framework of dual-route theory, the key features of surface dyslexia (i.e., regularised reading of exception words and good nonword reading) are explained as a breakdown in the lexical route with subsequent reliance on an intact grapheme-phoneme conversion route. The explanation given for the mixed error pattern of the Type II SD is that there are two functional lesions, one to the lexical route as evidenced by the poor reading of exception words, and a second to the GPC route which occasions poor regular and non-word reading. But as Behrmann and Bub (1992) point out this explanation is made entirely by default.

Connectionism is the other major approach to reading. It holds that there is only one procedure for mapping spelling to sound and that this procedure is sublexical. According to connectionism, rule-like behaviour emerges from a homogeneous associationist process which strengthens frequent correlations between sub-symbolic input and output feature patterns. The principal influences on orthography are the frequency with which a word and a pattern of words appear in print, the consistency with which any given grapheme or graphemic group is translated into the same phonetic unit. It also postulates that automatic feedback from phonology and semantics are also important to the perception of orthographic units.

Plaut, McClelland, Seidenberg & Patterson (1996) have constructed several types of connectionist systems which implement these ideas and lesioned them in various ways in order to find the simulation which best accounts for both the development of normal reading skills and the reading deficits in surface dyslexia. The most satisfactory simulation led to the proposal that normal readers come to rely heavily on semantic feedback for reading words with irregular grapheme-phoneme correspondences. When the semantic support is withdrawn as seems to be the case in cases of Type I surface dyslexia (see above) the resultant system consists in a highly regular grapheme-phoneme system. In strong support of this model, Patterson and Hodges (1992) found in a sample of 6 patients with either dementia or progressive aphasia that the level of irregular word reading was directly related to the severity of comprehension loss. Plaut et al. (1996), do not directly address the question of Type II dyslexics but presumably the model could account for their deficits by additional damage to the links between orthography and phonology.

In summary the two approaches explain the pure cases of surface dyslexia. According to dual-route theory surface dyslexica is due to a breakdown in the whole word translation of orthography into phonology and a reliance on GPC rules. According to the most successful connectionist simulation, it is due to a loss of semantic (and hence phonological) input to the resolution of irregular words.

Although the two reading theories have very different explanations to surface dyslexia, explanations of how lexical decision is performed are very similar. Dual route theory says that lexical decision takes place by checking whether the orthographic string that is presented visually is present within the orthographic lexicon which receives feedback from the phonological and semantic lexicons. RTs to words are a function of word frequency and may possibly be influenced by semantic variables such as concreteness and imageability. As mentioned earlier, pseudohomophones which are close orthographically to their word will be rejected slowly because GPC route does partially activate representations in the phonological lexicon. This in turn will increase the activation of the pseudohomophone's base word in the orthographic lexicon, slowing its rejection as a word. In the connectionist framework of Seidenberg and McClelland (1989) visual lexical decision is performed by comparing the degree of fit between the activation of orthography by the input with that which is activated by feedback from phonology. Close fits are judged to be words, while more distant fits are judged to be nonwords.

The testing of surface dyslexics in the context of this thesis provides us with a way of isolating the effects of phonology from the effects of semantics. As noted above it can be shown that in certain surface dyslexics there is very little direct activation of semantics by orthography. They tend instead to use phonological recoding to understand printed words. The use of pseudohomophones as foils in the experimental task, however, renders phonological recoding a useless strategy for regular words and will tend to bias the subjects away from the correct answer for irregular words. A surface dyslexic then must either base his or her response strictly on the orthography of the stimulus. If then auditory priming facilitates the surface dyslexic in visual lexical decision, it is an indication that phonology can activate orthography either directly or by semantic mediation.

INTERPRETING CROSS-MODAL PRIMING EFFECTS: ARE ORTHOGRAPHY AND PHONOLOGY MODALITY SPECIFIC?

In this research cross-modal priming is used in conjunction with visual lexical decision in order to provide a background against which the effect of phonology on orthography can be evaluated. Two questions naturally arising from the use of this particular experimental paradigm in this context are addressed in this section. The first question asks whether the task of making forced choice decisions between a word and its pseudohomophone has more to do with spelling than with reading processes. This question only has relevance here, however, if there are two orthographic lexicons, one for reading and one for spelling. While evidence for both the single and two lexicon model is presented in this section, the conclusion drawn is that, for the purposes of this thesis, a distinction between reading and spelling lexicons is unnecessary. The second question addressed in this section is more significant and asks whether it is appropriate to use auditory phonology to probe the issue of phonological feedback in reading. Here the most relevant literature examines whether there is one phonological lexicon for both reception (i.e. hearing) and production (i.e., reading aloud and speaking) or whether there are two . Although the issue cannot be adjudicated here, the issues are set forth in order to better situate auditory priming effects in respect with other pertinent research.

Reading and Spelling, One Lexicon or Two?

The task of visual lexical decision is used in this thesis to interrogate access to orthographic representations in reading. While it is interesting to consider in this context the evidence for two stores for the representation of the orthographic forms of words, it will become clear in what follows, even for those who propose there are two lexicons (i.e., one for reading and one for spelling), that lexical decision stands as a means for indexing the strength of the reading or input lexicon in contrast with the spelling or output lexicon.

Neuropsychological dissociations between spelling and reading have long been documented. Thus there are cases of pure agraphia in which patients cannot spell but can read (Roeltgen, 1992) and cases of alexia without dysgraphia in which patients cannot read but can spell (Friedman, Ween & Albert, 1992). Dissociations between reading and spelling such as these could suggest either that there are two orthographic lexicons, one for reading and one for spelling (Patterson & Kay, 1982), or that access by the two modalities to a unique orthographic lexicon can be impaired differentially (Friedman & Hadley, 1992).

One way to show that the same lexicon is used for reading and spelling would be to show that subjects make errors on the same words in both modalities. This approach however is complicated by the fact that both reading and spelling accuracy are in general a function of word frequency and so errors on the same words in both production tasks may simply reflect a common level of difficulty for the words in both lexicons. Two papers (Coltheart & Funnell, 1987; Behrmann & Bub, 1992) have been able to show that even after the effect of word frequency has been partialled out for two patients there is a high association between item accuracy in the two modalities (i.e., reading and spelling). Similarly, Bub & Arguin (1992) have shown in a patient with reading and spelling difficulties that there was an item specific correspondence in accuracy across tasks of spelling, naming and visual lexical decision as well as in RTs to the same words.

Campbell (1987), however, maintains that some poor spellers manifest deficits which are difficult to explain within a single lexicon model. She reports testing carried out on two university students with marked spelling problems. It was found that there were many words which the students consistently misspelled in the same way. In a test of visual lexical decision the students' performance was equivalent to normal spellers in recognizing when these words were correctly spelled but only at chance at detecting that their own misspellings were incorrect. As she points out, a reading lexicon will contain not only correct spellings but also the misspelled versions of words particularly if they are repeatedly spelled in the same way. If there were only one lexicon, however, poor spellers would not consistently select the misspelled entry for writing. She compares this to the fact (Campbell & Coltheart, 1984) that, although normal readers have no trouble reading *Gandhi*, they consistently misspell it *Ghandi*. Inconsistencies in response to spelling and reading tasks need not be explained by two lexicons, however, if orthographic knowledge is represented by a distributed pattern of activation. Spelling to dictation, and reading each access orthography by different modalities (i.e., hearing and vision) and, while the same word will most frequently activate similar patterns irrespective of the modality of access, it is possible that different modalities of access produce slightly different patterns of activation and produce different responses.

In this thesis, in order to evaluate the activation of (reading) orthography the task of visual lexical decision has been used. This task has consistently been interpreted in both normal and impaired readers and spellers as involving either a single orthographic lexicon or the input lexicon of reading and never the output lexicon for spelling. For present purposes, then, it is not really necessary to take a position as to the issue of whether reading and writing activate the same orthographic representations.

Is Phonology Modality Specific?

In this research auditory priming is used to make inferences about the effect of phonology on orthography in reading. A question which will become central in the final analysis is: do hearing a word and producing a word in response to a printed stimulus activate the same phonological store? Or, are there two phonological lexicons: one involved in the reception of auditory words, the other in speech production and presumably in deriving a phonological representation of visual words?

Gipson (1986) examined what kind of pretask would prime subjects for recognizing auditory words in artificial noise. Subjects were presented with words in one of three modes and asked to **not** say the word aloud but to tell how many syllables the word had. The three modes of presentation were: heard as it was read by the experimenter, printed on paper or illustrated on a card. Subjects were only facilitated by the heard word condition. In a second experiment, hearing words and reading aloud pseudohomophones but not words, facilitated auditory recognition 10 minutes later. This priming effect which varies according to whether words were previously heard words or self-generated (silently, or aloud) is quite surprising and points in the direction of two phonological lexicons: one for reception and one for production. Notwithstanding these results, Gipson (1986) proposes that a single store connectionist model may be able to explain all findings. He anticipates, as was suggested for input and output orthographic lexicons, that in an interactive model with distributed representations, different traces of activation will be produced by different modalitites on the same units of representations.

Allport and Funnell (1981) argue also that cross-modal priming experiments which fail to show a transfer between reception tasks and production tasks do not neccessitate separate input and output phonology lexicons. Rather than considering priming to be a process which produces a long time change in the word-units, they hold that it is the pathway of access to the logogen which is facilitated (or not) in these experiments. They maintain that in a similar manner dissociations in patients need not be interpreted as differential breakdown in input and output lexicons but as impairments in the access or output paths to a unique phonological store.

Ellis and Young (1988), on the other hand, have advocated two phonological stores: an input lexicon which would correspond here to the store auditory priming activates, and an auditory output lexicon which receives input from both the visual lexicon (orthography) and the auditory input lexicon. This framework (see Figure 1, page 23) is used to explain the dissociation in which patients can demonstrate good auditory comprehension and yet poor repetition of auditory words. They also cite the case of a deep dysphasic who could not repeat simple nonwords and made numerous semantic errors in word repetition, such as saying daffodil for crocus. The subject, however, did not make similar errors in reading aloud. These deficits suggest that there is both an input and output lexicon for phonology and that in the case of this dysphasic subject, an auditory input could only access phonological output by semantic mediation whereas the visual input of a printed word could access the phonological output lexicon directly.

Another indicator of separate input and output phonological lexicons comes from experimental cognitive psychology. Shallice, McCleod & Lewis (1984) report that in a dual task experiment there was only a slight decrement in accuracy from single to dual task performance when subjects were asked to simultaneously monitor an auditory input for a girl's name and read aloud. There was, however, a tremendous decrement when subjects were asked to monitor for two-syllable words and read, or, shadow and detect a name. These experiments suggest that hearing a word for understanding and producing a phonological form for a word rely on different resources (i.e., lexicons).

Shallice et al. (1984) carefully monitor for factors which might indicate that, contrary to the separate lexicons hypothesis, the subjects' good dual task performance was achieved by switching between tasks, or, using a hypothetical common resource.

The sum of this review of the literature concerning one or two lexicons for phonology is that there are reasons to keep an open mind as to the equivalence of heard phonology and reading-generated phonology. The issue is unresolved and, as will be seen, the results of this thesis add to the complexity of the evidence for and against two lexicons.

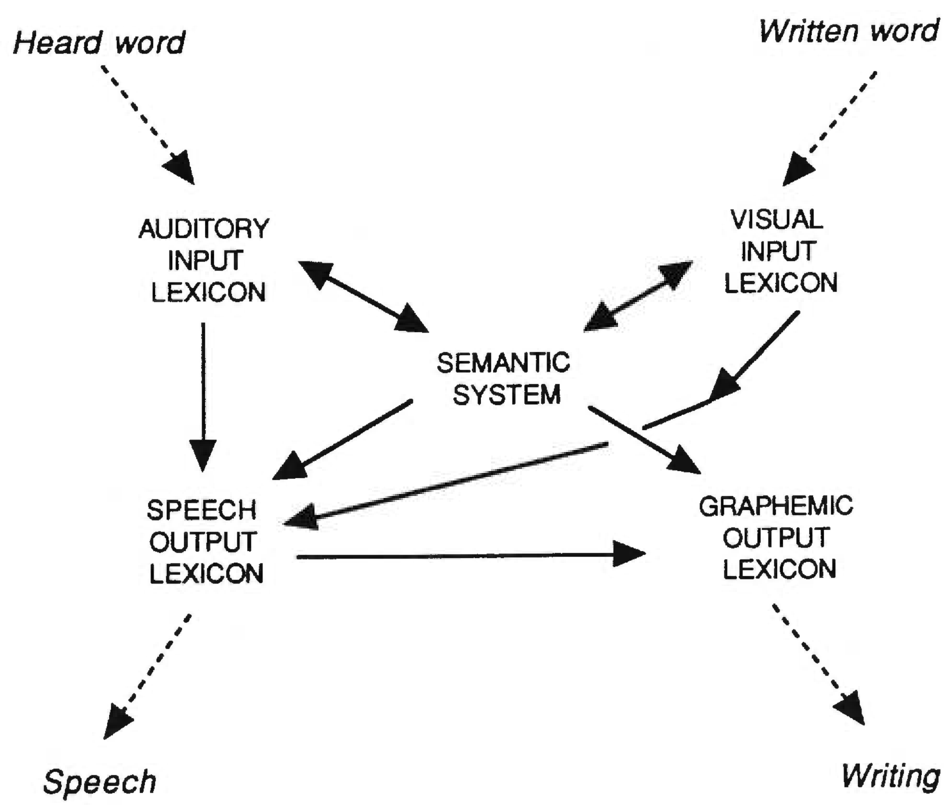

Figure 1. Central elements of Ellis and Young's composite model (1988) for spoken and written language.

AN OVERVIEW OF THE MOTIVATION AND RESULTS OF THE EXPERIMENTS

The motivation of both experiments of the first article was to see whether auditory phonology in the form of a simultaneous auditory prime could rapidly access orthographic representations and facilitate the visual recognition of words. The experiments used essentially the same format to tests three surface dyslexics of very different etiologies (IH, JF & EL, Experiment 1) and a group of normal readers (Experiment 2). On each trial the subject was presented with two orthographic stimuli, a word and a nonword, and was asked to indicate which of the two was the word. On critical trials (which made up 2/3 of trials in Experiment 1 and all trials in Experiment 2) the nonword was a pseudohomophone of the word (word = brain/ nonword = brane). The main results of the experiment are that, while the three dyslexics are facilitated by auditory priming, normal readers are not. The facilitation that the dyslexics experience indicates that auditory phonology can access orthographic representations. There is a strong positive correlation between the dyslexics RT without priming and the size of the auditory priming effect, suggesting that the lack of a priming effect in normal readers may be due to their very rapid access to orthography.

The second article examines two questions relating to the auditory priming effect in surface dyslexics. First, it looks at whether the effect of the auditory prime is due simply to some alerting effect which is unrelated to the linguistic match between the prime and the target. Secondly, it looks at whether sublexical congruencies between the prime and the target can also influence RTs in one direction or the other. The results show that the priming effect is due to the linguistic overlap between the prime and the target. Whole word congruency appears to be essential to the facilitatory effect for both subjects tested (IH and JF). There is a hint from one subject (JF) that sublexical congruencies between the prime and the nonword can produce an inhibitory effect. The article concludes that the neccessity of whole word congruency between the prime and the target may indicate either that phonology directly activates orthography by word-to-word activation (i.e., that lexical and not sublexical representations are involved) or alternatively that phonology activates orthography by semantic mediation.

The third article examines the question of semantic mediation more closely. The first experiment shows that both subjects IH and JF can be facilitated by an auditory prime which is a semantic associate of the visual target (e.g., auditory prime = blue, visual stimuli = sky, skie). This indicates that auditory phonology can activate orthography by semantic mediation in these patients. In the second experiment the semantic component in auditory priming is examined by comparing the effect of auditory priming for function words which have weak semantic representations (auditory prime = EACH, visual stimuli = each/eech) and for nouns which have strong semantic representations (auditory prime = TABLE, visual stimuli = table/tabul). It is found that while both types of words can be facilitated by auditory priming, they appear to be calling on different processes. Together the results of both experiments strongly suggest that, while phonology can activate orthography by semantic mediation, direct phonology -to-orthography activation can also take place.

In the last chapter an experiment carried out with normal readers examines the time course of phonology to orthography activation by varying the prime-to-target onset asynchrony (SOA). It is found that relative to a neutral beep, subjects are faster to respond when the prime and the target are the same word at an SOA of 950 ms and 225 ms but not at 0 ms. An auditory prime which is an orthographic neighbour of the target stimulus (auditory = TONE, visual = bone/boan) produces an inhibitory effect at an SOA of 225 ms and 0 ms. A prime which is unrelated to the target (auditory = LEFT, visual = bone/boan) produces an inhibitory effect at an SOA of 0 ms. The results are taken as further evidence that phonology can activate orthographic representations and that this activation can be automatic and not subject to strategies. As with the dyslexic subjects the results indicate that facilitation is dependent on lexical (i.e. whole word) activation between the domains. A principle of lateral inhibition within orthographic space is proposed to explain the complex pattern of facilitatory and inhibitory effects observed.

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Chapter Two

Article #1: Cross-Modal Priming Evidence for Phonology-to-Orthography Activation in Visual Word Recognition

Article #2: Visual Word Recognition Facilitated by Auditory Priming in Surface Dyslexia

Article #3: Evidence of Unmediated Cross-Modal Activation

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

Christine Whatmough[1], Martin Arguin[1], Daniel Bub[2]

(In press)

Brain and Language

1- Groupe de recherche en neuropsychologie expérimentale, Département de psychologie, Université de Montréal, et Centre de recherche de l'Institut Universitaire de Gériatrie de Montréal, Canada

2-Department of Psychology, University of Victoria, Canada

ABSTRACT

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.

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 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 & Van Orden (1997) who found that words which had pronunciation bodies with more than one possible spelling (e.g., heap, deep) were slower to identify as words 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 & Smith (1974) and more recently McKone & 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 the nonwords result 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 digitised recording of the word whose onset was almost simultaneous (visual-to-auditory SOA= 16ms) 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 characterised 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 "regularisation" 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 regularisation 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 EVALUATION 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 haematoma. He presented with a right-homonymous hemianopia, anomia, and reading and spelling difficulties. IH has been previously described in Bowers, Arguin & 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 regularisations 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. 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 regularisations (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 abandonned 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 regularisations 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 digitised 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 orthographic 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 and 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 seen first 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 previuos test 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 lower-case 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 digitised 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 (page 61). IH made significantly less errors on the control trials (seek/heek; error rate: 5%) than on critical trials (goes/goze; error rate: 19%) [χ^2 = 19.64, $p < 0.001$]. On critical trials (word/pseudohomophne pairs) he made significantly more errors with irregular words than with regular words [χ^2 = 6.23 $p < 0.05$]. Presentation of the auditory input had no significant effect on error rates globally [χ^2 = .74, n.s.] but it did reduce his error rates on control trials [χ^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 analysed 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 (page 63). 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.

Figure 2 (page 64) 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 (page 61). 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 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 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 non-homophonic 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 (page 65). 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 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 (page 62). 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 (page 66). 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 × 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 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 Exp. 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. Similarily, 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.

Method

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 ththe 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 Expt.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 (page 67). 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 ($p < .05$) 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 (Exp. 1), the results argue in favour 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 digitised 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 digitised 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.

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 (page 62) 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. regularisations 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. facilitory 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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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.

With audio, regular (11%) vs irregular (26%): $\chi^2 = 7.46, p < .01$

Control (5%) vs critical (19%): $\chi^2 = 19.64, p < 0.001$

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.

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

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.

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

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

NOR: Normal readers

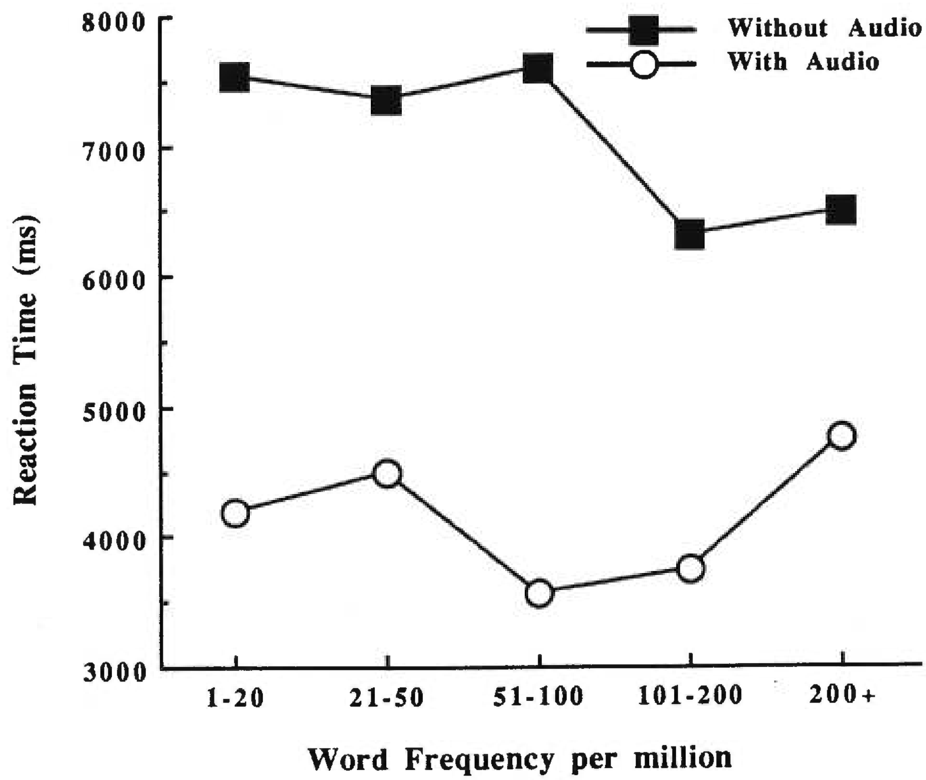

Figure 1. IH's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

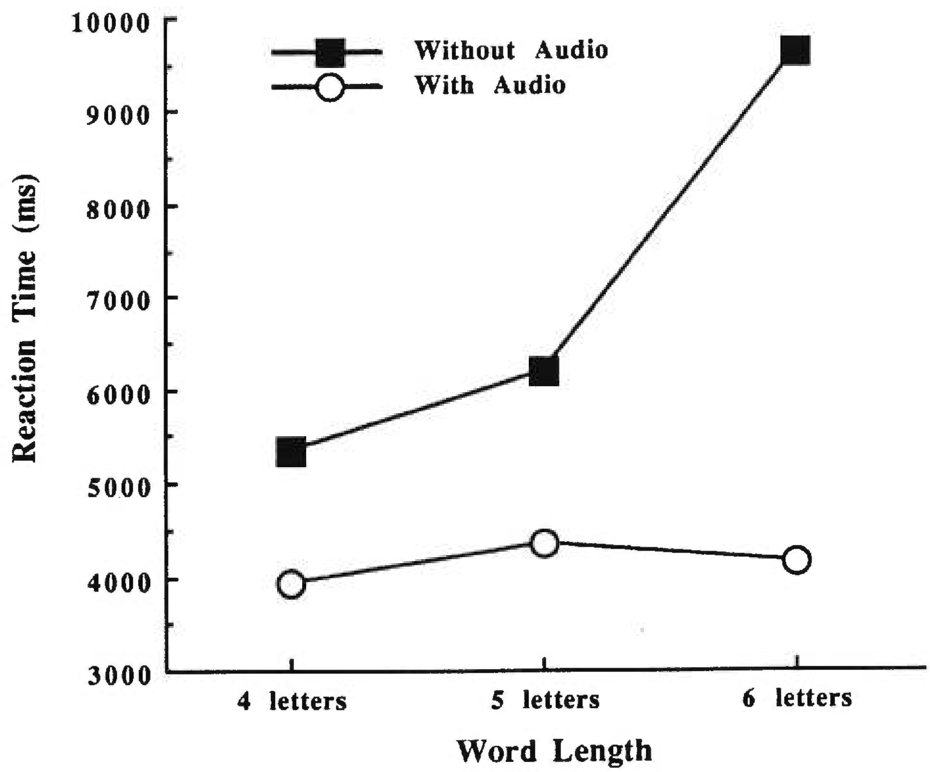

Figure 2. IH's mean latency in the visual lexical decision task with and without auditory input as a function of word length.

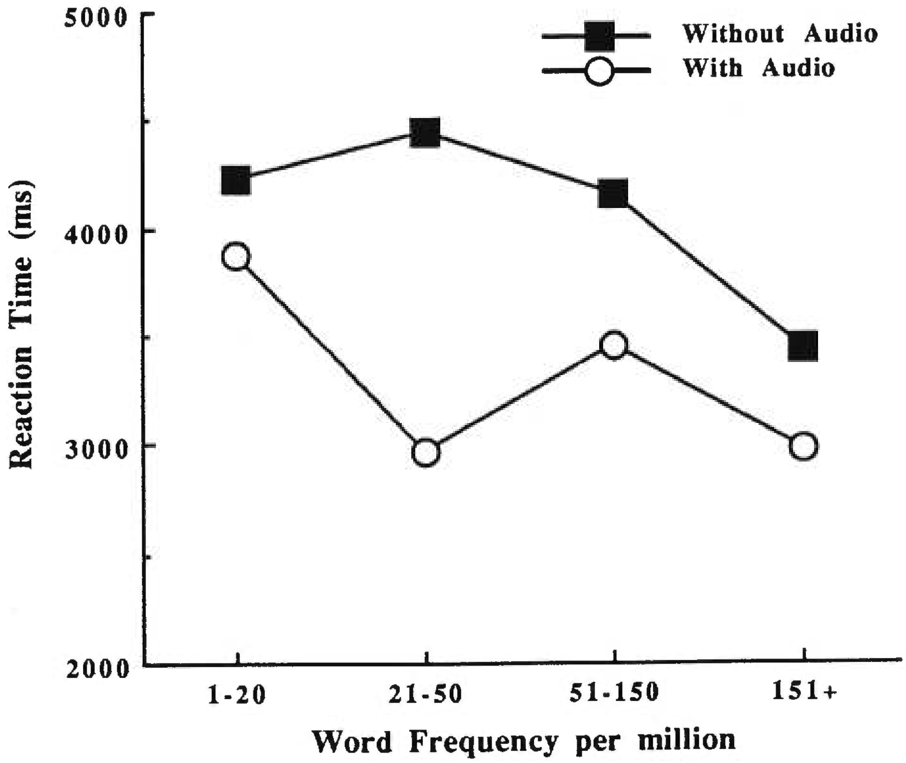

Figure 3. JF's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

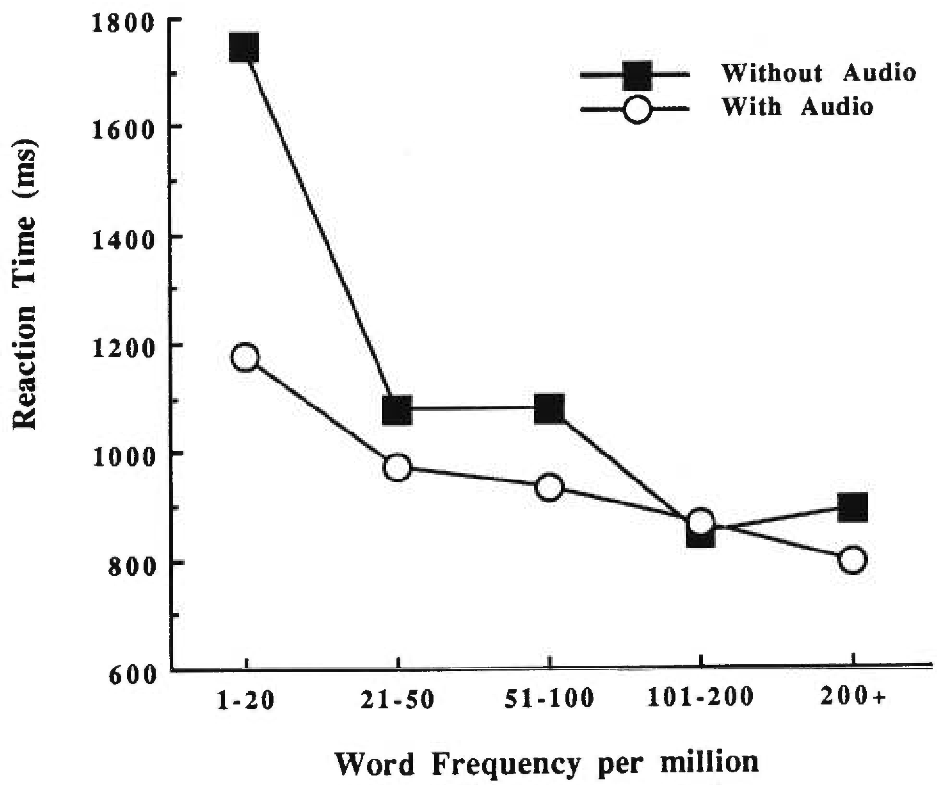

Figure 4. EL's mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

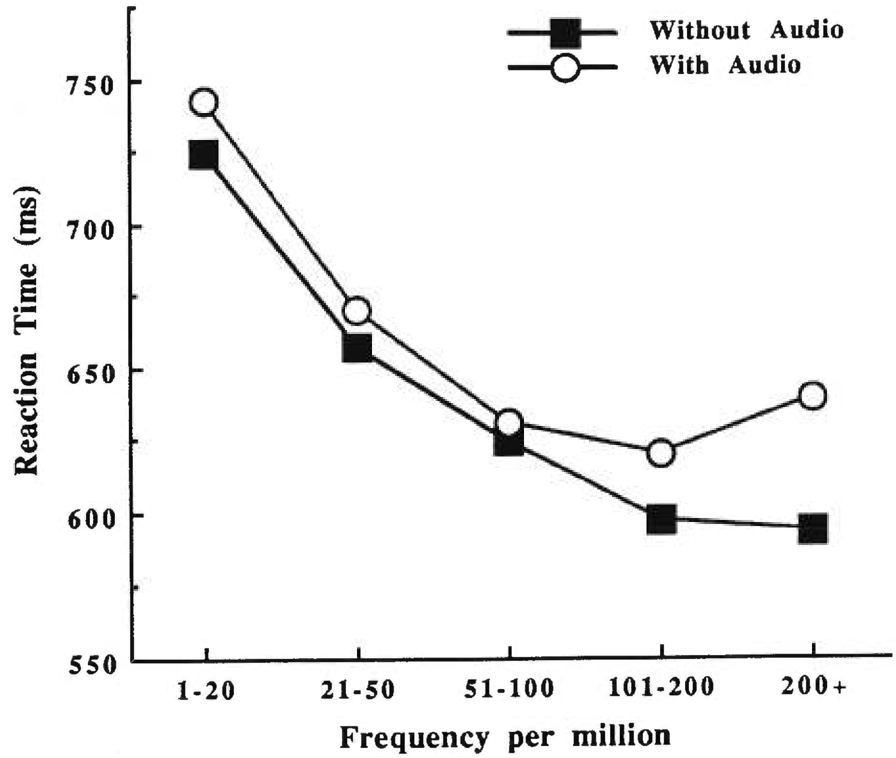

Figure 5. Normal readers' mean latency in the visual lexical decision task with and without auditory input as a function of target frequency.

Visual word recognition facilitated by auditory priming in surface dyslexia

Whatmough, Christine

Arguin, Martin

(Submitted to Neurocase, July 1998)

Groupe de Recherche en Neuropsychologie Expérimentale, Département de psychologie, Université de Montréal & Centre de recherche, Institut Universitaire de Gériatrie de Montréal, Montreal, Canada.

ABSTRACT

We show that two slow responding surface dyslexics are facilitated by simultaneous auditory word priming in a task of visual lexical decision and that the priming effect is more than a general alerting effect. The unit size of information associated between the phonological and the orthographic domains is also examined. The subjects, one English-speaking and one French-speaking made forced choice decisions between a word and a nonword homophonic to it (e.g., tone/toan). In Experiment 1, same-word priming condition (e.g., auditory = TONE, visual = tone/toan) was compared with a nonword congruent (foil prime) condition (e.g., MOAN: tone/toan) and a neutral prime condition (<beep>: tone/toan). Both subjects were facilitated by same-word priming but only one was sensitive to the foil prime. In Experiment 2, an auditory prime word which was congruent with the target word (e.g., BONE: tone/toan) failed to affect visual lexical decision performance. These results suggest that phonology can activate specific lexical-orthographic representations. The facilitatory effect of this activation is contingent on complete congruency between the prime and the target. Indications as to the locus of functional impairment in these subjects are discussed.

INTRODUCTION

Three domains of representation interact in normal reading: orthography, especially linked to the perceptual process, phonology and semantics. A major conceptual difference exists among reading researchers with regards to the importance attributed to interactivity among domains for the resolution of orthographic representations. According to some, phonological activation and feedback to orthography are an integral part of visual word recognition (Seidenberg and McClelland, 1989; Coltheart *et al.*, 1991; Plaut *et al.*, 1996). For others, the orthographic lexicon for reading cannot be directly accessed by phonology (Ellis and Young, 1988; Monsell, 1985) rather, interactions between those representation domains are feedforward only; from the orthographic lexicon to phonology.

Whatmough *et al.* (in press) examined the issue of interactions between phonology and orthography by assessing whether auditory phonology can activate lexical orthographic representations and aid visual word recognition. The task used was one of visual lexical decision, a task frequently used to index variables which affect visual word recognition. The possibility that phonology can participate in this process was examined by evaluating the effect of same-word auditory priming on visual lexical decision.

Previous to the Whatmough *et al.* (in press) experiments, Kirsner and Smith (1974) used auditory priming in conjunction with visual lexical decision and demonstrated that it facilitates performance. Their results, however, cannot be interpreted as providing unequivocal evidence that phonology can activate orthography.

The reason for this is that, in this study, all pseudowords had a nonword phonology (e.g., hine), and it was possible for subjects to carry out the visual lexical decision task exclusively on the basis of the phonology of the visual stimuli. That is, the subjects could perform the task by deciding, either implicitly or explicitly, whether the pronunciation of the visual stimulus sounded like a known word. Auditory priming, in that case, may have facilitated the phonological rather than the orthographic processing of the target words. In order to constrain an interpretation of auditory priming effects in terms of a facilitation of orthographic, not phonological processing, Whatmough *et al.* (in press) tailored the task to discourage phonological recoding. On each trial two visual stimuli, a word and a nonword, were presented and the subject's task was to indicate which was the word. On critical trials, (which made up two-thirds of trials for dyslexics and all trials for normals), the nonword was homophonic with the word (e.g., note, noat). Since the pseudohomophones had the same phonology as the target words, lexical decisions had to be based on the orthography of the stimuli.

Whatmough *et al.* (in press) tested both surface dylsexics and normal readers in these experiments. The interest in testing surface dyslexics stems from their seeming over-reliance on phonology for the recognition of printed words. The defining characteristic of surface dyslexia is a disproportionate difficulty in reading words which have irregular grapheme-phoneme correspondences such as the *ea* in *bear* . The most frequent response of surface dyslexics to these exception words is a regularised rendition of the word. For example the word *bear* is read to conform to the more common grapheme-phoneme correspondance of *ea* and is pronounced beer. Typically, surface dyslexics also derive the meaning of printed words from their pronunciation of them so that a printed word such as bear would be understood to be a reference to the beverage (see Howard and Franklin, 1987, however, for an interesting exception to this).

Whatmough *et al.* (in press) contrasted the subjects' response to blocks of unprimed (silent) trials with their response to blocks of primed trials in which each pair of visual stimuli was simultaneously accompanied by an auditory prime. On each trial the auditory prime was the same word as the visual target (e.g., auditory = NOTE: visual = note/noat). It was found that while dyslexic subjects were greatly facilitated by auditory priming, normal readers, whose overall RTs were strongly marked by word frequency, displayed an inhibitory effect (45ms) which was specific to words from the highest frequency range. Examination of the relation between the size of the priming effect and reaction times (RTs) on unprimed blocks revealed that there was a linear correlation (r (4) = +.96, P < .001) which was continous across dyslexic and normal readers. Thus, the slowest responding dyslexic, IH, was facilitated the most by the auditory prime (facilitation of 2700ms relative to unprimed trials), and the fastest responding dyslexic, EL, was facilitated the least (facilitation of 571ms). Normal readers showed no auditory priming effect to low frequency words—words to which they responded the most slowly in the unprimed condition— and an inhibitory effect to high frequency words —words to which they responded the most quickly without the auditory prime.

Whatmough *et al.* (in press) contend that the results from both types of readers indicate that phonology can activate orthography, either through direct phonology-to-orthography mapping or, alternatively, through a semantically mediated interaction between phonology and orthography. In the latter case, the proposition would be that the auditory prime activates a semantic representation which in turn activates the corresponding orthographic representation. The direction of the effect of an auditory prime (facilitatory or inhibitory) could be explained by the relative speeds with which vision and hearing can activate orthography for any individual reader. Very slow responders (e.g., with RTs above 1 sec.) such as dyslexics visually activate correct orthographic representations very slowly, such that the auditory prime has time to intervene and facilitate the process. Because normal readers, on the other hand, activate orthographic representations from a visual input very quickly, they do not benefit from simultaneous auditory priming. The inhibitory effect on the recognition of high frequency words may indicate that the initial activation effected by audition is weak and diffused over close neighbours, whose activation would interfere with the processing of the target.

A potential problem, however, in this interpretation of these past findings results from the fact that in these experiments there was no auditory stimulation at all in the blocks of unprimed trials. It could be that for the dyslexic subjects the auditory prime served as a form of warning for the incoming trial which was unavailable in the unprimed blocks. According to this view, the priming effects observed in the experiments would be explained by a general alerting (Bertelson, 1967; Posner and Boies, 1971) caused by the prime rather than by its linguistic value, which would in fact be irrelevant to the priming effect. One reason why this alternative account appears unlikely, however, is that auditory priming also interacted in interesting ways with other linguistic factors such as word frequency, grapheme-phoneme regularity and word length. For instance, the subject IH, a letter-by-letter reader displayed his usual word length effect without priming but he showed no word length effect with auditory priming. For the subject EL, a developmental surface dyslexic, auditory primes facilitated the visual lexical decisions for regular words but not irregular words. The interaction between such factors and priming would be difficult to include in a non-linguistic, attentional explanation of the priming effect. In order to provide a clearer decision as to the correct interpretation of the auditory priming effects observed in the past experiments, an auditory input was presented on every trial in the current set of experiments. This auditory input was either a word or a neutral beep, and trial type was randomly distributed within blocks. In this way, same-word auditory priming can be compared with other types of auditory inputs while equating priming conditions on their alerting effects.

A second goal of the present research is to examine the issue of the unit size of representation which phonology activates in orthography. According to dual route models of reading (e.g., Besner and Smith, 1992; Coltheart *et al.*, 1991), words are represented holistically as lexical units in both the orthographic and phonological domains. Connections between the lexicons are bidirectional and one-to-one (word-to-word). In contrast, connectionist models (Seidenberg *et al.*, 1989; Plaut *et al.*, 1996) have no whole word units and so only embody associations between phonology and orthography at a sublexical (e.g., grapheme to phoneme) level. Still other models (e.g., Stone *et al.*, 1997) propose that multiple unit size associations take place simultaneously.

In the present experiments we addressed the issue of the unit size involved in mappings between phonology and orthography by using auditory primes which were only partially congruent with the visual stimuli. By partially congruent we mean that the orthography of the auditory prime shared some but not all letters of the visual target or foil. The assumption underlying the use of this condition is that if phonology-to-orthography activation takes place at a sublexical level, then partial orthographic (i.e., graphemic level) overlap between auditory words and visual word targets or nonword foils should affect RTs of dyslexics in the task of auditorily primed visual lexical decision. If, there is no priming effect either facilitatory or inhibitory then cross-modal interactions are not based on sublexical activation. As in our previous experiments, the task took the form of a forced choice between a word and a pseudohomophone of the word. In Experiment 1 of this research, we sought to induce an inhibitory priming effect with an auditory prime whose orthographic representation was congruent with the nonword foil (e.g., auditory = CLAIM, visual = frame/fraim). In the second experiment, the auditory prime was partially congruent with the target word (e.g., auditory = TONE, visual = bone/bown), which, if the auditory priming involves sublexical activation of orthographic representations, had the potential of inducing a facilitatory effect.

EXPERIMENT 1

Experiment 1 had two separate goals. First it was designed to replicate previous findings (Whatmough *et al.*, in press) which showed that slow responding surface dyslexics are facilitated by auditory priming in visual lexical decision, and to establish that this facilitation is more than the result of auditory alerting and is due to the lexical match between the auditory prime and the target word. Secondly, the experiment was designed to examine whether the phonological representations map onto lexical or sublexical units within orthography by including an auditory foil prime condition in which the auditory stimulus was partially congruent with the foil pseudohomophone. In order to achieve these goals within a block of trials three types of auditory prime-visual stimuli ensembles were presented in random order: the visual stimuli could be accompanied by either a beep (neutral prime), a digitised recording of the target word (same-word prime: e.g., auditory = FRAME, visual = frame/fraim) or a digitised recording of a word which contained elements only present in the pseudohomophone (foil prime: auditory = CLAIM, visual = frame/fraim). It is predicted that, first, RTs will be shorter when there is a same-word prime than when there is either a neutral beep or a foil prime. This would replicate the findings of our previous experiments and assure that the facilitation was linked to the linguistic match between the prime and the target. Secondly it is proposed that, if the orthographic activation by phonology is sublexical, then the foil prime should favour the activation of the nonword. This should be evidenced by either longer RTs and/or increased error rates on foil prime trials than on beep trials.

Method

Subject IH. The subject, IH, is a right-handed English-speaking male with a college degree. When he was 45 years old (12 years prior to the experiments reported here), he suffered a subarachnoid haemorrhage which was drained surgically. The neurological report indicates that he suffered a left temporo-occipital haematoma. Since the cerebral vascular accident (CVA), he suffers from a right hemianopia, anomia, and reading and spelling difficulties which are described in more detail below. A WAIS (completed post-CVA) indicated an IQ in the low normal range (90) with no asymmetry between the verbal (89) and performance (92) scales. IH was a subject of our previous cross-modal priming experiment (Whatmough *et al.*, in press) and has been described in the paper reporting it, as well as in Bowers*et al.* (1996).

IH's reading deficits conform to the pattern of letter-by-letter surface dyslexia (Friedman and Hadley, 1992). His mean latency in reading four-letter words is 1625ms and he displays a pronounced linear word length effect of approximately 500ms for each additional letter. His error rate in visual word naming is 60 % for exception words and 16% for regular words. Errors on exception words are regularisations 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 conforms to descriptions of surface dysgraphia, in which spellings, though mainly incorrect, are plausible at a sublexical level. For example, he spelled *DIRT* *d-u-r-t* and *hazy* *h-a-z-e*.

Subject JF. JF is a right-handed French-speaking female with six years of formal education. At the time of testing she was 73 years old and was living independently. JF was a subject of our previous cross-modal priming experiment (Whatmough *et al.*, in press) and is also described in that paper. JF had been experiencing speech problems for one or two years and a diagnostic of primary progressive aphasia had been suggested. 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.

Her speech disorder consisted predominately of speech apraxia and speech hesitancy. She had trouble planning any verbal output, was unable to repeat words, and had marked word finding difficulty. Comprehension appeared normal and she had no difficulty with visual spatial function or visual memory and no obvious frontal lobe dysfunction. One year after her first admission for evaluation, the neurological report indicates that her condition appeared stable.

Testing of JF's single word reading displayed a profile of surface dyslexia. On words with a frequency of 25 or more per million (Content *et al.*, 1990) she made no error on regular words but had an error rate of 23% for exception words. For low frequency words (1-10 per million, Content *et al.*, 1990) her error rate increased to 13% for regular words and to 43% for exception words. Her errors consisted mostly of regularisations (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>). Her mean latency in single word reading was 746ms for high frequency words (> 50 per million, Content *et al.*, 1990) and 820ms for low freqency words (1-10 per million, Content *et al.*, 1990). The RT difference in naming high and low frequency words was not significant (t (55) = 1.1, *n.s.*). In a task of visual lexical decision she incorrectly rejected 8% of high frequency words and 28% of low frequency words, and incorrectly accepted 26% of nonwords. The difference in error rates for high and low frequency words in this task was not significant ($\chi^2(1)$ = 3.4). Despite her reading problems, at the time of testing, she still enjoyed reading novels.

JF was able to correctly write to dictation eight out of twenty common words. On the twelve other words the patient could not begin to write them or abondonned writing them after she had made a mistake on the second or third letter.

English Stimuli (for IH). The visual stimuli consisted of fifty word/nonword pairs. Words ranged from three to seven letters in length with a mean of 4.9 letters. The mean word frequency was 81 per million (Francis and Kucera, 1982). The nonword of each pair was a pseudohomophone of the target word (e.g., claim/clame). Digitised recordings were made of each target word (same-word prime) and of another word (foil prime) which had a sublexical orthographic unit which was present in the nonword and distinguished it from the target word. For example, the same-word prime CLAIM and the foil prime FRAME were recorded to be coupled to the visual stimuli claim/clame. The mean orthographic frequency of the auditory foil words was 85 per milllion (Francis and Kucera, 1982) which is about the same mean frequency as the visual words. Thirty-four of the 50 foil words had the same orthographic ending as the nonword (e.g., auditory = CIRCLE, visual = local/locle), and 16 had the same orthographic onset as the nonword (e.g., auditory = JERSEY, visual = journal/jernal).

A 1000 Hz beep which lasted 600ms was also digitised to serve as an neutral auditory prime.

French Stimuli (for JF). The visual stimuli consisted of fifty word/nonword pairs. The mean word frequency was 177 per million (Content *et al.*, 1990). The nonword of each pair was a pseudohomophone of the target word (e.g., six/sice). As for the English stimuli, digitised recordings were made of the target word (same-word prime) and of a word congruent to the nonword (foil prime) to be coupled with each word/nonword pair. An example of a same-word prime and a foil prime for the French stimulus pair six/sice are respectively: SIX and VICE. The mean orthographic frequency of the auditory foil prime words was 111 per milllion (Content *et al.*, 1990). Thirty-two of the 50 foil prime words had the same orthographic ending as the nonword (e.g., auditory = VICE, visual = six/sice), 12 had the same orthographic onset as the nonword (e.g., auditory = ANGLAIS, visual = encore/ancore) and eight had other orthographic elements which were unique to the nonword (e.g., auditory = PAGE, visual = jeu/geu). A 1000 Hz beep which lasted 600ms was also digitised to serve as an auditory input on neutral trials.

Procedure. Each pair of visual stimuli was presented in random order once in each of three blocks, coupled in each block to a different auditory input: the beep, the foil word or the target word. Within each block, one third of the trials were primed by the beep, one third by the foil word, and one third by the target word. The order of auditory prime condition was randomized within blocks.

The subjects were tested on only one block in any weekly session. IH completed the English set of three blocks twice and JF completed the French set once.

The visual stimuli appeared in lower case Geneva 24-point print on a 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 centre of the screen for 1020ms. Its offset was followed 595ms later by a word/nonword pair displayed 2 cm above and 2 cm below the fixation location. The position of the word was randomly assigned. The auditory input was initiated 16ms after the visual stimuli appeared. The visual stimuli remained on the screen until the subject responded. The experimenter initiated the next trial when the subject was ready. The subject was asked to indicate which of the two stimuli was the word by pressing one of two keys designated to represent the "upper" or "lower" item. The program Psychlab (Bub and Gum, 1995) controlled stimuli exposure and recorded the subjects' response and reaction time.

Results

Subject IH. IH had a mean error rate of 26%; he made 27 errors on foil trials, 25 on neutral trials, and 27 on target trials. The difference in error rates among priming conditions was not significant ($\chi^2(2) < 1$, *n.s.*). His mean RT on error trials was 6306ms. There was no speed-accuracy trade-off, as the correlation between mean correct RT's and error rates across conditions, although negative, was not significant (r (1) = -.43, *n.s.*).

Correct RTs more than three standard deviations above or below the subject's mean per condition were removed (n = 21) from the analysis of correct RTs. The subject's mean correct RT was 4728ms on foil prime trials (e.g., auditory = CIRCLE, visual = local/locle), 4615ms on neutral trials (auditory beep, visual = local/locle) and

3508ms on target trials (e.g., auditory = LOCAL, visual = local/locle). Analysis of his lexical decision times with three levels of auditory priming condition (foil, neutral, same-word) revealed a significant priming effect ($F(2, 197) = 9.3$, $P < .001$). A post hoc analysis using Scheffe's method showed that RTs with the foil and the neutral trials did not differ from each other but that they both differed significantly from the same-word prime condition (foil $P < .001$, neutral $P < .01$). There was a facilitation on the same-word prime trials over the neutral trials of 1107ms and of 1220ms over the foil trials.

Subject JF. JF's overall error rate was 12%. She made 7 errors on foil trials, 6 on neutral trials, and 5 on same-word trials. The difference in error rates among priming conditions was not significant ($\chi^2(2) < 1$, *n.s.*). Her mean RT on error trials was 5169ms. There was no speed-accuracy trade-off, as the correlation between mean correct RTs and error rates across conditions was positive (r (1) = .99, *n.s.*).

Correct RTs more than three standard deviations above or below the subject's mean for each auditory condition were removed from the analysis of correct RTs (n = 5). Analysis of her lexical decision times with three levels of auditory condition (foil, neutral, same-word) revealed a significant effect of auditory priming ($F(2, 120) = 3.3$, $P < .05$). A post hoc analysis using Scheffe's method showed a significant RT difference between foil prime trials and same-word prime trials ($P < .05$) but no difference between foil and neutral trials or same-word and neutral trials. The subject's mean correct RTs for each condition were: 3187ms (foil), 2927ms (neutral), and 2520ms (same-word), a facilitation effect of 517ms for same-word trials over foil trials.

Discussion

Both subjects were facilitated by a simultaneous auditory prime which was the same word as the visual target. IH's mean RT was shorter on same-word trials than on both foil and neutral trials. JF's mean RT was shorter on same-word trials than on foil trials.

One of the goals of this experiment was to establish that the auditory priming effect displayed by the subjects in the Whatmough *et al.* (in press) experiment was indeed due to the fact that the subjects were benefiting from the match between the auditory and visual inputs and not just from a general attentional alerting factor produced by an auditory warning signal. Word frequency, word length and the grapheme-phoneme regularity of the stimuli are equivalent in both experiments for each subject, so any RT difference between the experiments cannot be attributed to these variables.

In the case of IH, an inter-experimental comparison indicates that he does in fact respond faster when the visual stimuli are accompanied by auditory stimulation than when they are not, and this irrespective of the nature fo the auditory prime, linguistic or otherwise. IH's mean RT to neutral (beep) trials in Experiment 1 is 4615ms. His mean RT to visual stimuli on blocks of unprimed (silent) trials in the Whatmough *et al.* (in press) experiment was 6871ms. This inter-experimental difference is highly significant ($F(1, 235) = 13.6, P < .001$). A relative priming effect was calculated for each experiment by subtracting the mean RT on same-word prime trials from the mean RT on unprimed trials and dividing the result by the mean RT on neutral trials. This calculation showed that the relative priming effect was 40% in the Whatmough *et al.* (in press) experiment but only 25% in Experiment 1. Undoubtedly, then, a portion of the large priming effect in the Whatmough *et al.* (in press) experiment can be attributed to general attentional (alerting) factors. Not all of the priming, however, can be attributed to increased attention when there is an auditory input. This is because, in Experiment 1, IH also responded faster when there was an auditory same-word prime than when there was the neutral beep. The effect, then, of a simultaneous same-word auditory prime on IH's RTs in visual lexical decision is the sum of an alerting effect and an effect attributable to the linguistic match between the prime and the target.

The fact that the auditory condition was blocked in one experiment but randomised in the other does not appear to have influenced IH's RTs to auditory priming. His mean RT was 4115ms on prime trials in the Whatmough *et al.* (in press) experiment and 3508ms on same-word prime trials in Experiment 1 where auditory condition was randomised, a 607ms difference which is not significant (F (1, 226) = 1.5, *n.s.*).

In the case of JF, a direct comparison between experiments is not possible because her method of responding was not the same in the two experiments. In the Whatmough *et al.* (in press) experiment she indicated her response by touching the appropriate stimulus on the computer monitor which was recorded in turn by a key press of the experimenter, whereas in Experiment 1 she used the keyboard directly to respond. Having said this, we note that her mean RT on unprimed (silent) trials was 4027ms in the Whatmough *et al.* (in press) experiment and 2927ms on neutral (beep) trials in Experiment 1. In the Whatmough *et al.* (in press) experiment the relative priming effect represents a facilitation of 18% over RTs on unprimed (silent) trials . In Experiment 1, the relative priming effect is 8% of neutral (beep) trials and is not significant. All the priming in the Whatmough *et al.* (in press) experiment, however, should not be attributed to an attentional factor because the patient did respond faster to auditory same-word prime condition than to auditory foil prime condition in

Experiment 1. This indicates that she is responsive to the linguistic match between auditory and visual inputs.

It can be concluded that the auditory priming effect exhibited by these subjects is the result not only of alerting produced by an auditory signal but also of linguistic priming. It therefore provides evidence that phonology can activate orthographic representations and that this activation can contribute to visual word recognition. In the report on the Whatmough *et al.* (in press) experiment, it was shown that there was a linear correlation ($r = .96$) between the size of the priming effect and RTs in the unprimed conditon for dyslexic and normal readers. This correlation of the effect size to mean RT in unprimed condition (either silent or beep) remains very high across experiments, $r\ (4) = .91$, $P < .02$ (subjects included are EL (at two levels of word frequency), IH and JF of the Whatmough *et al.* (in press) experiment, and IH and JF of Experiment 1 reported here). Thus, the slower a subject was in responding to visual words the greater he or she was facilitated by simultaneous auditory priming. This suggests that the auditory priming effect results from differences in the relative speeds with which audition and vision can activate orthography in an individual, and that the visual activation of orthography is abnormally slow for the dyslexics we have tested.

The second question of interest in this experiment was whether partial congruency between an auditory prime and a visual pseudohomophone would slow RTs or increase error rates in this forced choice task. If an auditory prime could bias responses toward the nonword foil, this might indicate that orthography is represented by sublexical units. Here the results are mixed. Neither IH nor JF were significantly slower on foil prime trials than on neutral trials. However, JF's RTs were significantly faster on same-word prime trials only when compared with foil trials. This may indicate that for JF the auditory priming effect is the sum of both a facilitatory influence of same-word primes and an inhibitory influence of foil primes relative to the neutral condition. Therefore, while there is no evidence that IH was influenced by a sublexical orthographic match between an auditory prime foil and a visual nonword when making lexical decisions, results suggest that such an influence may have occurred for JF.

EXPERIMENT 2

The previous experiment produced contradictory results with regards to the effect of partial congruency between auditory and visual stimuli. Sublexical congruency between the auditory prime and the visual foil did not have an inhibitory effect on the RTs of IH but may have had a such an impact on JF's performance. An alternative way to demonstrate that phonology can activate sublexical orthographic representations is to show that an auditory prime whose orthography is partially congruent with a target word can facilitate the visual recognition of the word. In this second experiment, we sought evidence of sublexical phonology-to-orthography mapping by using an auditory prime which was partially congruent to the target word (e.g., auditory = TONE, visual = bone/bown). If auditory priming is taking place at a sublexical level, then subjects should be faster to respond on trials which are primed than on unprimed trials.

Method

English Stimuli (for IH). The orthographic stimuli consisted of 62 word/nonword pairs. Words ranged from four to seven letters in length with a mean of 4.9. The nonword of each pair was homophonic to the word (e.g., bone/bown).

Digitised recordings were made of a word (word congruent prime) which had sublexical orthographic units present in the word only and not the nonword foil. For example, TONE was recorded to be coupled to bone/bown. The mean orthographic frequency was 75 per milllion (Francis and Kucera, 1982) for the target words and 147 per million for the auditory prime words. Thirty-two of the 62 prime words had the same orthographic ending as the target word (e.g., auditory = GREET, visual = sweet/swete), 30 had the same orthographic onset as the target word (e.g., auditory = FATE, visual = fame/faim). Only one pair of visual stimuli (talk/tock) had been used in the previous experiment. A 1000 Hz beep which lasted 600ms was also digitised for the neutral trials.

French Stimuli (for JF). The orthographic stimuli consisted of 50 word/nonword pairs. As with the English stimuli, the nonword of each pair was a pseudohomophone of the target word (e.g., serre/sère). Digitised recordings were made of a word (word congruent prime) which had sublexical orthographic units present only in the word. For example, TERRE was recorded to be coupled to serre/sère. The mean orthographic frequency of the auditory prime words as well as that of the visual target words was 180 per milllion (Content, et al, 1990). Twenty-five of the 50 prime words had the same orthographic ending as the target (e.g., COEUR, sœur/seur), 25 had the same orthographic onset as the target (e.g., laine/lenne LAITUE). A 1000 Hz beep which lasted 600ms was digitised for the neutral trials.

Procedure. Each pair of visual stimuli was presented in random order once in each of two blocks coupled to a different auditory input in each block: the neutral beep or the neighbour prime. Within each block, half of the pairs were accompanied with the beep (neutral condition) and half with the word congruent prime, with priming condition distributed randomly within blocks. The subjects completed the blocks one week apart.

Results

Subject IH. Two trials were not included in the data because the subject tripped the response key too quickly (RT < 100ms).

IH had a mean error rate of 28%; he made 14 errors on primed trials, and 19 on neutral (beep) trials. The difference in error rates between priming conditions was not significant ($\chi^2(1) = 1.0$, *n.s.*). His mean error RT was 9514ms. There was no speed-accuracy trade-off, as the correlation between mean correct RT's and error rates across conditions was positive.

In general, IH's overall correct RTs (Mean = 7326ms) in Experiment 2 were very long and in the range of that for the silent trials of the Whatmough *et al.* (in press) experiment. A possible explanation for his slow RTs may be that, because the primes in this experiment were very close to the target words, he used extra caution in responding on all trials.

RTs more than three standard deviations above or below the subject's mean for each condition (primed, neutral) were removed (n = 3) from the analysis of correct RTs. The subject's mean correct RTs were 7200ms on primed (word congruent) trials, and 7451ms on neutral (beep) trials. Analysis of his lexical decision times revealed no auditory prime effect ($F(1, 84) < 1$).

Subject JF. JF made 7 errors on primed trials (14%), and 3 on neutral (beep) trials (6%). The difference in error rates between priming conditions was not significant ($\chi^2(1) = 1.8$, *n.s.*). Her mean error RT was 6559ms. There was no speed-accuracy trade-off, as the correlation between mean correct RT's and error rates across conditions was positive.

RTs more than three standard deviations above or below the subject's mean for each condition (primed, neutral) were removed from the analysis of correct RTs (n = 7). An analysis of the subject's mean correct RTs revealed no auditory prime effect ($F(1, 81) = 1.0$, *n.s.*). JF's mean correct RTs on primed (word congruent) trials was 2878ms and 2684ms on neutral (beep) trials.

Discussion

In Experiment 2 auditory primes were words which were partially orthographically congruent with the visual targets and incongruent with the nonword foil. The partial orthographic congruency between the auditory prime and the visual target failed to produce a facilitatory effect in subjects IH and JF. This contrasts with the very large facilitatory effects which they demonstrated in previous experiments when there was complete congruency (i.e. the prime and the target were the same word). This suggests that the facilitatory priming effect of an auditory word is highly specific and that it involves the activation of whole word, lexical orthographic representations.

GENERAL DISCUSSION

In two experiments we examined the nature of phonology-to-orthography activation in two surface dyslexics. In Experiment 1 subjects IH and JF were facilitated in a task of visual lexical decision by simultaneously hearing the target word. For the slower responding subject, IH, the same-word priming effected faster RTs than both neutral and foil word priming, with no significant difference between his RTs to foil prime trials and beep trials. For JF the facilitation effect was significant when target word priming was compared with foil word priming, with RTs to beep trials falling halfway between the mean RTs on same-word and foil trials. The auditory priming effect is therefore shown to be more than the result of a nonspecific alerting effect produced by an auditory input such as a beep, and indicates that incident auditory phonology can activate orthographic representations. Although auditory foil primes which were partially congruent with the pseudohomophones failed to have an effect on the RTs of IH relative to the beep, it is possible that they had an inhibitory effect on those of JF. In Experiment 2 we pursued the possibility that the facilitation effect of same-word auditory priming was due to sublexical congruencies between the prime and the target by examining the effect of primes which are orthographic neighbours of the target. Neighbour primes produced no effect, either facilitatory or inhibitory relative to the beep and it must be concluded that complete prime-target congruency is necessary to produce the facilitatory effect.

If phonology appears to be activating lexical orthographic representations and not sublexical units, it may be that its effect is mediated by semantics rather than by a direct phonology-to-orthography connection. In their review of neuropsychological dissociations related to language, Ellis and Young (1988) could find no evidence that phonology directly activates orthography. In their model of reading, the only system that can access the visual input lexicon, other than the visual analysis system, is the semantic system. If, as their model suggests, the phonology-to-orthography route is mediated by semantics, sublexical congruencies between phonology and orthography would not be expected to affect RTs in our experiments. This could explain the current pattern of results and yet maintain the possibility of orthographic knowledge being maintained exclusively across sublexical units.

Consideration of IH and JF's performance in these experiments and in the Whatmough *et al.* (in press) experiment provides some insight into the nature of their reading difficulties. First it should be noted, as was in the Whatmough *et al.* (in press) experiment, that the subjects' accuracy does not improve with auditory priming. Thus, while the activation of orthographic representations by phonology can accelerate lexical access, it does not appear to have any restorative capacities for these subjects. Secondly, while auditory priming diminished the patients' RTs, it did not reduce them to normal levels (i.e. RTs of neurologically intact readers). In Experiment 2 of Whatmough *et al.* (in press) the mean RT of normal readers ranged from 594ms for high frequency words to 724ms for low frequency words. Thirdly, it appears that the reason the dyslexics, and not the normal readers, are facilitated by simultaneous auditory priming is that the dyslexics are abnormally slow without priming. This is indicated by the strong positive correlation between mean unprimed RTs and the magnitude of the priming effect. In the same task normal subjects show some priming, but it is only inhibitory and only for high frequency words (Whatmough *et al.*, in press). It follows from these observations that part of the dyslexics' problems stems from the visual mode of access, or activation, of orthographic representations. The visual access problem which is bypassed by auditory priming is of a higher level than a visual feature encoding problem, however. We argued this in the Whatmough *et al.* (in press) experiment for the reasons which follow. In that experiment there were control trials in which there was only a one-letter difference between the word and the nonword (e.g., seek/heek), whereas many of the critical word/pseudohomophone trials included several letter change differences (e.g., motion/moshun). This should have made the control trials more difficult on a perceptual level. Indeed, this expectation was borne out by the fact that JF was slower to respond on control trials than on critical trials. If auditory priming was facilitating the perceptual level of analysis, then, we might have expected greater facilitation on control trials than on critical trials. RTs to auditory priming, however, did not interact with trial type (i.e. control vs critical) for any of the subjects. That is, priming was just as large in each case. The subjects, then, appear to have problems in the visual access to printed words but this access problem is at a higher level than the perceptual level where physical letter features must be distinguished. Together these three points suggest that there has been some kind of degradation to representations within the orthographic lexicon which can be partially overcome by same-word auditory priming.

In summary we confirm previous findings that show that an auditory prime can facilitate slow reading dyslexics in visual word recognition. This indicates that phonological activation can be transmitted to orthography. Further, manipulations of the orthographic overlap between the auditory prime and the target word indicate that whole word concordance between the auditory prime and the visual target is essential to the priming effect in dyslexics. This latter finding would be predicted by two hypotheses which are not mutually exclusive. The first hypothesis is that orthographic word representations are coded as holistic lexical units, and the second is that the auditory priming effect is semantically mediated.

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Evidence of unmediated cross-modal activation

Christine Whatmough

Martin Arguin

(Submitted to Cognitive Neuropsychology, August 1998)

Groupe de Recherche en Neuropsychologie Expérimentale, Département de psychologie, Université de Montréal & Centre de recherche, Institut Universitaire de Gériatrie de Montréal, Montreal, Canada.

ABSTRACT

Studies have shown that the recognition of visual words can be primed by auditory words. This cross-modal priming effect has been assumed by some to take place by semantic mediation. In this study we tested for evidence that direct phonology-to-orthographic activation can also take place. In Experiment 1 two surface dyslexics JF and IH demonstrate some measure of facilitation to auditory semantic priming (e.g.,, auditory prime =BLUE and visual target = sky). The effect is not as consistent, however, as previous demonstrations of same-word auditory priming (e.g., auditory = NOTE, visual = note) in that each subject performed one block of trials in which there was no priming effect. In Experiment 2: Block 1, IH demonstrates greater facilitation from same-word auditory priming for nouns than for function words. This indicates that same-word auditory priming can be semantically mediated. In Block 2, performed one week later, the stimuli which were presented with auditory priming in Block 1 were presented without priming and vice versa. IHs mean RT is reduced in Block 2 and, this time, he manifests a same-word auditory priming effect for function words but not for nouns. The strong consistent effect of same-word auditory primes on function words (which have very little semantic content) suggests that cross-modal priming can take place by direct phonology -to-orthography activation.

INTRODUCTION

Normal reading involves three domains of representation: orthography, phonology and semantics. Views on the relative importance of interactions between the domains vary widely. Several researchers (Coltheart & Rastle, 1994; Lukatela & Turvey, 1994; Plaut, McClelland, Seidenberg, & Patterson, 1996; Stone, Vanhoy, & Van Orden, 1997) hold that the usual identification of a printed word (i.e., orthography) involves feedback from phonology. Some of these (Lukatela et al, 1994; Stone et al, 1997) also contend that access to semantics from print is not usually direct but is predominately a process which is mediated by phonology. One explanation for the relative importance of mediated access over direct orthography-to-semantics is that direct interactions between orthography and semantics do not have the advantage of covariation between domains which exists between graphemes (orthography) and phonemes (phonology) in languages such as English, rendering associations between orthography and semantics more arduous.

For others, in particular those who argue in favor of the assumption of whole word or lexical representations (Besner & Smith, 1992; Ellis & Young, 1988), direct interactions between orthography and semantics are important aspects of normal reading. For instance Besner et al. (1992) contend that visual lexical decision, a task which is commonly used to determine factors which influence visual word recognition, is a semantic task and performance in it reflects direct interactions between orthography and semantics. Similarly, in Ellis and Young's (1988) model of reading, although visual input is sufficient to activate orthographic representations, there are direct bidirectional links between orthography and semantics. Phonology, on the other hand, according to the Ellis and Young model, can only access orthography by semantic mediation.

Those who have used cross-modal priming (auditory prime/visual target or visual prime/auditory target) to investigate what might be the basis for interactions between the two modalities have generally agreed with Ellis and Young's model. They have assumed (Rugg, Doyle, & Melan, 1993) or concluded (Holcomb, & Anderson, 1993; Monsell, 1985) that hearing a word does not directly activate its orthographic representation. In those experiments where hearing a word subsequently facilitates its visual recognition, facilitation is said to take place because both auditory and visual words feedforward to phonology and/or semantic ("amodal") representations where the priming effect takes place. Indeed, this is a very plausible explanation of the effect because the nonwords used in these experiments have both the phonology and the orthography of nonwords (e.g., grusp) and it was possible for the subjects to base their visual lexical decisions on a phonological recoding of the visual stimuli. If that were the case, it is not necessary to attribute the facilitatory effect of auditory priming to its activation of orthography. Rather the auditory priming effect could be limited to an activation within phonology which does not carry forward to orthography.

In previous experiments we have shown (Whatmough, Arguin and Bub, in press; Whatmough & Arguin, 1998a; Whatmough & Arguin, 1998b), however, that cross-modal priming (auditory prime/visual target) can facilitate visual lexical decision even when all the nonwords are pseudohomophones (e.g., hedd) and subjects can not base their decisions on the phonology of the stimuli. These results suggest that phonology can activate orthographic representations and facilitate the identification of printed words. In these experiments we tested both surface dyslexics and normal readers in a task of visual lexical decision. Subjects were required to make a forced choice between a target word and a nonword homophonic to it, such as the stimulus pair *sweet, swete* . We found that both surface dyslexics and normal readers were faster in identifying the target word when they were primed with an auditory recording of the target word. Different prime/target stimulus onset asynchronies (SOAs) for each type of reader, however, were neccessary to obtain the facilitation effect. While surface dyslexics could be primed with a simultaneous prime/target presentation, it was necessary for auditory primes to be presented in advance of the visual stimuli in the case of normal readers (i.e., SOA of 225ms). The fact that normal readers required earlier auditory priming than the surface dyslexics indicate that the latter (i.e., the dyslexics) were facilitated by a simultaneous prime because they abnormally slow in visually activating orthographic representations.

The finding of facilitatory cross-modal priming in surface dyslexics was particularly remarkable. The defining characteristic of surface dyslexia is a seeming close adherence to grapheme-phoneme rules in both naming (i.e., reading out loud) and deriving meaning from printed words (Marshall, 1976, Coltheart, Masterson, Byng, Prior & Riddoch, 1983). Their apparent tendency to phonologically recode words at a sublexical level does not particularly hamper naming regular words or nonwords but frequently causes errors on words with irregular grapheme-phoneme correspondences. For example surface dyslexic will read a word such as *break* as /brik/ and not understand to what it refers. Secondly, they confuse the meanings of homophones so that a word such as *pair* can be understood to mean either a piece of fruit or a set of two. Surface dyslexics, then, seem to access semantics by phonological mediation and not benefit from lexical (whole word) associations between orthography and phonology (which would permit one to understand the word break) or orthography and semantics (which would permit the understanding of the word pair). A parcimonious explanation of both difficulties would suggest that the root of their problem is within the orthographic lexicon.

In previous studies, we found that activating the phonological representation of the stimuli by auditory priming facilitated slow reading dyslexics so that they could distinguish a word from a nonword homophonic to it (e.g., auditory prime = SWEET, visual stimuli = sweet, swete) more than 500ms faster than with unrelated primes. Varying the nature of the auditory prime so that it had a partial orthographic overlap with the target word (auditory = GREET, visual = sweet, swete) or with the foil (auditory = CODE, visual = toad, tode) failed to produce a priming effect, either facilitatory or inhibitory, relative to a neutral beep. These last results suggested that the facilitatory priming effect of same-word auditory primes was based on whole-word (i.e., lexical) correspondances between orthography and phonology rather than on sublexical units.

Alternative explanations for the lack of a priming effect when there was partial orthographic overlap between the prime and the target are possible, however. Either, as indicated above, phonology-to-orthography activation operates on lexical and not sublexical representations, or, the priming effect is semantically mediated. If the auditory priming effect is semantically mediated, that is, the activation produced by the auditory prime exclusively goes from phonology-to-semantics-to-orthography, then we would expect semantic factors and not sublexical phoneme-to-grapheme correspondences to be influential in the cross-modal priming effects for dyslexics. Therefore, the lack of a priming effect from auditory words with a partial orthographic overlap with the target need not imply that phonology-to-orthography mappings are based on lexical units.

In the experiments reported here we explore the possibility that same-word (also called repetition priming by others) auditory-to-visual cross-modal priming is semantically mediated. In the first experiment we show that two surface dyslexics, IH and JF, who had taken part in our first cross-modal priming experiments, can be facilitated by an auditory prime which is a semantic associate of the target word (e.g., auditory = BLUE, visual = sky, skie). Certain characteristics of the semantic priming effect, however, distinguish it from same-word auditory priming (e.g., auditory = GOES, visual = goes, goze) and suggest that semantic mediation may not be responsible for all of the same-word auditory priming effect. In the second experiment we examine the importance of semantics in same-word auditory priming by comparing the facilitation the subject IH exhibits for nouns (e.g., auditory = DOCTOR, visual = doctor, docter) and for function words (e.g., auditory = EACH, visual = each, eech), words thought to be respectively strong and weak in semantic strength (suggested by Coltheart in a note in Besner & Smith, 1992). This second experiment provides evidence that semantic mediation accounts for only a part of the cross-modal priming effect and that direct phonology-to-orthography activation also takes place.

CASE DESCRIPTIONS

IH: IH is a right-handed, English-speaking male who is a college graduate. He was 57 years old at the time of testing. Thirteen years previously he had suffered a stroke which left him with a right homonymous hemianopia, anomia and difficulties reading and writing. He was a subject in our previous cross-modal priming experiments (Whatmough, et al, in press; Whatmough & Arguin, 1998a) and has been described in those papers as well as in Bowers, Arguin and Bub (1996). His anomia was documented by administering the Boston Naming test on which he obtained a score of 6/60, despite providing clear indications that he did recognise the stimuli which he could not name.

In single word reading tests, IH manifests deficits of letter-by-letter surface dyslexia (Friedman & Hadley, 1992). His latency in reading single words ranges from 290ms to 9900ms with a pronounced word length effect. His RTs in naming words increases approximately 500ms with each additional letter in the word. His error rate in visual word naming is 60 % for exception words and 16% for regular words. Errors on exception words are regularisations 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>).

Comprehension of Printed Words

In order to assess IH's ability to access meaning from print, we presented him with a picture/homophone test. In this test, picture/word pairs were presented to the subject who was asked to indicate whether the picture illustrated the word. Thirty-six pictures were presented four times in all, twice the picture was paired with the appropriate word (e.g., picture = ANT, word = ant), once with a homophone (e.g., picture = ANT, word = aunt) and once with an unrelated word (e.g., picture = ANT, word = plug). Pairings were randomly ordered. IH rejected 6/72 correct pairings (8% error rate). IH also incorrectly accepted 24/36 picture/homophone pairings (67%) but only 3/36 unrelated pairings (8%). Chi square analysis revealed that IH made more mistakes on homophone pairings than on related pairings [χ^2 (1) = 26.1, $P < .001$]. A month later we presented the same 36 pictures and asked him to indicate which of two printed words, the target word or its homophone (e.g., picture = ANT, words = ant, aunt) was illustrated by the picture. In this forced choice task he made 7/36 errors (19%). Together these results indicate that IH usually derives meaning from single printed words by translating their graphemes into a phonological word. This causes him to make many errors on the meaning of homophones. However, if he is forced to use orthography as an indication of meaning, as was the case in the latter task, his accuracy improves.

JF: JF is a French-speaking right-handed woman with six years of education. She was 74 years old when she participated in this study, having been a subject in previous experiments using cross-modal priming (Whatmough et al, in press; Whatmough & Arguin, 1998a). She had been suffering from severe speech output problems for two years and had been diagnosed with progressive aphasia. In conversation she usually produced the first two or three words of her intended sentence after which she would continue no longer.

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 (Content, Mousty & Radeau, 1990) 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, Content et al, 1990) her error rate increased to 13% for regular words and to 43% for exception words. Her errors consisted mostly of regularisations (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 frequency range words and accepted 26% of nonwords.

Comprehension of Printed Words

At the time of testing the subject still read novels which suggests that she had maintained comprehension of printed matter when it was in context. We were able to assess to some measure her access to semantics from print first with a task of double lexical decision. In this task printed stimuli are presented in pairs of which half are word/word pairs, half are nonword/word pairs. The task of the subject was to indicate whether both of the stimuli were words. In this test none of the nonwords had the phonology of a French word. There were two sets of two blocks of 60 trials each. On half of the word/word trials the words were related by category, such as in gold/silver, and on the other half they were not, as in desk/cat. All the words were repeated in the second block of the set but were paired differently so that those which were categorically paired in the first block were not in the second (gold/juice) and vice versa (desk/chair). JF responded significantly [F (1, 111) = 6.1, $P < .02$] faster to related pairs (RT = 2303ms) than to unrelated pairs (RT = 2638ms), indicating that the meaning of the words influenced her response latencies. As all the nonwords in this test had a nonword phonology it is possible that she was using phonology to decide if the stimuli were words. If this were the case, she was probably also deriving meaning from the phonology of the stimuli and not directly accessing semantics from orthography.

As a test of what might be her method of accessing meaning we administered a French version of the picture/homophone test described for IH. JF accepted all correct picture/word pairs (30/30). She incorrectly accepted 10/15 picture/homophone pairs (66% errors) and 2/15 picture/unrelated pairs (13%). Chi square analysis revealed that JF made more mistakes on homophone pairings than on unrelated pairings ($\chi^2(1)$ =

8.9, $P < .01$). These results suggest that JF principally uses phonology to access meaning.

To summarize, both subjects demonstrate a heavy reliance on grapheme-phoneme correspondences to read aloud. Although they are sometimes able to distinguish the meaning of printed homophones, indicating there is some direct orthography-to-semantics activation, most of their semantic access from print is mediated by phonology (i.e., orthography-to-phonology-to semantics). Further, we know by IH's poor performance on the Boston naming test that activation in the semantic-to-phonology direction is very weak for him.

EXPERIMENT 1

Swinney, Onifer, Prather & Hirshkowitz (1979) demonstrated that, in a task of visual lexical decision, normal readers respond more quickly to words that have been auditorily primed by related words (e.g., DOCTOR—nurse) than to words primed by unrelated words (e.g., DOCTOR—chair). Similarly, Holcomb & Anderson (1993) tested for an auditory semantic priming effect at three SOAs: 0ms, 200ms and 800ms. Subjects demonstrated a facilitatory effect to the primes at all three SOAs. The auditory priming of visual lexical decision, then, can be semantically mediated for normal readers. It is therefore possible that the same-word auditory priming effect previously demonstrated by surface dyslexics is not an indication of direct phonology to orthography activation but rather an effect which is mediated by semantics.

In this experiment, we show that two surface dyslexics, IH and JF, who have exhibited large facilitatory effects to same-word auditory priming in visual lexical decision, can also be facilitated by an auditory prime which is semantically related to the target (e.g., BLUE/ sky, skie). This provides evidence that the phonological activation of orthography can be mediated by semantics for these subjects and suggests that the same-word auditory priming effect they demonstrate is at least in part semantically mediated.

Method

English Stimuli (for IH). The orthographic stimuli consisted of 50 word/nonword pairs. The nonword of each pair was a pseudohomophone of the target word (e.g., sky/skie). Digitised recordings were made of a semantic prime for each target word. For example, BLUE was recorded to be coupled to sky, skie for the prime condition. Auditory prime and visual target words were chosen from the 1952 Minnesota Word Association Norms (Jenkins, 1970). The median orthographic frequencies of target words and auditory prime words were, respectively, 89.5 and 50.5 per milllion (Francis and Kucera, 1982). A practice list of six trials with visual stimuli and auditory primes similar to those in the experimental list was also prepared.

French Stimuli (for JF). The orthographic stimuli consisted of 80 word/nonword pairs. The nonword of each pair was a pseudohomophone of the target word (e.g., sang, sant). Digitised recordings were made of a semantic prime word for the prime condition for each target word (e.g., auditory= ROUGE, visual = sang, sant). The auditory prime and the orthographic target word were chosen from Rosenzweig's (1976) normalised French version of the Kent-Rosanoff word association list.

Rosenzweig lists the frequency of responses for both students, male and female, and workmen in free association to high frequency word stimuli. Visual target words were chosen from among the responses to the stimuli which were used as the auditory primes in this experiment. In order to avoid either repeating stimuli or using very long words, the primary responses of Rosenzweig's list were not always used as target words. There were 53 target words which were primary responses (e.g., ROUGE-sang, "*RED-blood*") and 27 target words which were secondary responses, chosen from the second, third or fourth most frequent response (e.g., AIGRE-acide:"*BITTER-acid*"). The median orthographic frequencies of the auditory prime words and target words were both 102 per milllion (Content, Mousty & Radeau, 1990). There was no significant difference in printed word frequency between primary and secondary response targets ($F < 1$).

Procedure for both French and English Experiments. Each orthographic pair was presented once in random order in each of two blocks. A digitised recording of a 1000 Hz beep which lasted 600ms served for the unprimed trials. In Block 1, half of the orthographic pairs were coupled to the beep (unprimed trials) and half to the prime. Pairs which had been primed in Block 1 were coupled to the beep in Block 2 and vice versa. Within each block, the frequencies and word lengths of the visual stimuli on primed and unprimed trials were similar. The order of primed and unprimed trials was randomized within blocks. The subjects completed Block 1 and Block 2 one week apart.

The visual stimuli appeared in black over a white background and were printed in lower case Geneva 24-point 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 centre of the screen for 1020ms followed 595ms later by a word/nonword pair displayed 2 cm above the fixation location and the other 2 cm below. The position of the word (i.e., above or below) was randomly assigned. The auditory input began 16ms after the visual stimuli appeared. The visual stimuli remained on the screen until the subject responded. The experimenter initiated the next trial when the subject was ready. The subject was asked to indicate which of the two stimuli was the word by pressing one of two keys designated to represent "upper" or "lower". The program Psychlab (Bub and Gum, 1995) controlled stimuli exposure and recorded the subjects' response and response time.

Results

Subject IH. IH made 4 errors on prime trials (8%), and 2 on unprimed trials (4%). This difference in error rates was not significant [$\chi^2 = .71$, 1 df, n.s.]

RTs more than three standard deviations above or below the subject's mean per condition (n=1) were removed from the analysis of correct reaction times. The subject's mean correct RTs are graphed in Fig. 1 (page 127). Analysis of his lexical decision times with auditory priming (primed, unprimed) and repetition (Block 1, Block 2) as factors revealed a main effect for repetition [$F(1, 89) = 7.8$, $P < .01$], and an auditory priming by repetition interaction [$F(1, 89) = 4.0$, $P < .05$]. IH's mean RT in Block 1 and Block 2 were respectively 4533ms and 3588ms, a repetition effect of 945ms. Analysis of the simple effects of the auditory priming by repetition interaction showed that auditory priming significantly reduced RTs in Block 1 [$F(1, 89) = 4.4$, $P <$

.05] but not in Block 2 [$F(1, 89) < 1$]. In Block 1, his mean RT was 4060ms on primed trials, and 5048ms on unprimed trials an auditory priming effect of 988ms.

Subject JF. JF made 3 errors on primed trials (3.7%), and 5 on unprimed trials (6.3%). This difference in error rates was not significant [$\chi^2 = .53$, n.s.].

RTs more than three standard deviations above or below the subject's mean per condition (n = 3) were removed from the analysis of correct reaction times . Analysis of variance of her correct RTs with auditory priming (primed, unprimed), repetition (Block 1, Block 2) and association strength (primary response, secondary response) as factors revealed a main effect of repetition [$F(1, 141) = 4.7, P < .05$]. The first week (Block 1) her mean RTs was 2307ms, the second week (Block 2) 2758ms, an increase of 451ms. The analysis of variance also revealed two-way interactions of auditory priming by repetition [$F(1, 141) = 7.5$ $P < .01$] and auditory priming by association strength [$F(1, 141) = 4.$ 5 $P < .05$]. Figure 2 (page 128) plots the three way interaction.

Simple effects analysis of the auditory priming by repetition interaction revealed that auditory priming had an effect on RTs in Block 1 which was opposite in direction from the effect in Block 2. In Block 1 auditory priming had a marginally significant inhibitory effect on RTs[$F(1, 75) = 3.$ $4, P = .07$]. Conversely, in Block 2, auditory priming had a facilitatory effect [$F(1, 66) = 4.1, P < .05$]. In Block 2 JF's mean RT was 2484ms on primed trials and 3190ms on unprimed trials, a priming effect of 706ms. Even though the three-way interaction of auditory priming by repetition by association strength was not significant, it is quite apparent from Fig. 2 that in Block 1 the inhibitory effect was greater on trials which used the weaker semantic associates (i.e., second response stimuli) and that the facilitatory effect in Block 2 performance occurred only when the target word was a primary semantic associate of the prime.

Discussion

The purpose of this experiment was to see if IH and JF would demonstrate a facilitatory effect to cross-modal priming when the auditory prime was a semantic associate of the visual target as they had when the auditory prime was the same word as the target. If so, it would suggest that at least part of the activation of orthography by phonology in same-word auditory priming is semantically mediated.

In separate papers, we previously reported two experiments in which these subjects were tested using same-word auditory priming. The experiments are described briefly here in order to compare the results. In Whatmough et al. (in press) the effects of frequency, word length and grapheme-phoneme regularity were systematically varied within blocks of primed and unprimed trials. In that experiment auditory primes were recordings of the same word as the visual target. In Experiment 1 of Whatmough & Arguin (1998a), a paradigm similar to that of the present experiment compared RTs on unprimed trials (in which the subject heard a beep) to two types of auditory word primes: same-word primes (e.g., auditory = CLAIM, visual = claim, clame), and foil primes in which the auditory prime overlapped with the nonword and unprimed trials (e.g., auditory = FRAME, visual = claim, clame). Auditory condition was randomly assigned from trial to trial within blocks. Visual stimuli were repeated in three blocks in order to couple them once with each type of auditory condition. In the case of IH, because his error rate was rather high and, in order to obtain sufficient correct RTs, the set of three blocks were presented twice. JF completed the three blocks of French stimuli of Experiment 1 (Whatmough & Arguin, 1998a) once. The subjects completed only one block in each weekly session.

IH's error rate of 6 % in Experiment 1 is considerably lower than his rate of 26% in Experiment 1 of Whatmough & Arguin (1998a). We looked for differences in the stimuli of Experiment 1 (Whatmough & Arguin, 1998a) which might explain the very low error rate of Experiment 1. In both experiments the proportion of words with regular grapheme-phoneme correspondences was high: 43/50 (Experiment 1, Whatmough & Arguin, 1998a); 45/50, Experiment 1. However, the mean frequency of target words in Experiment 1 (150 per million) was higher than in Experiment 1 (81 per million) of Whatmough & Arguin (1998a). In Whatmough et al. (1997) in which word frequency and regularity were systematically varied, error rates were lowest for high frequency regular words. IH's low error rate in Experiment 1, then, may be explained by the fact that the stimuli were words which were both regular and very common. It should be noted however, that in Whatmough et al. (in press), word frequency did not have a significant effect on overall RTs or on the size of the priming effect for IH.

In the present experiment IH's RTs showed that he could be facilitated by an auditory prime which was semantically related to the target word. This effect, however, was not consistently found, as he was facilitated only on the first block of trials. The relative priming effect (facilitation / RT for unprimed condition) in this experiment in Block 1 was 24 %. This is the same effect size as was obtained over the six blocks of trials in the Whatmough & Arguin (1998a) experiment. Repetition of stimuli had not been considered as a factor in the Whatmough & Arguin (1998a) experiment and a retrospective look at the error rates and RTs of the six blocks revealed no repetition effect. RTs were variable from week to week (i.e., block to block) and IH showed no sign of a learning (repetition) effect. However, despite IH's variability in the Whatmough & Arguin (1998a) experiment, in each block mean RTs were shorter on same-word priming trials than on unprimed trials. This distinguishes it from his RTs in the present semantic priming experiment in which his mean RTs on primed trials were not significantly different from unprimed trials in Block 2. As IH displayed a significant reduction in RTs from Block 1 to Block 2, it is possible that IH benefited from the repetition of the visual stimuli in this experiment in a way that he did not in the Whatmough & Arguin (1998a) experiment. This benefit may have produced a floor effect and prevented the manifestation of an auditory priming effect also. This phenomenon of a lack of auditory priming effect for semantically salient material which is repeated reappears in the experiment which follows and is discussed in greater detail in the discussion of that experiment.

We turn now to subject JF. JF's error rate in this experiment (5%) was low but not significantly lower than in the Whatmough & Arguin (1998a) experiment (12%) [$\chi^2 = 3.5$, *n.s.*]. JF responded faster in Block 1 than in Block 2 . There is no obvious explanation for the increase in her RTs from the first week (Block 1) to the second (Block 2) but the fact that JF was facilitated by an auditory semantic prime only in Block 2 when her overall RTs were longer is consistent with our finding that the facilitation from simultaneous auditory priming emerges when subjects are quite slow in responding.

In both blocks of trials JF demonstrated that in visual lexical decision she was subject to the effects of auditory semantic priming. This indicates that for JF auditory phonology can activate orthography by semantic mediation. The effects of auditory semantic priming, however, were reversed in that, in Bock 1, the effect was inhibitory and in Block 2 it was facilitatory. Further, in both blocks there were sets of prime-target stimuli to which she demonstrated little if any effect (i.e., Block 1, primary response targets, Block 2, secondary response targets). How might these inconsistencies be explained? While no study has particularly looked at the effects of semantic priming in cases of progressive aphasia, Henik, Dronkers, Knight & Osimani (1993) tested for semantic priming effects in patients with single brain lesions in the anterior or posterior left and right hemispheres. Of the 20 left lesion patients 16 had some pattern of aphasia (anomic, Broca's or conduction). They found that the left lesion group did not exhibit facilitation to semantic primes as did both the right lesion group and a group of older controls. In fact, on the whole, the left anterior group demonstrated longer RTs to related primes than to unrelated primes, although this effect was not significant. Bushell (1997) also has found that Broca's aphasics displayed inhibitory priming effects to related primes. These two studies suggest that the spread of semantic activation is not always beneficial to aphasic subjects in tasks of lexical decision, which is similar to waht we find with JF in Block 1.

JF exhibited a facilitatory effect to auditory semantic primes which was limited to the primary response prime/target associations. Primary response trials, it will be remembered, were composed of the prime-target pairs stimuli most commonly paired in a test of free association. The size of the priming effect on these trials was 22% in Block 2. In the Whatmough & Arguin (1998a) experiment a significant auditory priming effect emerged only when RTs to same-word prime trials were compared with foil prime trials. The size of the effect in the Whatmough & Arguin (1998a) experiment was 16% for JF and her RTs were lower on target (i.e., same-word) trials than on foil trials in each of the three blocks.

The results of the experiment show that both subjects could be facilitated by an auditory word which is a close semantic associate of the visual target. Because the nonword foils were pseudohomophones of the target words, the subjects could not base their decisions on the phonology of the stimuli. The auditory prime was, therefore, not facilitating a phonological decision process. Further, because these subjects appear to access the meaning of printed words by phonological recoding and not by direct orthography to semantics mapping, we do not think the subjects were making semantic based judgments about the stimuli they viewed. In other words we do not think they were asking themselves (either explicitly or implicitly) what does sky or skie mean but propose rather that the subjects were making orthographic based decisions and the priming effect relects the following direction of activation: auditory prime-to-phonology-to-semantics-to-orthography.

The similar size in the priming effect for same-word auditory priming and semantic auditory priming strongly suggests that the same-word auditory priming effect is at least partly mediated by semantics. The instability of the effect from week to week, however, differentiates it from same-word auditory priming. This difference could be due to the difference in strength of association between even a close semantic associate and a target-word (semantic priming) and between the target-word and itself (same-word priming). Alternatively, it could be that same-word auditory priming involves different processes than does semantic auditory priming such as direct phonology-to-orthography activation.

EXPERIMENT 2

In this experiment we evaluate the contribution of semantics to same-word auditory priming by comparing the priming effect of content words (in this case nouns) and function words, considered to be, respectively, high and low in semantic content (Coltheart, 1980). Our hypothesis is that if same-word auditory priming is mediated by semantics, then, there should be greater priming for nouns than for function words because of their stronger semantic representations.

Method

Subject. IH served as a subject in this experiment.

Stimuli. One hundred twenty word/pseudohomophone pairs for the orthographic stimuli were compiled. Sixty of the words were function words (pronouns, prepositions and auxilliary verbs) and sixty were content words (nouns). There were 39 four-letter words, 40 five letter words and 41 six letter words. Function and content words were matched for word length and grapheme-phoneme regularity. The median frequencies per million of the function and content words were 281 and 187, respectively (Francis & Kucera, 1982). Digitized recordings were made of each target word for the prime condition and of a 1000 Hz beep that lasted 600ms for the unprimed condition. In Block 1, half of the function words and half of the content words were assigned to the prime condition and the rest to the unprimed condition. In Block 2, words which were primed in Block 1 were unprimed, and vice versa. Visual stimuli in the primed condition were coupled to the digitized recording of the word (e.g., TABLE, table, tabul) and those in the unprimed condition were coupled to the beep. Order of presentation as to word class (nouns, function words) and auditory condition (primed, unprimed) was randomized over trials.

Procedure. The procedure was the same as in the first experiment. The subject completed Blocks 1 and 2 one week apart.

Results

IH's overall error rate is 12%. Error rates for nouns and function words under each condition are reported in Table 1 (page 126). Priming had no effect on overall error rates but repeating the stimuli did reduce error rates between Block 1 (percent error = 17%) and Block 2 (percent error = 8%) [$\chi^2 = 3.8$, 1 df, $P = .05$].

Correct reaction times three standard deviations above or below the mean per condition (n = 8) were not included in the analysis. Analysis of IH's correct reaction times with factors of auditory priming (primed, unprimed), word class (content, function) and repetition (Block 1, Block 2) revealed main effects of auditory priming [$F(1, 194) = 64.4$, $P < .001$] and repetition [$F(1, 194) = 18.3$, $P < .001$]. The three way interaction (auditory priming by word class by repetition) was also significant [$F(1, 194) = 8.7$, $P < .01$]. This interaction is graphed in Figure 3 (page 129). IH's mean RT was 2769ms on primed trials and 4389ms on unprimed trials, a facilitation effect of 1620ms (37%). IH's mean RT was 4029ms in Block 1 and 3210ms in Block 2, a repetition effect of 819ms.

Simple effects analysis of the three way interaction showed that in Block 1 there was both a significant auditory priming effect [$F(1,91) = 46.0$, $P < .001$], and a priming by word class interaction [$F(1, 91) = 4.1$, $P < .05$]. Investigation of the simple effects of auditory priming revealed that both content words [$F(1, 46) = 39.1$, $P < .001$] and function words [$F(1, 45) = 11.3$, $P < .01$] were significantly primed by the auditory prime. The significant interaction between priming and class type in Block 1 indicates that the facilitation effect for content words was significantly greater than it was for function words. In Block 1 the facilitatory priming effect for content words was 2637ms (effect size of 50 %) and 1431ms (effect size of 29 %) for function words.

Simple effects analysis of Block 2 showed that there was a significant auditory priming effect [$F(1, 103) = 20.3$, $P < .001$], and a priming by word class interaction [$F(1, 103) = 4.7$, $P < .05$]. Investigation of the simple effects of priming revealed that only function words [$F(1, 52) = 22.0, P < .001$] and not content words [$F(1, 51) = 2.7$, *n. s.*] were significantly primed by the auditory stimulus. IH displayed 1889ms of facilitation (effect size of 44%) for function words the second week (Block 2).

Whatmough et al. (in press) reported that IH did not demonstrate a word length effect when under the auditory priming condition. As the word length effect is a defining characteristic of letter-by-letter reading the result was particularly striking, we were interested in seeing if he would again demonstrate this dissociation in this experiment. A 2 (primed, unprimed) by 3 (4-, 5-, 6-letter word) analysis of variance of correct RTs produced significant main effects of priming, and word length. The two-way (priming by word length) interaction is graphed in Figure 4 (page 130). As this interaction was significant [$F(1,196) = 3.2$ $P < .05$] we looked at the simple effects of word length under primed and unprimed conditions. This analysis showed that there was a significant word length effect in the unprimed [$F(1,100) = 7.1, P < .005$] but not primed condition [$F(1,96) = 2.2$, ns]. Simple regression of word length unto RTs produced a slope of 824ms in the unprimed condition ($r(1) = .97$). This then replicates the effect of auditory priming noted for IH in the Whatmough et al. (in press) experiment. Auditory priming appears to activate orthographic stimuli in such a way that it exempts IH, a letter-by-letter reader, from the word length effect.

Discussion

The first time IH responded to the visual stimuli (i.e., in Block 1), he displayed a facilitatory effect to auditory priming for both content and function words. The facilitatory effect was significantly greater for content words than for function words.

This indicates that the facilitation manifested by IH in visual lexical decision by auditory priming is in part mediated by semantics. However, because IH was also facilitated by the auditory presentation of function words which have little semantic strength, it suggests that direct orthographic activation by phonology also occurs.

In the second block of trials an interesting phenomenon noted in Experiment 1, is replicated. In Experiment 1, IH's RTs diminished on the second presentation of the visual stimuli (Block 2) and the effect of the auditory prime vanished. Likewise, in Block 2 of this experiment, IH's RTs decreased on trials with content words and he manifested no auditory priming effect for these stimuli. This effect of repetition was not true for the function words, indicating that either the semantic dimension which distinguishes content and function words, or more directly, some deeper difference intrinsic to word class is critical to the repetition effect. A tally of the word class of target words in Experiment 1 shows that, of the 50 target words, 31 are nouns, 14 adjectives and 5 verbs (none auxillary verbs). The word class of the target stimuli, then, in Experiment 1 resembles that of the content words (which were all nouns) in Experiment 2, thereby suggesting that the vanishing of the priming effect in Block 2 of both experiments is due to the same factor.

The strong reduction in IH's RTs from Block 1 to Block 2 indicates that something about the episodes of lexical decisions in Block 1 is carried over into his Block 2 performance. Since this occurs for content words but not function words, semantic saliency or perhaps some aspect of grammatical representation is crucial to this carry over effect. One possibility is that mapping to orthography mediated by semantics (which occurs for content words but is unlikely for function words) has a a long term effect on the "stability" or "accessibility" of orthographic representations. It is this that transforms how words primed in Block 1 are processed (as unprimed) in Block 2, and results in dramatiacally faster RTs. We attribute the loss of the primng effect in Block 2 to this large RT reduction, as the occurrence of cross-modal priming appears dependent on delayed (i.e., much slower than normal) lexical-orthographic access. This modification of orthographic processing in IH by Block 1 experience appears not to last indefinitely, however, as an attempt by a colleague in rehabilitating IH using repetition and auditory priming failed completely.

As indicated above semantic mediation contributes to the auditory priming effect for nouns. Function words, on the other hand, have little or no semantic content, suggesting that a semantic route is unlikely to mediate the auditory priming effect for these words. In addition, while there is a reduction of priming with repetition for content words, no such change occurs with function words. Thus, besides the semantically mediated orthographic activation suggested by Experiment 1, the present observations point to another pathway by which an auditory word can activate its orthographic representation, which is a direct phonology-to-orthography mapping.

GENERAL DISCUSSION

In previous experiments we had found that surface dyslexics which were normally very slow in the task of visual lexical decision were faster when they heard the target word at the same time as they viewed it. The fact that partial sublexical overlap between the prime and the target failed to affect RTs either positively or negatively suggested either that phonology was activating orthography directly by whole word-to-word mappings or that phonology was activating orthography by semantic mediation.

The goal of the present reseach was to explore the possibility that same-word cross-modal priming effects are semantically mediated.

In the first experiment we show that IH and JF, two surface dyslexics, are sensitive to the semantic dimension of the auditory prime. In this experiment auditory prime words were coupled with visual words which were semantic associates (e.g., auditory prime = BLUE, visual stimuli = *sky, skie*). Both subjects demonstrated that they could be facilitated by semantic primes and that when the effect was present it was similar in size to same-word priming. However, unlike same-word auditory priming, each of the subjects performed a block of trials in which they exhibited no facilitation to the auditory primes. Together the results suggested that semantic mediation contributed to same-word cross-modal priming, but at the same time that this indirect pathway was probably not sufficient to completely explain past observations.

In Experiment 2 we tested IH with same-word auditory priming and contrasted its effect on words considered to be high and low in semantic content (i.e., nouns and function words). As in Experiment 1, IH was tested on the visual stimuli twice. On one week, half of the stimuli were primed and the other half were unprimed. The next week, the stimuli which had been primed were presented unprimed and vice versa. The first week (i.e., Block 1), IH was facilitated by same-word auditory priming for both nouns and function words. The effect, however, was greater for nouns which strongly suggested that same-word auditory priming is semantically mediated. The next week, IH's RTs were much shorter, especially for nouns, and auditory priming had no effect on the visual recognition of nouns but had a strong facilitatory effect on function words. Since function words have little semantic content we conclude that the same-word auditory priming effect for function words results from a direct activation of orthography by phonology.

CONCLUSION

Two surface dyslexics were facilitated in a task of visual lexical decision by an auditory prime which was a close semantic associate of the target word. Although the effect size was similar to that obtained for same-word auditory priming, the effect was not as consistent in that neither of the subjects demonstrated facilitation to semantic associates in both blocks of trials. In a second experiment in which one of the subjects participated, greater facilitation to same-word auditory priming of nouns was found than to function words the first time the subject encountered the the visual stimulus pairs (i.e., Block 1). Together these results show that the auditory priming of printed words can be semantically mediated. However, the consistently strong facilitatory effect of same-word auditory priming on the visual recognition of words which have little semantic content (i.e., function words) suggests that auditory phonology can also directly activate orthographic representations.

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Table 1. Error rates (%) for IH in Experiment 2

Block	Stimuli	Unprimed	Primed
Block 1			
	Nouns	17	13
	Function words	20	17
	Total	18	15
Block 2			
	Nouns	10	7
	Function words	1	13
	Total	7	10
	Both blocks	13	13

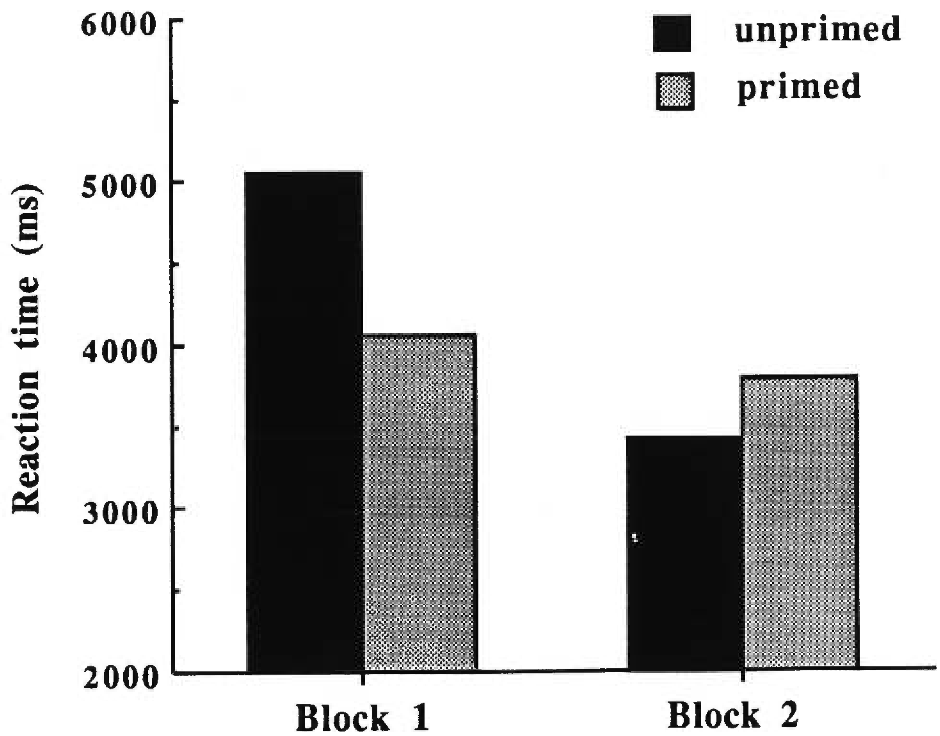


Figure 1. IH's mean latency in Experiment 1 as a function of auditory prime condition (primed vs unprimed), and repetition of visual stimuli (Block 1 vs. Block 2).

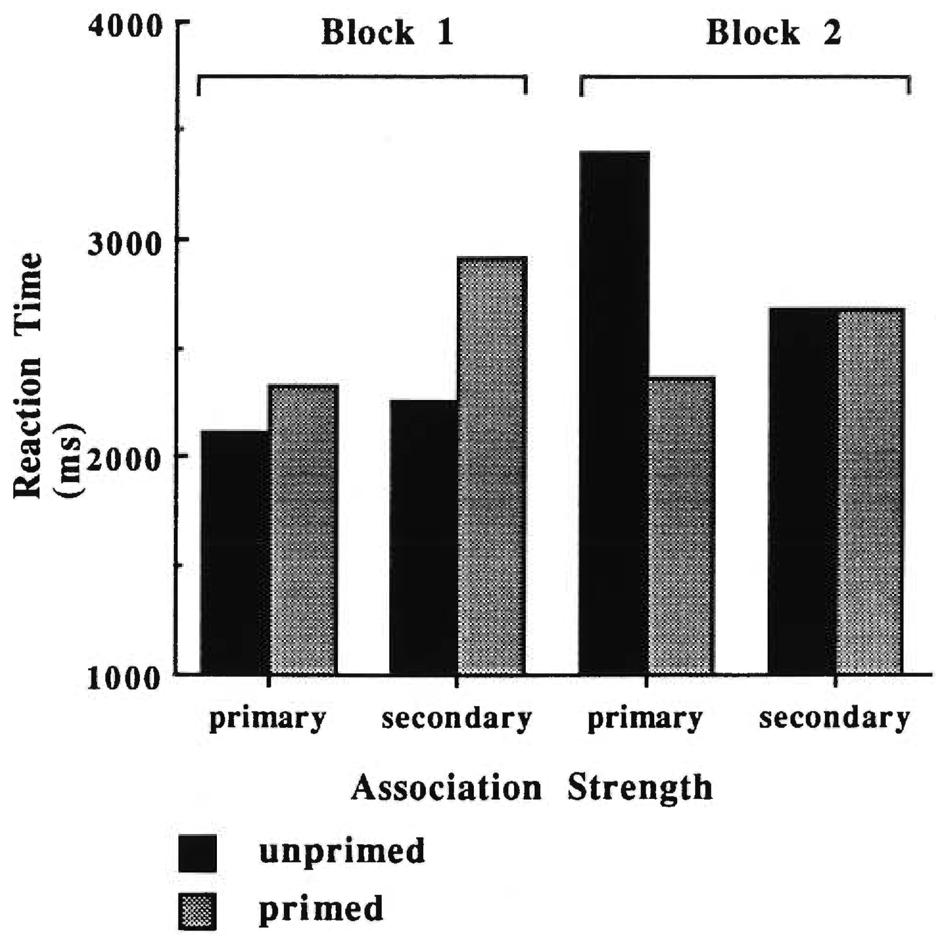


Figure 2. JF's mean latency in Experiment 1 as a function of auditory prime condition (primed vs unprimed), association strength (primary response vs. secondary response), and repetition of visual stimuli (Block 1 vs. Block 2).

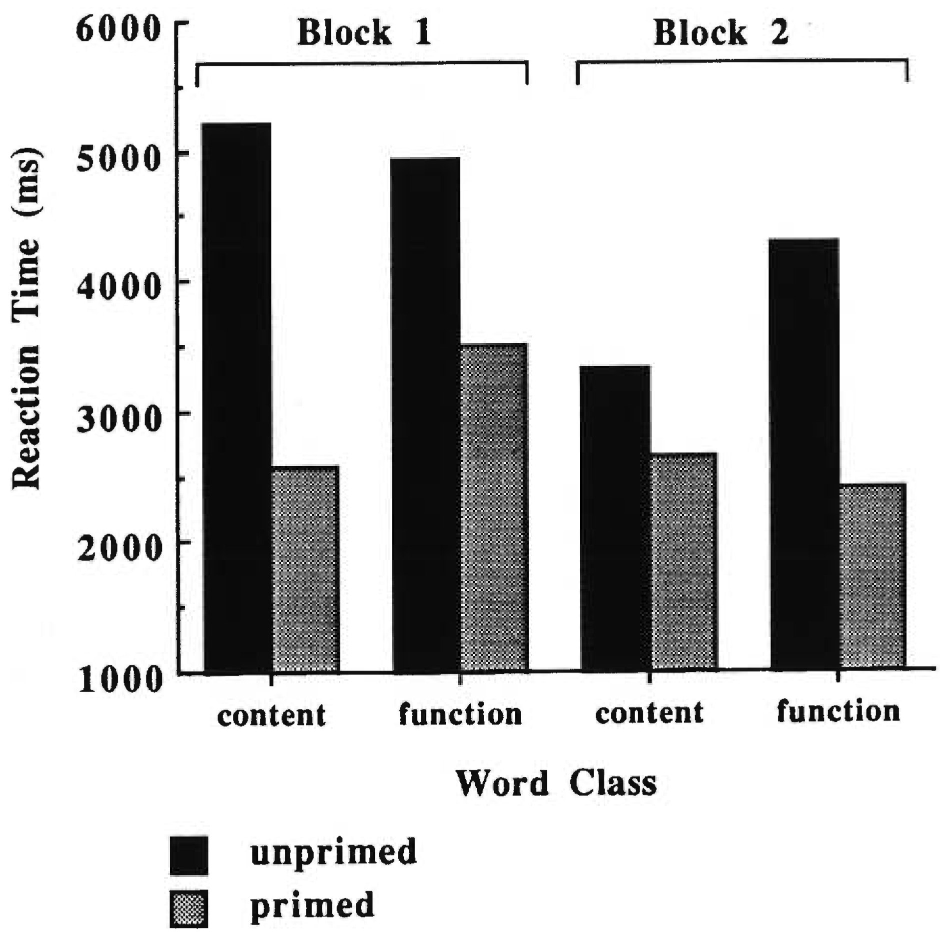


Figure 3. IH's mean latency in Experiment 2 as a function of auditory prime condition (primed vs. unprimed), word class (content vs. function) and repetition of visual stimuli (Block 1 vs. Block 2).

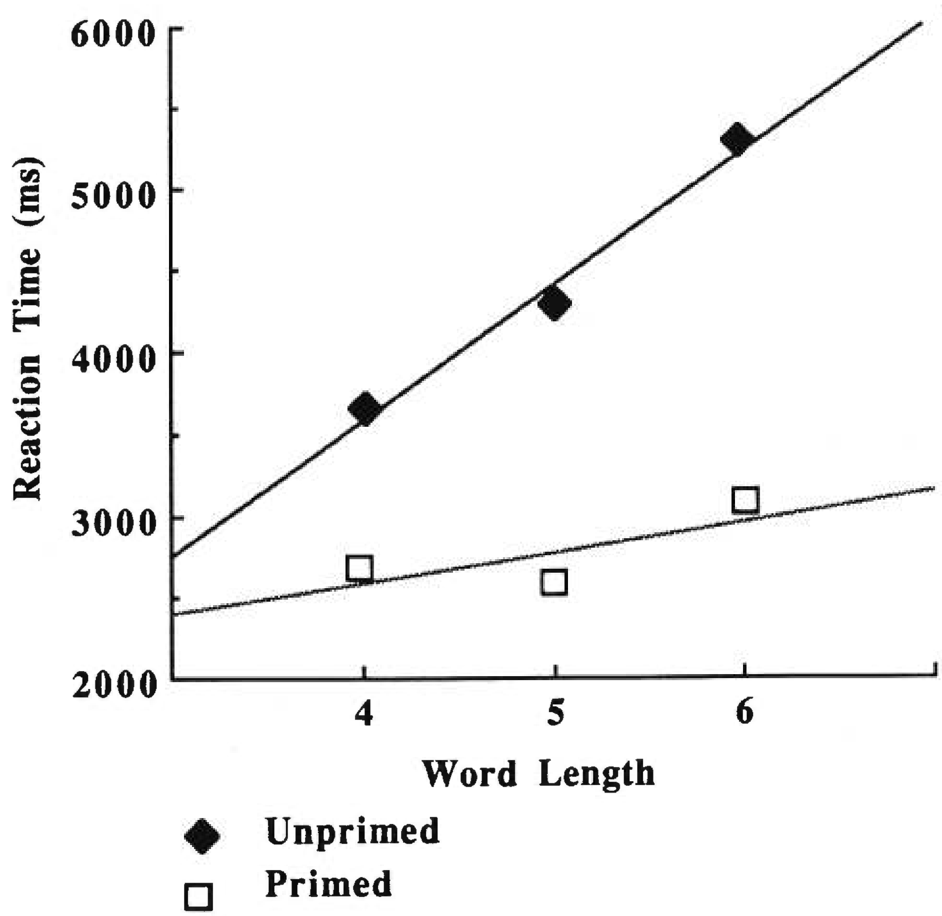


Figure 4. IH's mean latency in Experiment 2 plotted as a function of auditory prime condition (primed vs. unprimed) and word length.

Chapter Three

General Discussion

The Auditory Activation of Orthography

This thesis has focused on the question of whether auditory phonology can activate orthography. A more general goal has been to provide information by which the question of automatic feedback from phonology onto orthography can be considered. Two main sections comprise this final chapter. The first section summarises the principal findings of the articles and briefly reports an experiment carried out with normal subjects which enables us to better situate the results from the dyslexic subjects within the context of normal reading processes. The final section considers, now in the light of the experimental findings of this thesis, two questions of debate raised in the first chapter : proposals of phonological feedback onto orthography in reading and the issue of whether there are separate phonological lexicons for reception and production.

THE AUDITORY ACTIVATION OF ORTHOGRAPHY

The three articles provide evidence that phonology can activate orthographic representations by showing that surface dyslexics are faster to make visual lexical decisions if they simultaneously hear the target word. While the experimental format of auditory priming in conjunction with visual lexical decision has been used previously by others to investigate similar questions, the research reported in this thesis is unique in that the visual stimuli were constrained such that the lexical decisions could not be based on the phonology of the stimuli. In this way it permits us to interpret the effects of the auditory prime as acting on the orthographic processing of the visual target and not simply on a phonological recoding process.

Auditory priming of surface dyslexics

In the first two articles, we show that surface dyslexics are facilitated by an auditory prime which is the same word as the target (e.g. auditory = NOTE, visual = note, noat). The effect of a reduction in RTs is present when measured against both a silent condition (Experiment 1, first article) and a foil word prime condition (Experiment 1, second article) and, for the subject IH (Experiment 1, second article), relative to a beep condition. The size of the facilitatory effect is very large ranging from 517ms to 2756ms depending on the subject and contrast condition. Partial orthographic overlap between the prime and the target word (e.g., auditory = GREET, visual = sweet, swete) fails to produce even a small facilitatory effect suggesting that the activation between phonology and orthography is word-to-word and not phoneme-to-grapheme or syllable-to-syllable, i.e., sublexical. Activation of orthography by phonology, besides facilitating orthographic processing, is also shown to exempt the dyselxic readers from the abnormal effects of factors which predominate when access is visual only. Thus, the very large word length effect to which IH is subject in the unprimed condition, is absent with priming. Similarly the developmental dyslexic EL, who is slower to respond to regular words than to irregular words without priming, displays no such effect with auditory priming. A final observation from these articles is that in all the experiments response latency is the only performance indicator affected, error rates neither increase nor decrease with priming conditions on critical trials.

In the first article it is observed that there is a strong positive correlation between the size of the priming effect and the subjects' mean RT without priming, so that the slower the subject is to respond without priming, the more he/she benefits from priming. Thus, the slowest subject (IH), is facilitated the most by auditory priming and the fastest subject (EL) the least. In fact, the developmental dyslexic EL displays a significant facilitatory effect only for words of the lowest frequency range, words to which she responded the slowest without priming. Normal readers, on the other hand, whose mean RTs are under 750ms, do not display a facilitatory effect to simultaneous auditory priming. Instead they show an inhibitory effect (45ms) which is limited to words from the highest frequency range— words to which they respond the fastest without priming. The results from both the dyslexic and the normal readers then suggest that the speed with which a subject performs the task visually (as measured in the unprimed condition) will determine whether and how much he/she benefits from simultaneous priming. Subjects who perform the task rapidly in the unprimed condition (with RTs under 1000ms) do not benefit from priming. This suggests that in normal readers the visual activation of orthography is too fast for simultaneous auditory activation to be of benefit. It further suggests, however, that normal readers should benefit from auditory priming if the auditory prime is presented sufficiently in advance. Below we report an experiment carried out to test this hypothesis but first we outline another issue that is also addressed by the same experiment.

The fact that the IH and JF did not demonstrate even a small facilitatory effect when there was partial overlap between the auditory prime and the visual target (Experiment 2, second article) is surprising. Studies of normal readers (Andrews, 1989; Andrews, 1992) have suggested that, within orthography, lexical similarity between words is a factor which influences RTs in lexical decision and naming tasks. These studies show that words which resemble many other words, such as *came* which resembles *case*, *care*, *cake*, *tame*, *same*, *lame*, etc. are responded to faster than are words which resemble few other words (e.g., *desk*, *disk*). This effect, termed the neighbourhood density effect, strongly suggests that the representations of words within orthography retain something of their sublexical makeup. It is therefore surprising to find that partial congruency between the prime and the target did not facilitate IH and JF's performance. As was concluded in that article this lack of a priming effect could indicate either that phonology to orthography activation is word-to-word or that the effect is semantically mediated. Investigations into semantic mediation in the third article provide evidence for both semantic mediation and direct phonology to orthography mapping in same-word priming. This implies that even when there is semantic mediation, auditory priming may also directly activate orthography and the question of whether direct phonology-to-orthography route is susceptible to partial orthographic overlap between prime and target then remains. In other words, the existence of semantic mediation in same-word auditory priming is not sufficient to explain the lack of sublexical priming effects. Other possible explanations are that it is in some way related to the subjects' reading disability or alternatively, to insufficient prime-target overlap in the experimental stimuli. In order to see if this lack of a priming effect with partial orthographic overlap is related to the impaired reading of the dyslexic readers and/or insufficient overlap between the prime and the target, and to verify the hypothesis (proposed above) that normal readers could be facilitated by same word primes if they heard the word sufficiently in advance, an experiment with normal readers (Whatmough & Arguin, 1998) was carried out and is reported briefly below.

Auditory priming of normal readers

In this experiment normal readers performed a visual lexical decision task similar to that used throughout the thesis. The task required subjects to indicate which of two orthographic stimuli, a word and a pseudohomophonic form of the word (e.g., file/phile) was a word. Each trial was accompanied by an auditory prime which was either a beep or an auditory word. On any one trial there was an equal probability that the auditory prime was a beep, the same word as the target, an orthographic neighbour of the target, or a word completely different from the target. Three groups performed the task, each at a different prime-target SOA: 0ms (simultaneous), 225ms and 950ms.

Method

Subjects. Thirty-six Université de Montréal students (22 women and 14 men) served in the experiment. All were native French speakers and the experiment was carried out in French.

Stimuli. The visual stimuli consisted of 60 French word/nonword pairs, presented one above the other. In half of the pairs the word was placed above the nonword, in the other half the word was below the nonword. The words had a mean frequency of 146 per million (Content, Mousty & Radeau, 1990). The nonwords which were paired to the target words were in each case a pseudohomophone of the word (e.g. bain/bein, *tone/toan*).

Digitised recordings of three types of auditory prime words (same, neighbour and different) were made for each visual pair. A **same prime** was the same word as the visual target (e.g., auditory = VASE: visual = vase, vaze). A **neighbour prime** had an orthography which differed by one letter from the target word (e.g., auditory = BASE: visual = vase, vaze). Of the 60 neighbour primes, most (58) were not only orthographic neighbours in that they differed by one grapheme from the target word but were also phonological neighbours in that they also differed by one phoneme. An English example of words which are both orthographic and phonological neighbours are the words *coat* and *boat* which differ from each other both by one letter, (*c*, *b* and also by one phoneme (/k/, /b/). This quality of the stimuli will be taken into account in the final discussion. **Different primes** had little or no orthographic overlap with the target word (e.g., auditory = PILE: visual = vase, vaze). A 1000 Hz beep which lasted 600ms was also digitised to serve as the **neutral prime**.

Procedure. The 60 visual word-nonword pairs appeared once in each of four lists which gives a total of 240 trials. In each list the word-nonword pair was coupled with a different type of auditory prime (i.e., same-word, neighbour, different, neutral). However, the auditory priming condition was not blocked within lists. Instead, within each list there was an equal number (n = 15) of each type of auditory prime. Trial order of a list was randomised separately for each subject.

Three groups of twelve subjects participated in the experiment, each group being tested at a different prime-target stimulus onset asynchrony (SOA). Each subject completed all four lists which means they performed the same lexical decisions four times, each time under a different priming condition. The order in which they completed a list is designated in the analysis as a "repetition" factor and has four levels: 1st, 2nd, 3rd & 4th. Within each SOA group no two subjects received the lists of trials in the same order.

The visual stimuli appeared on a computer monitor as a word/nonword pair one item above the other. Subjects indicated which of the two stimuli was the word by pressing designated "upper" and "lower" keys. The trial sequence for the 225ms SOA and 950ms SOA conditions was: fixation point (495ms), auditory prime, visual stimuli until response. The sequence for the 0ms SOA condition was fixation point (1005ms), interval (495ms), auditory prime & visual stimuli until response. This means that the time interval separating the onset of consecutive trials in the 0ms SOA condition was about the same as that with the 950ms SOA. The auditory primes or beep onset simultaneously with the visual stimuli in the 0 SOA condition, and 225ms and 950ms before the onset of the visual stimuli in the 225ms SOA and 950ms SOA conditions, respectively. The beep and the digitised recording of the word were generated by the computer.

Results

Analyses of variance with prime condition (beep, same, neighbour, different) and repetition (1st, 2nd, 3rd & 4th) as within subjects variables, and SOA (0ms, 225ms, 950ms) as a between subjects variable were carried out on mean error rate and correct RT data. Unless otherwise noted all the significant effects observed had $p < .001$. Table 1 (page 139) lists the mean RTs and error rates under the four priming conditions at each SOA.

The error analysis revealed no main effect for any of the factors (prime, repetition or SOA), or significant interactions among them.

The analyses of mean correct RTs revealed main effects of prime condition and repetition, and a significant interaction between SOA and prime condition. No other main effect or interaction approached significance. The effect of repetition was to reduce RTs between the first and second list the subject completed. Mean RTs for each successive list were: 726ms, 672ms, 655ms and 638ms. Repetition did not interact with other factors or combinations of factors. A simple effects analysis of the SOA by prime condition interaction showed that the effect of prime condition was significant at each SOA: 0ms SOA, 225ms SOA and 950ms SOA. Pairwise comparisons (using t-tests) of each priming condition with the neutral condition at each SOA were carried out. Significant effects were found at 0ms SOA for the neighbour and different prime condition (inhibitory effect), at 225ms for the neighbour prime condition (inhibitory effect) and the same word prime condition (facilitatory effect), and at 950ms SOA for the same word prime condition (facilitatory effect).

TABLE 1
Mean Reaction Time (RT: in milliseconds), and Percentage Error for each Experimental SOA

Prime condition	RT	% Error
	SOA = 0 ms	
Beep	635	3.6
Same word	637	4.9
Neighbour	677	5.7
Different	676	4.3
	SOA = 225 ms	
Beep	637	4.3
Same word	617	4.3
Neighbour	678	5.0
Different	657	6.0
	SOA = 950 ms	
Beep	737	3.6
Same word	644	3.1
Neighbour	750	3.6
Different	735	4.3

An effect size was calculated for each auditory priming condition (i.e., same-word, neighbour, different) by subtracting the mean prime RT from the mean neutral condition RT (i.e., beep) at each SOA. The results are graphed in Figure 1 (page 140).

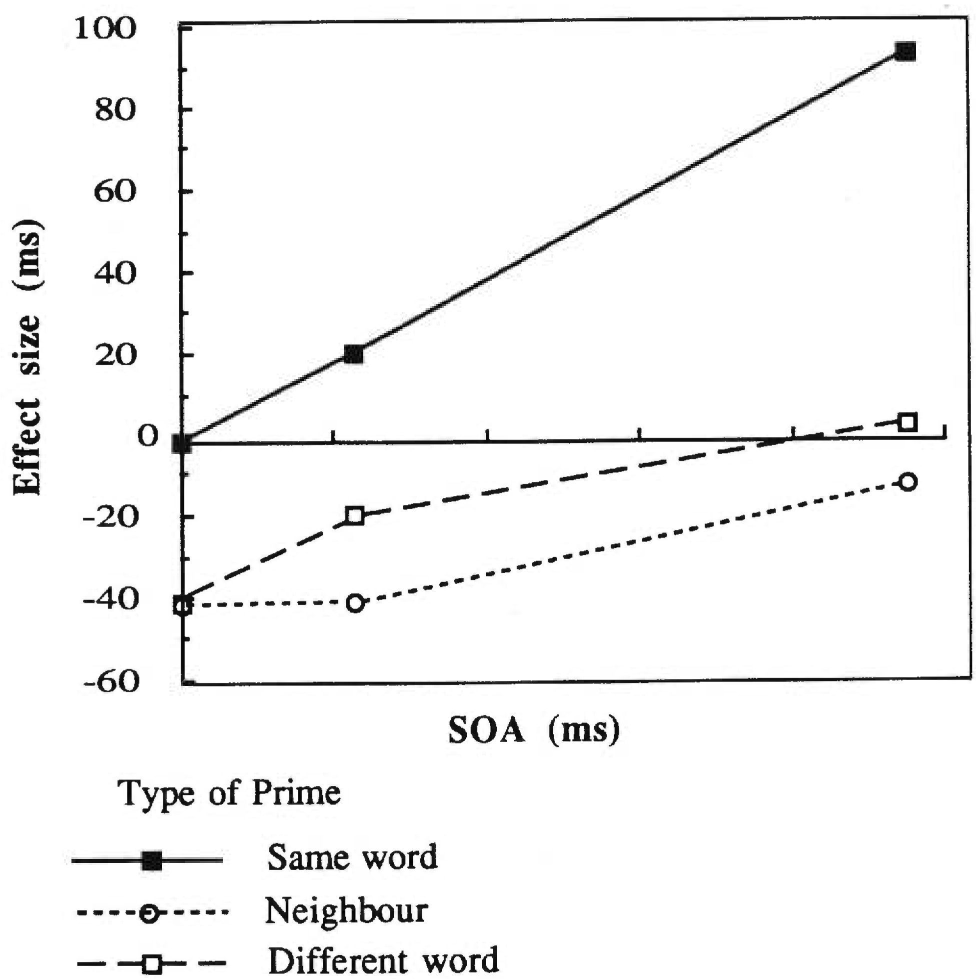


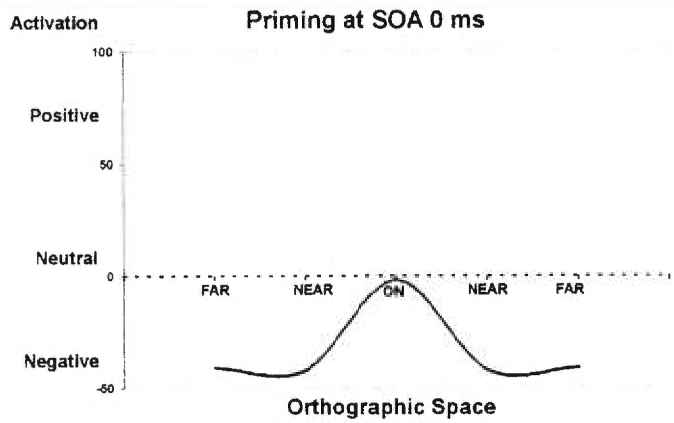
Figure 1. Priming effect at 3 SOAs

Discussion

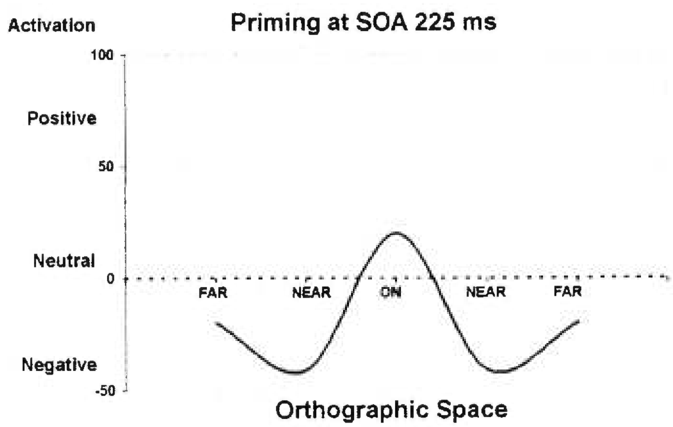
These results confirm that normal readers can be facilitated by same word auditory priming if the auditory prime onsets slightly in advance (i.e., 225ms) of the visual stimuli. The experiment then supports the claim that the lack of a facilitatory effect of same-word auditory priming in Experiment 2 of the first article was due to the very rapid visual activation of orthography by normal readers. This rapid visual access to orthography left no time for the auditory input to facilitate RTs. Because the task could not be based solely on a phonological recoding of the word and pseudohomophone, but required an orthographically based decision we can be confident that the auditory phonology was activating orthographic representations.

The results of this experiment suggest further that the auditory activation of orthography in the context of this experiment is automatic and not under the strategic control of the subjects. Consider the 0ms SOA group. These subjects did not manifest any facilitation to auditory priming but on two out of four trials (i.e., with neighbour and different word primes), the auditory input slowed their RTs. Under such circumstances an optimal strategy for the subjects to use would be to ignore the auditory input. The subjects, however, appeared unable to impede the auditory activation of orthography (which slowed their RTs) suggesting that the process was obligatory.

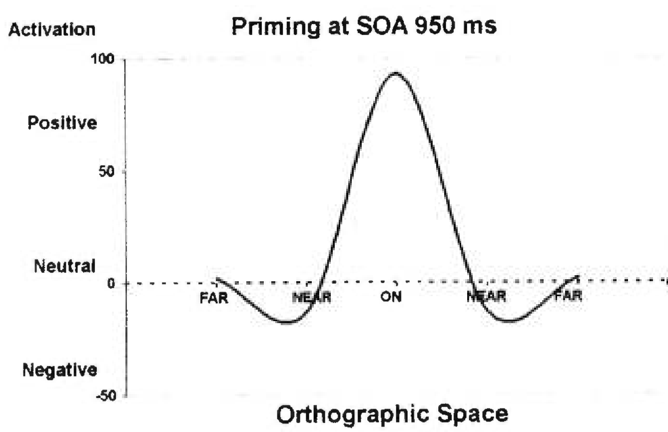
The subjects of this experiment who were normal readers were not facilitated by auditory primes that were very close orthographically (and phonologically) to the targets. Rather, at 0ms SOA and at 225ms SOA, the effect of auditory words other than the target, and of neighbour words in particular, was to slow RTs. The results then indicate that whole word overlap between the prime and the target is necessary to obtain the facilitatory effect. The lack of any facilitation by neighbour words even at short SOAs suggests that the activation of orthography by auditory phonology is lexically based (that is, word-to-word). In apparent contradiction with this, however, are the differential effects of neighbour and different (i.e., inhibitory vs nul) word primes at 225ms SOA which suggest that sublexical similarity is one of the dimensions of orthographic (or phonological) space. There are conceivably many ways in which both the facilitation of same word primes and the inhibition of neighbour and different primes (and the neighbourhood density effect) could be accounted for but they will not be considered here as it lies outside the goals of this thesis. We point out, however, that the inhibitory effects of orthographic neighbours and different words, and the facilitatory effect of same-word primes, appear to operate on a centre-surround mechanism of lexical activation. This suggested pattern of activation is illustrated in Figure 2 (page 143) which is based on the effect sizes obtained at each SOA. In this illustration, the initial effect of auditory priming within orthography is to inhibit competition from other words, in particular words which are close within orthographic space (Fig. 2a, b). Inhibition then recedes as activation of the target word by the prime facilitates its recognition (Fig. 2b, c).



2a.



2b.



2c.

Figure 2. A centre-surround explanation of the auditory activation of orthography. Values at ON, NEAR and FAR correspond to the auditory priming effects of, respectively, Same, Neighbour and Different words.

In Figure 2 we have assumed that the facilitation and inhibition effects of auditory priming are due to the relative proximity of the prime and the target within orthographic space. This is not of course necessary as the target and neighbour primes were also close within phonological space and this could also provide an account for the inhibitory effect. For example, suppose that visual lexical decisions always require feedback from the phonological lexicon. That is, orthography activates phonology which reactivates orthography. In this case providing incidental activation to phonology in the form of an auditory prime will also influence RTs even if the decision is ultimately based on the orthography of the stimuli. RTs, however, will also be affected by the way in which activation spreads within phonological space. Thus, if a subject sees *boat* but hears *coat*, he/she may be slower to respond to *boat* because it will take longer to activate the phonology of boat. To summarize this last point: if phonological feedback is a necessary part of visual word recognition, then the inhibitory effects of neighbour and different primes may arise either from within orthographic or phonological space. If however, the task can be performed without feedback from phonology, then it is orthogaphic proximity which must be the pertinent factor.

A comparison of the response of the dyslexics and normal readers to auditory priming indicates important similarities. First both normal readers and surface dyslexics exhibited a reduction in RTs with same-word auditory priming. On the other hand, neither type of reader was more accurate with priming. Secondly, facilitation is shown to be dependent on whole word overlap between the prime and the target in both types of readers. The significant difference between the dyslexics and the normal readers was the SOA required to obtain facilitation (i.e., 0ms for dyslexic readers, 225ms for the normal readers) and the size of the priming effect which was much greater for the dyslexics (> 500ms dyselxics, < 100ms for normal readers). Together, these results suggest that the dyslexic response to auditory priming is qualitatively the same and that their slow RTs in visual lexical decision are due to the impaired activation of orthographic representations by the visual mode.

Is the Activation of Orthography by Phonology Direct or Semantically Mediated?

The results from both the dyslexic subjects and the normal readers just described support claims that the activation of orthography by auditory phonology takes place on a word-to-word basis and not by sublexical activation. In the third article the question addressed is whether the activation of orthographic representations is direct or mediated by semantics. If the priming effect is semantically mediated, it would explain why the priming effect appears to take place on a whole word level. That normal readers can experience semantically mediated cross-modal (auditory to orthographic) priming has already been demonstrated by Holcomb & Anderson (1993), and Experiment 1 of the third article shows that JF and IH can demonstrate semantically mediated auditory to orthographic priming. In both cases, when the effect is present, its size is similar to what the subject exhibits to same-word priming. However, the effect is not as consistently present since both subjects performed blocks of trials in which the semantic auditory primes had no effect on the RTs.

In the second experiment we tested for semantic involvement in same-word auditory priming by varying the semantic strength of the stimuli. Two classes of words were contrasted: nouns and function words. This contrast in word class is shown to tap some factor implicated in the task. The complete set of stimuli were presented once in each of two blocks one week apart. Half of the nouns and half of the function words were same-word primed in the first block, half were unprimed (beep condition). The second week those items primed previously were unprimed and vice versa. The results of the first block of trials provide clear evidence that there is a semantic contribution to the priming effect, as it is significantly greater for nouns than it is for function words. However, because function words have very little semantic content and yet there is priming for these words also, the results indicate that phonology can also directly activate orthography without semantic mediation. This latter conclusion is further supported in the second block of trials in which overall RTs to nouns are greatly reduced relative to the first block and auditory priming is of no effect for nouns whereas it remains very large for function words.

The proposition that is put forth here is that it is possible for phonology to directly activate orthography. What has not been explored in this thesis is whether direct or a semantically mediated activation has some kind of prevalence for normal readers. Although we proposed earlier that the activation of orthography by auditory phonology was automatic in that experiment, it is not inconsistent to suppose that within a particular experimental situation subjects can vary the relative weight they accord to semantic versus direct phonology to orthographic activation. For instance if a high proportion of the stimuli are concrete, subjects might use a semantically mediated activation more than if they were mainly abstract. Further this relative weighting of a semantic versus a direct route for the auditory prime need not be conscious. For a demonstration in another context of how subjects can unconsciously vary their control strategies, the reader is referred to Verstaen, Humphreys, Olson & d'Ydewalle (1995). In their research they show that subjects can be influenced to use, or not to use, a strategy of phonological recoding of orthographic stimuli by varying the nature of backward visual masks presented to rapidly for recognition.

PHONOLOGY-TO-ORTHOGRAPHY ACTIVATION AND READING

Do the findings of the experiments support phonological feedback in reading?

Given the rather rapid and beneficial effect that incidental auditory input can have on visual word recognition, it is interesting to consider whether phonology to orthography activation is an important part of normal reading processes. The connectionist approach takes a strong postion with regards to this route of activation and maintains that feedback from phonology (and semantics) is an integral part of visual word recognition. This position is discussed here not with the intent of providing an exhaustive comparison between the present results and the predictions of this approach but rather to raise some points which will permit the reader to view the findings of the present thesis from a broader perspective.

In this research it has been shown that an auditory word can rapidly activate its corresponding orthographic representation and facilitate its visual recognition. This is what would be predicted by connectionist frameworks in which phonological activation contributes via feedback to the final state of orthographic representations and which hold that no fundamental distinction is to be made between the phonology of a heard word and the phonology produced in reading. A result in this thesis which is unexpected by connectionist systems is the lack of facilitation from auditory words which are orthograpically close to the target word. A central principle of these systems is that words are represented by patterns of activities over units which are shared. Within such a system it is easy to explain why words from high density neighbourhoods are read more quickly than words with unusual spellings: every time a word is activated within a neighbourhood it is reinforcing the links which other words share. Interactions between domains such as orthography and phonology, also, take place at a sublexical level in these models so that learning to read neighbours such as *nose*, *pose* and *rose* contributes to reinforcing the association between the graphemes -ose and the phonemes /oz/. The lexical, word-to-word, nature which is shown in this thesis to be necessary for facilitation between phonology and orthography, then, seems at variance with the predictions of these models. Connectionist models and their parameters, however, are presently designed to account for the processing of single stimuli. In priming experiments we are observing the influence of one stimulus on another. Additional assumptions concerning the interactions of two stimuli may allow connectionist models to accomodate the priming data and maintain that the interactions between domains is of a sublexical nature. The research in this thesis does not falsify the sublexical interactions proposed by connectionist models. Rather it provides a constraint that should be addressed by any model, namely that the behavioral manifestations of the facilitatory activation of orthography by auditory phonology are at a lexical rather than a sublexical level.

Do the results inform about input and output lexicons?

In the opening chapter the issue was raised of whether there were two phonological lexicons (one for reception and one for production) or just one which serves both functions. The evidence in favour of two lexicons included neuropsychological dissociations and empirical results which show first that normal readers can perform reception and production phonological tasks simultaneously with little interference and, second, that there is frequently a lack of transfer in the form of priming between reception and production tasks. Arguments for the parsimonious position of a single lexicon essentially centred on demonstrating how a lack of internal transfer in priming experiments may be explained by maintaining that it is pathways to and from the lexicon which can be primed and not the representations themselves. The experimental evidence reported in this thesis sides with the parsimonious approach but for a different reason which is outlined below.

In reading, the obvious direction of activation is orthography-to-phonology in that a printed word activates orthography which in turn activates a phonological response. Through auditory priming effects, we have shown that activation in the phonology-to-orthography direction can also take place. The associations between phonological and orthographical representations, however, have necessarily developed in the context of learning to read. In this research, then, the phonology which is shown to activate orthographic representations by auditory priming is isomorphic with the phonology which orthography activates in reading. Parsimony would demand that there be only one phonological lexicon as explanations of the results within a dual lexicon model necessitate considerable redundancy in representations. If there were separate receptive and production lexicons for phonology, it would require the following explanation to the priming experiments: the auditory input activates reception phonology which in turn activates the production (pronunciation) phonology which has developed links to orthography in response to learning to read. This production, or output phonology would then activate orthography. The proposal would then be that there are separate input and output lexicons for phonology with bidirectional links between the output lexicon and orthography. (This is exactly what has been proposed by Coltheart and Coltheart (1997) to explain an ensemble of other experimental results too intricate to describe here.)

However, this research adds another element to the workings of phonology which may be an important factor in the final account. This factor has to do with the intentional or attentional mind-set of the subject. Throughout the thesis it has been maintained that the demonstrated automatic auditory activation of orthography has occurred in response to a particular task. In these experiments, the task was to recognise the orthography of words and the demands of the task are believed to have been essential for auditory words to activate orthography. What it is not proposed is that hearing words in normal conversation automatically activates the orthographic form of the words. This then suggests that there are mechanisms which control when phonology-to-orthography activation takes place and when it doesn't. We anticipate that, when the mechanisms which control activation are better understood, reconciling the evidence for and against two phonological lexicons will become easier by attributing evidence not to separate lexicons but to processes which control input and output from phonology.

SUMMARY AND CONCLUSION

In this thesis three surface dyslexics, IH, JF and EL, who normally respond very slowly in a task of visual lexical decision, are shown to be greatly facilitated by simultaneous auditory priming. Because the task requires a visual recognition of the orthography of the stimuli it indicates that phonology was participating in the processing of orthography and provides evidence that auditory phonology can activate orthographic representations. In further experiments with IH and JF, it is shown that auditory word primes which only partially overlap with the visual target words do not facilitate the recognition of visual words suggesting that phonology-to-orthography activation is either direct and word-to-word, or semantically mediated. Exploration of the possibility of semantic mediation in the task shows that while both JF and IH can be facilitated by a an auditory prime which is a semantic associate, the facilitatory effect is not as consistently present as with same-word auditory priming. This suggests that not all auditory priming effects are semantically mediated for these subjects. This proposal is supported in a final experiment which shows that IH is consistently subject to same-word auditory priming for function words, which have little semantic content. The sum of the experiments then indicate that auditory phonology can activate orthographic representations both directly and by semantic mediation.

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