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Auditory and Visual Semantic Priming in Lexical Decision: A Comparison Using Event-related Brain Potentials

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This study compared and contrasted semantic priming in the visual and auditory modalities using event-related brain potentials (ERPs) and behavioural measures (errors and reaction time). Subjects participated in two runs (one visual, one auditory) of a lexical decision task where stimuli were word pairs consisting of "prime" words followed by equal numbers of words semantically related to the primes, words unrelated to the primes, pseudowords, and nonwords. Subjects made slower responses, made more errors, and their ERPs had larger negative components (N400) to unrelated words than to related words in both modalities. However, the ERP priming effect began earlier, was larger in size, and lasted longer in the auditory modality than in the visual modality. In addition, the lateral distribution of N400 over the scalp differed in the two modalities. It is suggested that there may be overlap in the priming processes that occur in each modality but that these processes are not identical. The results also demonstrated that the N400 component may be specifically responsive to language or potential language events.

INTRODUCTION

Over the past 15 years, considerable effort has been invested in trying to determine the role played by contextual factors in written word recognition (e.g. den Heyer,1986; Fischler, 1977; Meyer & Schvaneveldt, 1971; Neely, 1976; 1977; Schvaneveldt & McDonald, 1981; Stanovich & West, 1983). A great deal of this research has focused on the influence exerted by the

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semantic properties of one word on the recognition of a second word presented a short time later. The basic finding that has been replicated many times is that words are recognised faster when they have been semantically primed by an earlier related word.

There is considerable agreement that one source of this facilitation is a by-product of the lexicon being organised semantically. In this account, priming results from the bottom-up activation of one lexical entry rapidly or "automatically" spreading to other semantically related entries (e.g. Collins & Loftus 1975; Neely, 1976). Another source of facilitation (and interference) in word pair priming tasks has been shown to result from manipulations that encourage subjects to actively attend to the relationship between the words. However, the locus of these "attention" effects has been questioned, with some arguing that they are subsequent to lexical access (e.g. Neely, 1977; Seidenberg, Waters, Sanders, & Langer, 1984).

Until recently, the influence of semantic factors in spoken word recognition have been neglected (for recent reviews, see Frauenfelder & Tyler, 1987; Marslen-Wilson, 1987). Semantic processes within the auditory modality are of interest for a number of reasons. First, there is the issue of generality. Are the processes underlying priming different during reading and listening or are they modality-independent, possibly reflecting more general properties governing the organisation of a single, a-modal lexicon? Studies reporting facilitation effects using pairs of pictures (e.g. Kroll & Potter, 1984), combinations of pictures and written words (e.g. Vanderwart, 1984), and even combined auditory and visual words (Swinney, Onifer, Prather, & Hirshkowitz, 1979) suggest that priming occurs between and within several modes of stimulus presentation, which is consistent with the notion of a single representational system at some level. However, none of these studies have systematically compared priming to auditory and visual stimuli and relatively few have adequately explored priming wholly within the auditory modality. This leaves open the possibility that different priming mechanisms are at work (but see Blumstein, Milberg, & Shrier, 1982; Marslen-Wilson, 1987; Zecker, Tanenhaus, Alderman, & Siqueland, 1986).

A number of studies (e.g. Marslen-Wilson & Welsh, 1978; MarslenWilson & Tyler, 1980; Miller & Isard, 1963) with sentences presented in the auditory modality strongly suggest that contextual effects at the sentence level play an important role in spoken word recognition. Using a variety of techniques, Marslen-Wilson and colleagues have shown that subjects can recognise a spoken word faster if it is embedded within a meaningful sentence than if it is presented in isolation or in a meaningless sentence. More recent work by Zwitserlood (1989) supports this conclusion. Zwitserlood used spoken sentences with strategically placed visual probe words and revealed that although context did not guide or aid initial spoken word activation, it did help select between competing candidates once some initial acoustic information was available. However, it is unclear whether these sentence level context effects involve the same mechanisms operative in word pair semantic priming tasks.

Another reason for contrasting written and spoken language has to do with the impact of language acquisition on brain development. Most speakers learn their native language through the auditory modality during a period of very rapid brain development. Early experience with language (as well as other early experiences) has been shown to have a profound influence on the functional organisation of certain brain systems (e.g. Neville, Kutas, & Schmidt, 1982; Neville & Lawson, 1987a; 1987b; 1987c). Written language, on the other hand, is typically not learned until much later during a period of less rapid brain development, and may play a lesser role in cerebral organisation (but see Lecours, Mehler, & Parente, 1988). In addition, a strong argument can be made that the human brain has evolved under the pressures of using and understanding a spoken and not a written language. Written language, as we know it, is only a few thousand years old, and for most of this relatively short time it has been used by only a small percentage of the population (Ellis, 1984). This evidence suggests that written word processing might be dependent to a large part on preexisting mental systems used for other purposes. Some of these would presumably be auditory in origin.

EVENT-RELATED POTENTIALS STUDIES

In a number of recent reports, semantic priming has been studied by recording event-related brain potentials (ERPs) to visually presented linguistic stimuli.' Of most relevance here are reports of a late negative component which begins as early as 200 msec and peaks near 400 msec (N400) post-stimulus onset. The pioneering work of Kutas and her colleagues (e.g. Kutas & Hillyard, 1980; 1984) has shown that the N400 component is larger to sentence final words that are anomalous (e.g. "He takes cream and sugar in his *attention"),* and is small or non-existent to 'ERPs are stimulus-bound voltage fluctuations that are embedded within the scalprecorded electroencephalogram (EEG). Typically, ERPs are obtained by averaging together a number of short segments of EEG (10-2000 msec in duration, depending on the experimental paradigm), each of which was time-locked to the onset of a different (but physically similar) stimulus event. The various peaks and valleys (positive and negative fluctuations) are relatively stable features of the ERP and are usually referred to as "components". Components are labelled by their polarity (N for negative and P for positive) and their ordinal position (P2 would be the 2nd positive component) or latency post-stimulus onset (N400 is a negative component peaking 400 msec after the onset of the stimulus).

highly probable "best completion" sentence endings (e.g. "He takes cream and sugar in his *coffee").* In a subsequent study, Kutas, Lindamood, & Hillyard (1984) demonstrated that N400 amplitude was a monotonic function of the cloze probability of sentence final words. N400 was largest to the most unpredictable final words (anomalies), was intermediate in amplitude to moderately predictable final words, and was smallest to highly predictable final words. This result parallels the data obtained in lexical decision tasks where low cloze probability words elicit prolonged reaction times relative to high cloze probability words (Fischler & Bloom, 1979). In a second experiment, Kutas et al. also showed that final words which were anomalous, but which were semantically related to the best completion ending (e.g. "The game was called when it started to umbrella"), produced an N400 intermediate between unrelated anomalies and best completion endings. Taken together these results suggest that N400 is sensitive to ". . . the degree to which a word has been primed by rapidly spreading activation within semantic networks" (Kutas et al., 1984, p. 237).

Kutas et al.'s (1984) conclusions agree with the results of a number of other ERP studies of semantic priming. For example, Fischler et al. (1983) have shown that a late negative component is larger to sentence final words when the subject and object of the sentence are discrepant (e.g. "A canary is a rock" or "A dog is not a bird") as opposed to when they are in agreement ("A canary is a bird"), regardless of the truth value of the sentence as a whole. One interpretation of these results is that N400 is larger in the discrepant condition because the subject of the sentence is not semantically related to the object (i.e. it is unprimed).

Of particular interest to the current study are three recent reports that explored changes in behaviour and ERPs while subjects were engaged in a lexical decision task using pairs of letter strings. Bentin, McCarthy, & Wood (1985) reported that visually presented target words preceded by a semantically related word were associated with a late positivity (670 msec), whereas target words and word-like nonwords following semantically unrelated words produced a negativity which peaked at approximately 400 msec. Bentin et al. suggested this negativity may be the same as Kutas et al.'s N400. A study by Rugg (1985) reported a similar pattern of results with a negativity (peaking at 400 msec) occurring to unrelated target words and a positivity occurring to related target words.

Finally, Holcomb (1988) also reported a larger N400 to both unrelated target words and target words following a neutral prime than to related target words. In addition, this N400 effect (the difference in ERPs between neutral or unrelated targets and related targets) was apparent both in the condition where instructions and the percentage of related trials (67% of word targets) induced subjects to attend to the semantic relationship between prime and target words, as well as in a block of trials where instructions and the percentage of related trials (17% of word targets) were ideally suited for producing only automatic priming effects (e.g. Posner & Snyder, 1975). The N400 effect was, however, significantly larger in the attention condition. Holcomb (1988) concluded that these results are in agreement with the substantial literature that supports a two-process account of semantic priming (e.g. den Heyer, 1986; den Heyer, Briand, & Dannenbring, 1983; Neely, 1976; 1977; Tweedy, Lapinski, & Schvaneveldt, 1977) and suggested that the N400 is sensitive to priming due to both automatic spreading activation and to the additional priming that results from the allocation of attentional resources.

All of the above studies used visual letter strings as stimuli. McCallum, Farmer, and Pocock (1984) performed an auditory replication of Kutas and Hillyard's (1980) original visual study. As in the visual report, the anomalous endings produced a large negativity and appropriate endings produced a positivity in the 400-msec time-band. McCallum et al. noted that their auditory N400s were later in peak latency and extended to somewhat more anterior sites than those of Kutas and Hillyard (1980).

The primary purpose of the research presented here was to initiate a series of studies designed to look at language comprehension between and within the visual and auditory modalities. Within this scheme, one goal of the current study was to begin to investigate whether similar mechanisms underlie semantic priming in spoken and written word processing or, alternatively, whether separate and different systems are used by the two modalities. Evidence supporting the same or similar mechanisms would be the finding of equivalent profiles of behavioural and electrophysiological results in procedurally similar semantic priming tasks administered in both modalities. Evidence against the same or similar systems position would be the finding of widely differing profiles or a qualitatively different pattern of effects between the modalities.

To examine this issue, a totally within-subjects design was chosen because it permits ERP and behavioural contrasts across modalities to the same stimuli under the same task conditions. Previous investigators have used both short (e.g. 200 msec) and long (e.g. 1000 msec) stimulus-onset asynchronies (SOA) to determine the relative contribution of automatic and attentional processes on priming (e.g. den Heyer, 1986; Neely, 1977). It was decided that in this initial study, a relatively long (1150 msec) primetarget SOA would be used, because the addition of a short SOA condition would have caused a prohibitive increase in the duration of the experiment and because even rapidly spoken auditory words would be only partially complete at short SOAs. Prior behavioural and ERP studies indicate that substantial visual priming can be obtained with intervals in the 1-sec range and longer, although it is usually argued that these effects are due to a combination of automatic and attentional factors (e.g. Holcomb, 1988; Neely, 1977).

A second goal of this study was to provide further information about the functional significance of the N400 by contrasting N400s derived from words and two types of nonwords. Holcomb (1988) and Kutas and Van Petten (1988) have argued that N400 is specific to language processing, and data from the automatic priming condition (Holcomb, 1988) and work by Kutas et al. (1984: reviewed above), further suggest that the amplitude of the N400 may reflect lexically based word recognition processes. If these assertions are true, then stimuli (e.g. primed words) that require relatively less bottom-up lexical input to achieve recognition (due to automatic spreading activation) should produce smaller N400s than stimuli that require a relatively greater amount of bottom-up input (unprimed words, pseudowords). On the other hand, un-word-like stimuli should not engage the lexical system and therefore should not produce N400s, either because some pre-lexical filtering process quickly rejects non-linguistic items (based upon aberrant physical characteristics) or because non-linguistic items have little or nothing in common with lexical entries and therefore do not generate lexical activity. If, on the other hand, N400 reflects the activity of a more general purpose mismatch detector (e.g. Polich, 1985), which is sensitive to mismatches at several levels (semantic, lexical, and physical), then N400 should be larger to nonwords that mismatch preceding words on most dimensions (i.e. un-word-like nonwords). To test these conflicting hypotheses, two types of non-English targets were included: stimuli that followed the phonological and orthographic rules of English, and stimuli that, although made up of units used in language (letters and human voice sounds), were phonologically and orthographically illegal.

METHODS

Subjects

A total of 16 volunteers (9 females, 7 males) between 20 and 32 years of age were paid $5.00 per hour to participate in this experiment. All of them were right-handed native speakers of English with normal visual and auditory acuity.

Stimuli and Procedure

All of the stimuli were generated and controlled by an IBM-PC computer and were presented either on a 23-inch Electrohome monitor (model EVM 2319) or binaurally through headphones (TDH 39P).

Each subject was run in two separate (blocks) lexical decision tasks, which were comprised of 40 trials in each of four pseudo-randomly arranged conditions. In one block of 160 trials, all of the stimuli were presented in the auditory modality and in the other block all stimuli were presented visually. The order of modalities was counterbalanced across subjects. In both blocks, two stimuli were presented on each trial; the first *(prime)* was always an English word (mean log frequency = 1.63, S.D. = 0.77: Francis & Kucera, 1982), whereas the second *(target)* was either a legal English word (mean log frequency = 1.72, S.D. = 0.62) or a stimulus constructed from a legal word. Half of the stimuli in this latter category were formed in accordance with the orthographic and phonological rules of English *(pseudowords,* e.g. JANK or GRUSP) and half were constructed so as to violate orthographic and phonological constraints *(nonwords).* Visual nonwords were constructed by randomly arranging strings of consonants (e.g. KCSRT). Auditory nonwords were English words played in reverse. [2] Of the legal word targets, half were semantically *related* to the preceding prime word (e.g. DOG-CAT) and half were *unrelated* to the prime (e.g. CAR-PEN). All of the word and pseudoword targets were single syllables, 3-6 letters in length. In summary, 160 prime-target pairs of stimuli were presented in the visual modality and 160 pairs were presented in the auditory modality. Of each 160, 40 had a word prime and a related word target, 40 had a word prime and an unrelated word target, 40 had a word prime and a pseudoword target, and 40 had a word prime and a nonword target.

Related and unrelated stimuli were selected from four similarly constructed lists of 40 related pairs of words (see Appendix) using a Latinsquare counterbalancing design (across subjects each list occurred in the related and unrelated condition and in the auditory and visual modality an equal number of times, but within subjects each list was presented once). Unrelated pairs were formed by rearranging related primes and targets in each list so that there was no semantic relationship between the prime and target words. There were two word-pseudoword lists and two wordnonword lists (see Appendix), with modality counterbalanced across subjects.

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[2]Although the term nonword will be used for referring to the non-linguistic stimuli in both modalities, it is clear that the across-modality comparisons will be weakest here due to the quite different procedures used to transform real words into these stimuli. In the visual modality, the basic language units, although scrambled in order, are structurally intact. However, in the auditory modality the basic units (speech segments) are scrambled as well as transformed into non-linguistic units. Therefore, direct comparisons will be restricted to simple descriptive evaluations.

Auditory stimuli were digitised (12 kHz, 12-bit resolution, 6-kHz Butterworth filter) letter strings spoken by a female voice and stored on the hard disk of the IBM-PC computer. Prior to the experiment, each stimulus was edited for precise time of onset so as to permit synchronisation with ERP digitisation and behavioural reaction time. During the experiment, the digital representations of the prime and target stimuli were output through a digital-to-analogue converter and played to the subject over headphones (65-dB NHL). Visual stimuli were displayed in upper-case letters (white on a black background) and subtended 1-2° of horizontal and 0.5° of vertical visual angle.

Subjects were instructed to rapidly and accurately press a button labelled "YES" with one index finger if the second stimulus in a pair was an English word, and to press a different button labelled "NO" with their other index finger if the target was not an English word (the hand used for each response was counterbalanced across subjects and modalities). The task was self-paced. A trial began with a press of either response button. Following a delay of 3000 msec, the prime was presented and was followed 1150 msec later by the target. In the visual block, both the prime and target stimuli (stimulus duration = 400 msec) were presented in the centre of the screen. Auditory stimuli (mean duration = 400 msec, range 270-700 msec) were presented binaurally over headphones. Each trial was delimited by the occurrence of a rectangular border illuminated on the computer screen (5° x 3°, border thickness = 0.25°). The subjects were asked not to move or blink while the border was illuminated. Each block lasted about 30 min and a 10-min break was given between blocks. A 10-trial practice block preceded each experimental block.

EEG Procedure. Tin electrodes (Electro-Cap International) were placed at several sites distributed across the scalp and at a single site below the left eye (all referenced to linked mastoids). The scalp sites included six standard International 10-20 system locations: occipital left (01) and right (02); parietal left (P3) and right (P4); and frontal left (F7) and right (F8). These are sites frequently used in cognitive ERP studies to sample electrical activity from a broad distribution of cortical areas. Four other electrodes were also placed at non-standard locations over the left and right temporo-parietal cortex (30% of the inter-aural distance lateral to a point 13% of the nasion-inion distance posterior to Cz: LTP and RTP) and over right and left temporal cortex (33% of the inter-aural distance lateral to Cz: LT and RT). These sites were selected because they (a) fill in areas not covered by the standard sites, (b) overlie brain regions believed to be important in processing language, and (c) have shown consistent differences in previous ERP language studies (e.g. Neville et al., 1982; see also Kutas & Van Petten, 1988).[3]

The electroencephalogram was amplified with Grass 7P511 amplifiers (3dB cut-off, 0.01 and 100 Hz) and digitised on-line at 200 Hz. Average ERPs were formed from trials on which a correct response occurred and that were free of ocular and movement artefact. Separate ERPs were formed for the four types of target stimuli (related, unrelated, pseudoword, and nonword) in both modalities (auditory and visual) at each of the electrode sites. In addition, two sets of "difference waves" were formed by subtracting the ERPs from the related condition from the ERPs in the unrelated and pseudoword conditions (unrelated-related and pseudoword-related).

Data Summary

Mean reaction times (RTs) for correct responses between 200 and 2000 msec and the percentage of errors to targets were calculated for each subject. The ERP data were quantified in four different ways. First, the peak amplitude (the voltage at the most positive or negative point) and latency (the number of msec post-stimulus onset of the peak amplitude) of the ERP components at the different electrode sites were calculated. Peak measurements are most useful for isolating differences in the amplitude and latency of "early" ERP components and components with clear peaks. For visual ERPs, the following windows were utilised for isolating the first four components usually found in ERP language studies: Pl (occipital and parietal sites), 50-150 msec; N1 (occipital and parietal sites), 125-225 msec; N1 (temporal and frontal electrodes), 50-150 msec; P2 (temporal and frontal sites), 130-300 msec; N400 (all sites), 280-550 msec. For auditory ERPs, the following windows were used (same window for all sites): P1, 0-100 msec; N1, 50-150 msec; P2, 150-300 msec; N2, 200

[3]Four electrodes were also placed down the centre of the head (Fz, Cz, Pz, and Oz) but data from these sites will not be presented here to keep the presentation of results more manageable. It should be noted that there were no major contradictions between the midline and lateral data sets.

[4]This approach has been used by others (e.g. Rugg, 1985) to help visualise the N400 component, which shows up in such waveforms as a broad negativity peaking at about 400 msec. One advantage of using difference waves is that modality-specific ERP components that are invariant between conditions cancel out making, for example, between-modality comparisons more meaningful. The rationale for subtracting the related word condition waveforms from both the unrelated words and the pseudowords was that it was the closest thing to a baseline or "no N400" condition. This procedure makes it possible to contrast directly the differences between unrelated words and pseudowords.

325 msec; N4, 300-600 msec. Secondly, five window or "epoch" measures (the mean voltage between two time points) were calculated: 0-150, 150300, 300-500, 500-750, and 750-1140 msec. These epochs were chosen because they roughly correspond to the latency ranges of the N1, P2, N400, P3, and slow-wave (SW) components typically reported in cognitive ERP studies. Mean amplitudes are better suited for use with slower and/or more broad-based ERP components. Thirdly, to facilitate between-modality comparisons, the mean amplitude between 200 and 700 msec was calculated at each electrode site, in both modalities for both types of difference waves (unrelated-related and pseudoword-related).

RESULTS

Data Analysis

The approach to statistical analysis involved the use of analyses of variance with either 2, 3, or 4 repeated measures (BMDP2V). Three separate analyses were performed on RT, errors, and the ERP epoch measures. These included contrasts between: (1) the two word targets (related vs unrelated; (2) the two nonword targets (pseudoword vs nonword); and (3) the two unprimed but orthographically and phonologically legal targets (unrelated vs pseudowords). The unrelated-related condition was contrasted with the pseudoword-related condition in analyses of the difference waves. For reaction time, errors, and difference waves, modality was included as a factor, but because of morphological (shape) differences in visual and auditory waveforms (see Figs 1 and 2), separate analyses were performed for each modality for the latency, peak amplitude, and area measures. Electrode site (occipital vs parietal vs temporo-parietal vs temporal vs frontal) and hemisphere (right vs left) served as additional factors in all ERP analyses. The Geisser-Greenhouse correction (Geisser & Greenhouse, 1959) was applied to all repeated measures with greater than 1° of freedom.

Behavioural Data

Mean RTs for each of the four target types are presented in Table 1. Visual target responses were on average 105 msec faster than auditory responses. In both modalities, related words were responded to faster than unrelated words [$F(1,15) = 58.05$, $P < 0.0001$]. This difference was greater in the auditory than the visual modality [modality x target type interaction: $F(1,15) = 12.63$, $P < 0.003$]. In both modalities, nonwords were responded to faster than pseudowords [$F(1,15) = 90.39$, $P < 0.0001$] and unrelated words were responded to faster than pseudowords [$F(1,15) = 39.89$, $P < 0.0001$].

TABLE 1

Mean Reaction Time (RT) and Percentage of Errors

	Related Words	*Unrelated Words*	*Pseudowords*	*Nonwords*
Visual				
RT	653(92)	686(79)	808 (103)	630(74)
% errors	0.5 (1.0)	1.6 (1.8)	2.8 (2.8)	0.7 (1.3)
Auditory				
RT	718 (89)	827 (87)	932 (110)	716(85)
% errors	0.4 (1.0)	1.8 (1.6)	3.8 (3.0)	0.4 (0.8)

Standard deviations are in parentheses.

The overall error rate was 1.5% and there was no *indication* of a speed accuracy trade-off in either modality (Table 1). Because of the large number of cases with 0% errors prior to analysis of variance, these data were transformed using the arc-sine procedure recommended by Myer (1979). There were no significant differences in the number of errors made between the modalities. Across the modalities, more errors were made to unrelated words than to related words [$F(1,15) = 18.47$, $P < 0.0006$], to pseudowords than to nonwords [$F(1,15) = 34.55$, $P < 0.0001$], and to pseudowords than unrelated words [$F(1,15) = 7.93$, $P < 0.013$].

Event-related Potentials

Components and Scale Distribution

The grand mean target ERPs from the two modalities are plotted in Figs 1 (words) and 2 (nonwords). As can be seen, there were both similarities and a number of differences between the modalities in the morphology and distribution of components across the scalp. As in previous studies, both auditory and visual stimuli elicited an anterior negativity that peaked around 100 msec (N1) followed by an anterior positivity around 220 msec (P2). In addition, over posterior regions visual stimuli elicited a positivity around 100 msec (P1) and a negativity around 160 msec (posterior N_1). In general, as in previous reports of ERPs elicited by language stimuli, the left hemisphere tended to be more negative than the right in this time period [0-150 msec: hemisphere effect for auditory stimuli, $F(1,15) = 8.86$, $P < 0.009$; hemisphere x electrode site for visual stimuli, $F(4,60) = 4.10$, $P < 0.022$; 150-300 msec: hemisphere effect for auditory stimuli, $F(1,15) = 17.47$, $P < 0.0008$; hemisphere x electrode site for visual stimuli, $F(4,60) = 2.64$, $P < 0.05$].

(a) Visual Targets

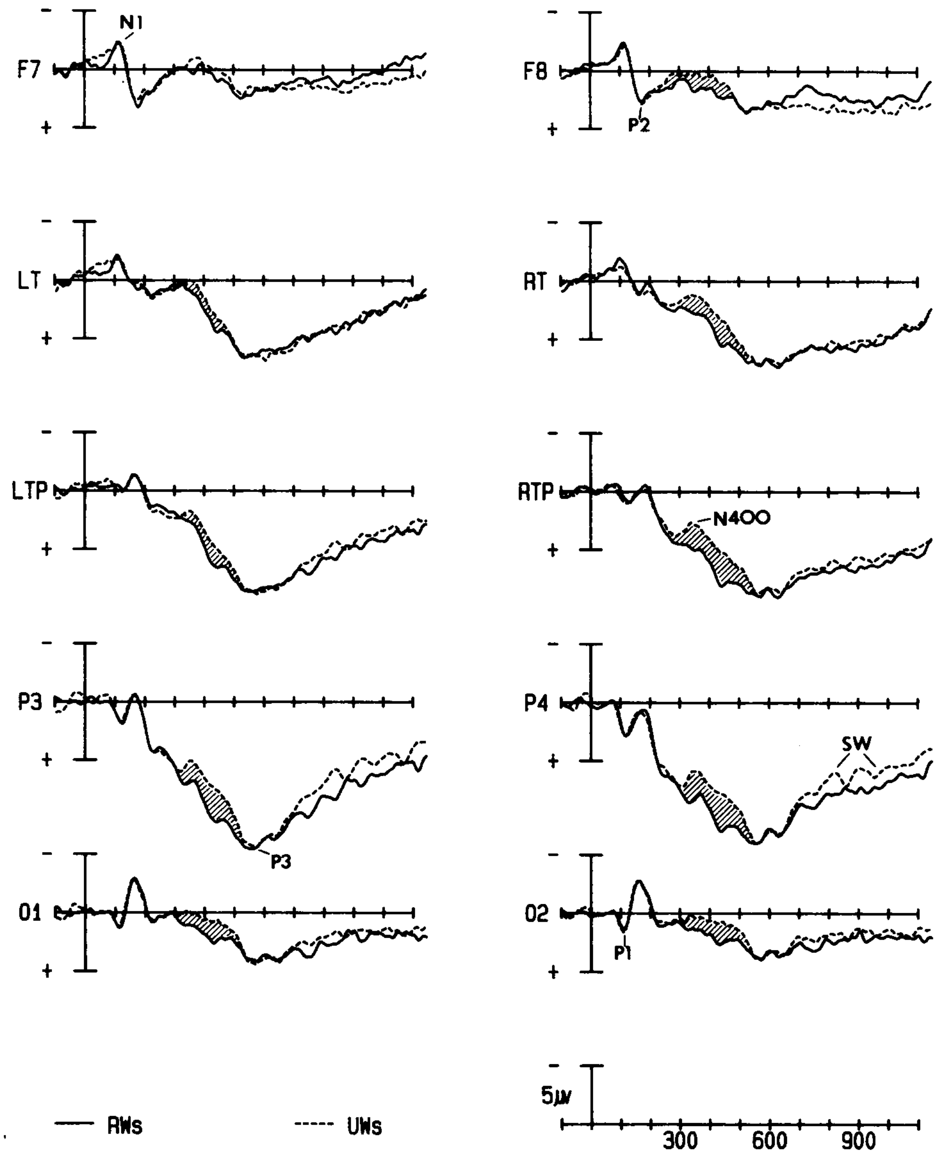
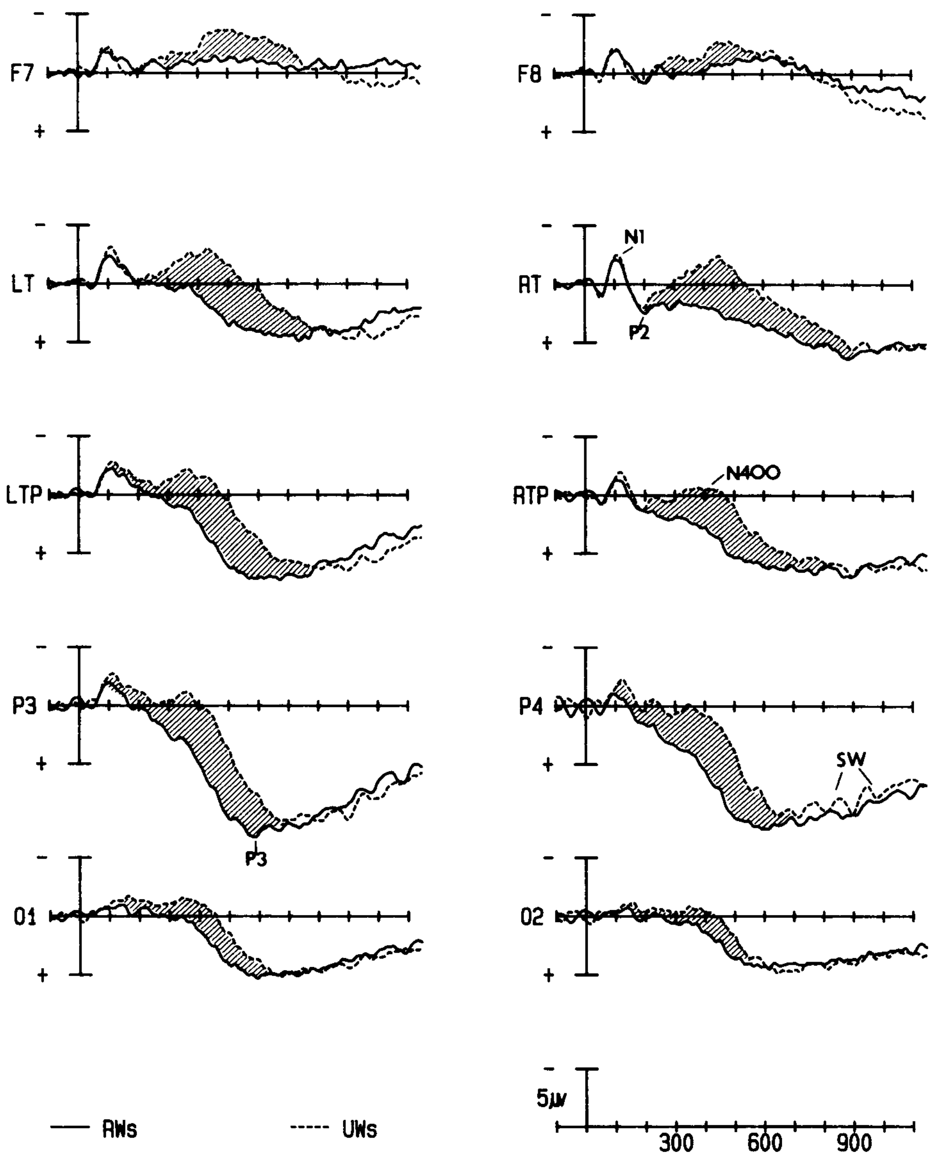


FIG. 1. Grand mean target ERPs to related (RWs) and unrelated (UWs) target words for the visual (a) and auditory (b) modalities. Time in msec, each tic mark is 100 msec. Stimulus onset is the vertical calibration bar. The diagonal hash lines represent the area of the N400 effect.

(b) Auditory Targets



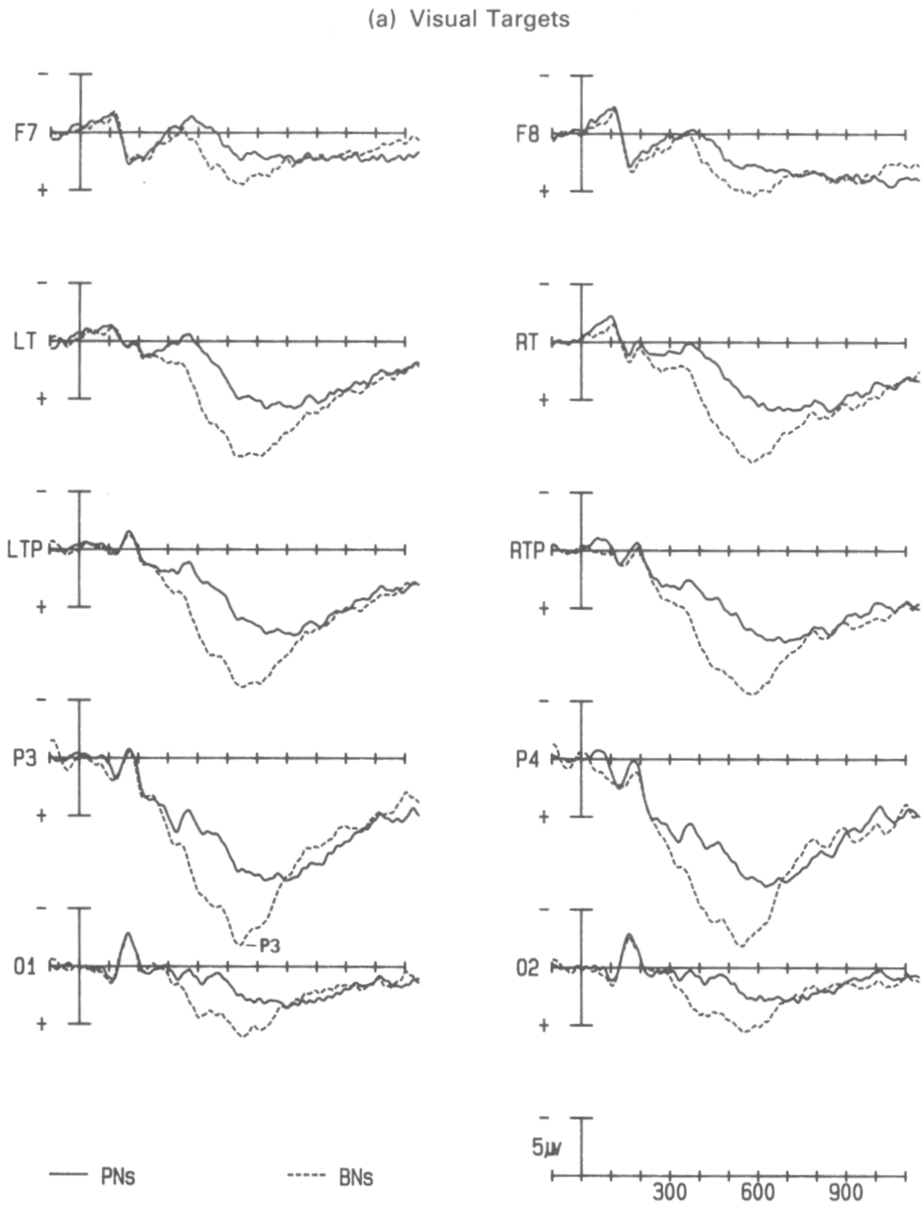
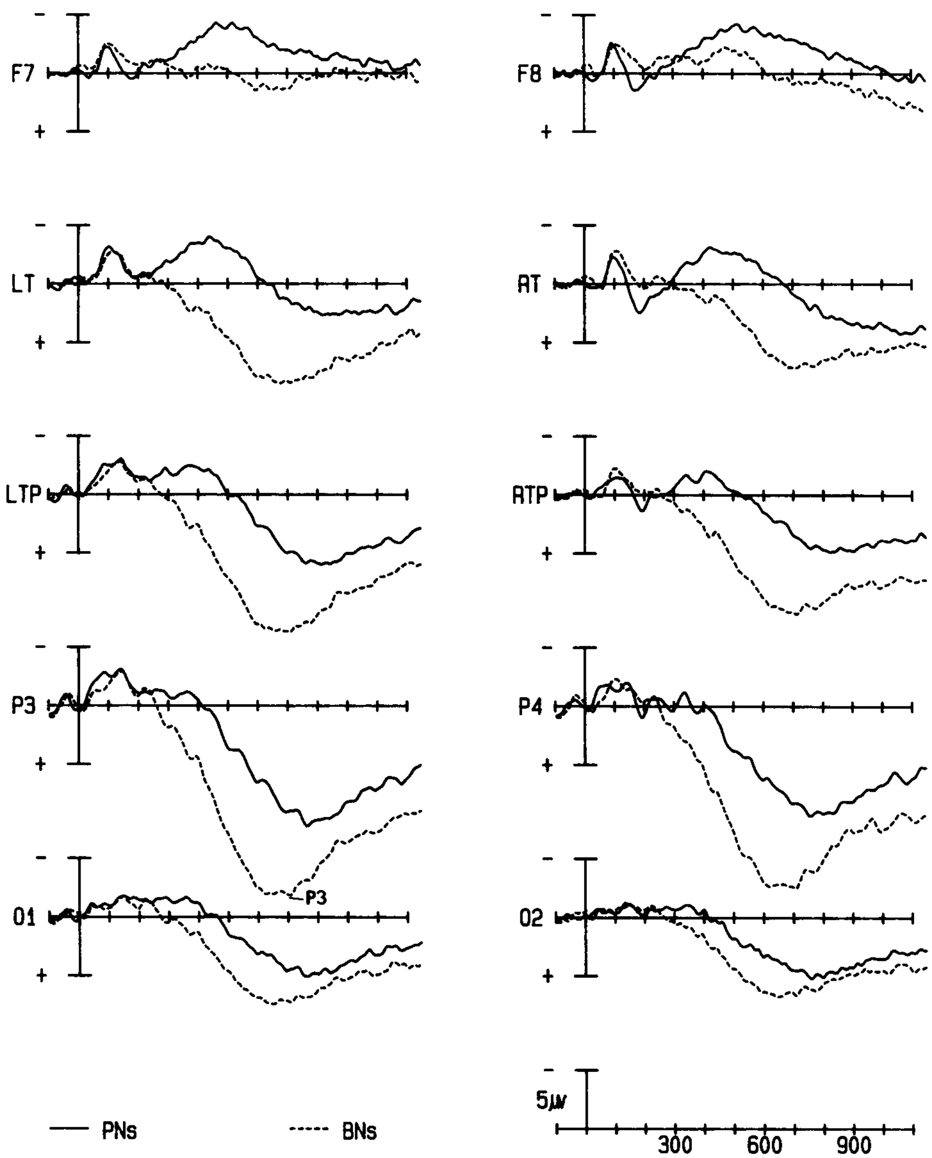


FIG. 2. Grand mean target ERPs to pseudowords (PNs) and nonwords (BNs) for the visual (a) and auditory (b) modalities. Time in msec, each tic mark is 100 msec. Stimulus onset is the vertical calibration bar.

(b) Auditory Targets



There were also several later ERP components visible in the waveforms from this study. Following P2, there was an anterior negative going wave that peaked between 350 and 500 msec (Fig. 1) and, as in previous visual studies (e.g. Neville et al., 1982), was larger over the left than the right hemisphere (hemisphere effect for related words at temporal sites: auditory, $F(1,15) = 18.10$, $P < 0.0007$; visual, $F(1,15) = 6.42$, $P < 0.02$]. Following this negativity, there was a large posteriorally distributed positivity (P3) that peaked between 500 and 700 msec (Figs 1 and 2). Finally, at the temporal, temporo-parietal, and parietal sites, there was a slow return to baseline (slow wave: SW) between 750 and 1140 msec. Neither of these two late positivities was significantly asymmetric.

Effects of Target Type

0-150 msec. An examination of Figs 1 and 2 suggests that there were no effects of target type on the ERPs to the target stimuli in the first 150 msec following stimulus onset. This observation was corroborated by the absence of main effects and interactions involving the target type variables.

150-300 msec. For the visual ERPs, there were no effects of target type in this time period. In contrast, auditory words were significantly different for the different target types. As can be seen in Fig. lb, the ERPs to auditory unrelated words were more negative than to the related words [main effect of target type: $F(1,15) = 18.35$, $P < 0.0007$] and this effect was most notable at the parietal and temporo-parietal sites [target type x electrode site interaction: $F(4,60) = 4.99$, $P < 0.021$]. The contrast between unrelated words and pseudowords was not significant in this time window. Auditory nonwords were more negative than pseudowords, but only at anterior and right hemisphere sites [target type x electrode site and target type x hemisphere interactions: $F(4,60) = 6.03$, $P < 0.007$; $F(1,15) = 7.92$, $P < 0.013$, respectively].

300-500 msec. As can be seen in Fig. la and b, between 300 and 500 msec, unrelated words were associated with a greater negativity than related words in both modalities [main effect of target type: auditory, $F(1,15) = 45.25$, $P < 0.0001$; visual, $F(1,15) = 12.22$, $P < 0.003$]. This effect was apparent at virtually every electrode location, but in the auditory modality was generally larger at the parietal, temporo-parietal, and temporal sites [target type x electrode site interaction: $F(4,60) = 18.39$, $P < 0.0001$]. Figure 2 makes it apparent that pseudowords were associated with more negative ERPs than nonwords at virtually every electrode site [main effect of target type: auditory,

$F(1,15) = 56.03$, $P < 0.0001$; visual, $F(1,15) = 39.06$, $P < 0.0001$]. Pseudowords and unrelated words were not significantly different between 300 and 500 msec in either modality. *500-750 msec.* Figure lb reveals that in the 500-750 msec epoch, auditory unrelated words remained more negative than related words [main effect of target type: $F(l,15) = 13.30$, $P < 0.0024$]. This effect was not apparent in the visual modality. ERPs to pseudowords were more negative than ERPs to unrelated words at most electrode sites in both modalities, but this effect was only consistent across electrodes for auditory stimuli [main effect of target type: $F(1,15) = 7.56$, $P < 0.015$]. Figure 2 also indicates that the nonwords were associated with a much larger P3 component than pseudowords [main effect of target type, pseudowords vs nonwords: auditory, $F(1,15) = 65.76$, $P < 0.0001$; visual, $F(1,15) = 19.81$, $P < 0.0005$].

750-1140 msec. In the final epoch (750-1140 msec), the only effects apparent in Figs 1 and 2 are in the auditory modality. Pseudowords were more negative than nonwords at all sites [main effect of target type: $F(1,15) = 21.18$, $P < 0.0003$] and pseudowords were more negative than unrelated words at the more anterior sites [target type x electrode site interaction: $F(4,60) = 3.92$, $P < 0.027$].

In summary, unprimed words (unrelated) were more negative than primed words (related) in both modalities, but this effect started earlier (150-300 vs 300-500 msec) and lasted longer (500-750 vs 300-500 msec) in the auditory than in the visual waveforms. The difference between wordlike (pseudowords) and un-word-like nonwords, also took the form of a larger negativity to the word-like nonwords (or, conversely, a larger positivity to nonwords). However, this effect did not differ in time of onset in the two modalities (300-500 msec), but lasted longer for the auditory than the visual stimuli (750-1140 vs 500-750 msec). The duration and size of the late negativity was greater for word-like nonwords (pseudowords) than for unrelated words, but the effects were only significant for auditory stimuli (from 500 to 1140 msec).

Difference Waves

The difference waves, formed by subtracting related from unrelated ERPs, and related from pseudoword ERPs, are plotted in Fig. 3. In both modalities, the most prominent feature was a large negativity with a peak between 400 and 475 msec and with a duration of several hundreds of milliseconds. This will be referred to as the N400 effect.

The average amplitude of the N400 effect across all electrodes between 200 and 700 msec was larger in the auditory than the visual modality [main

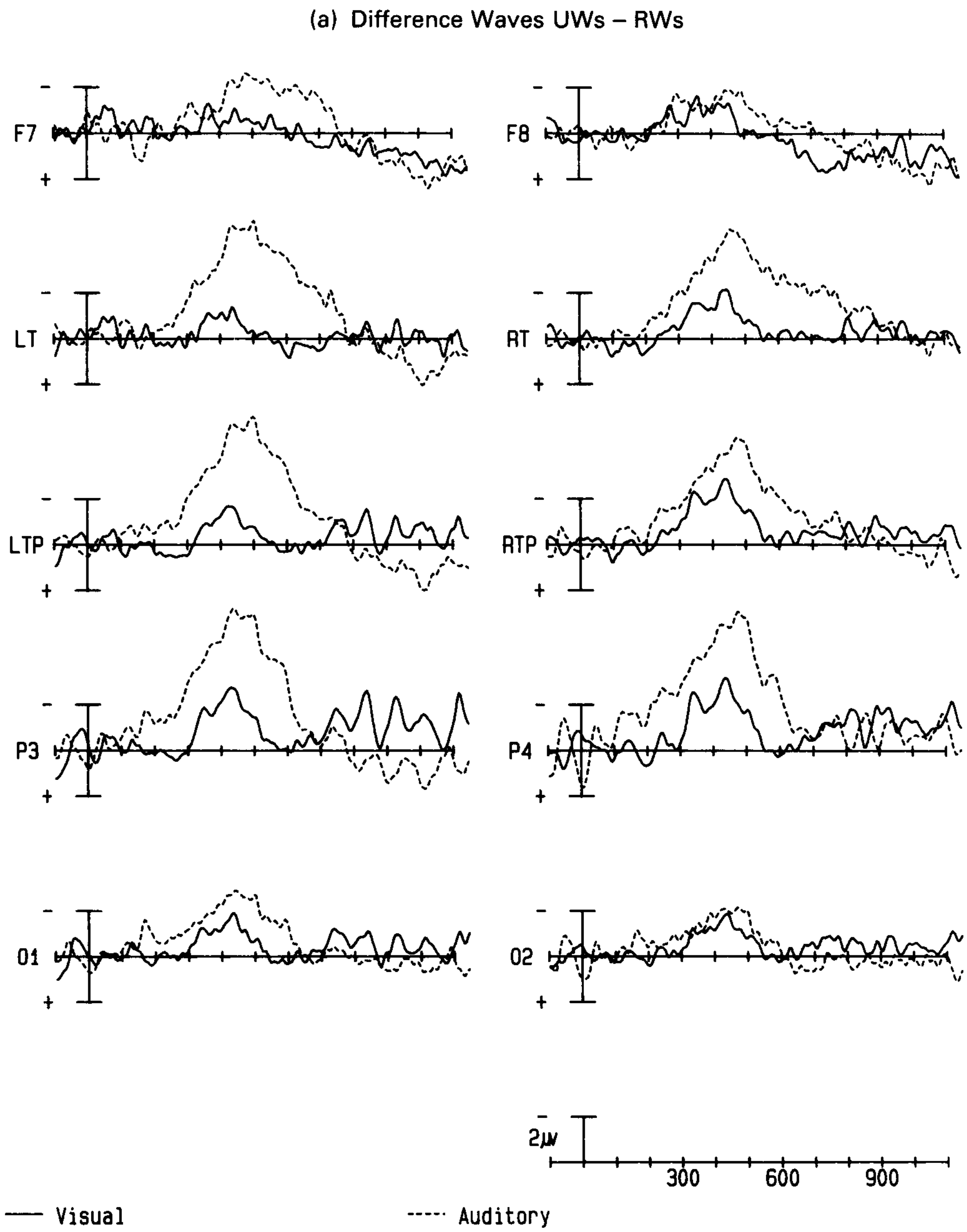
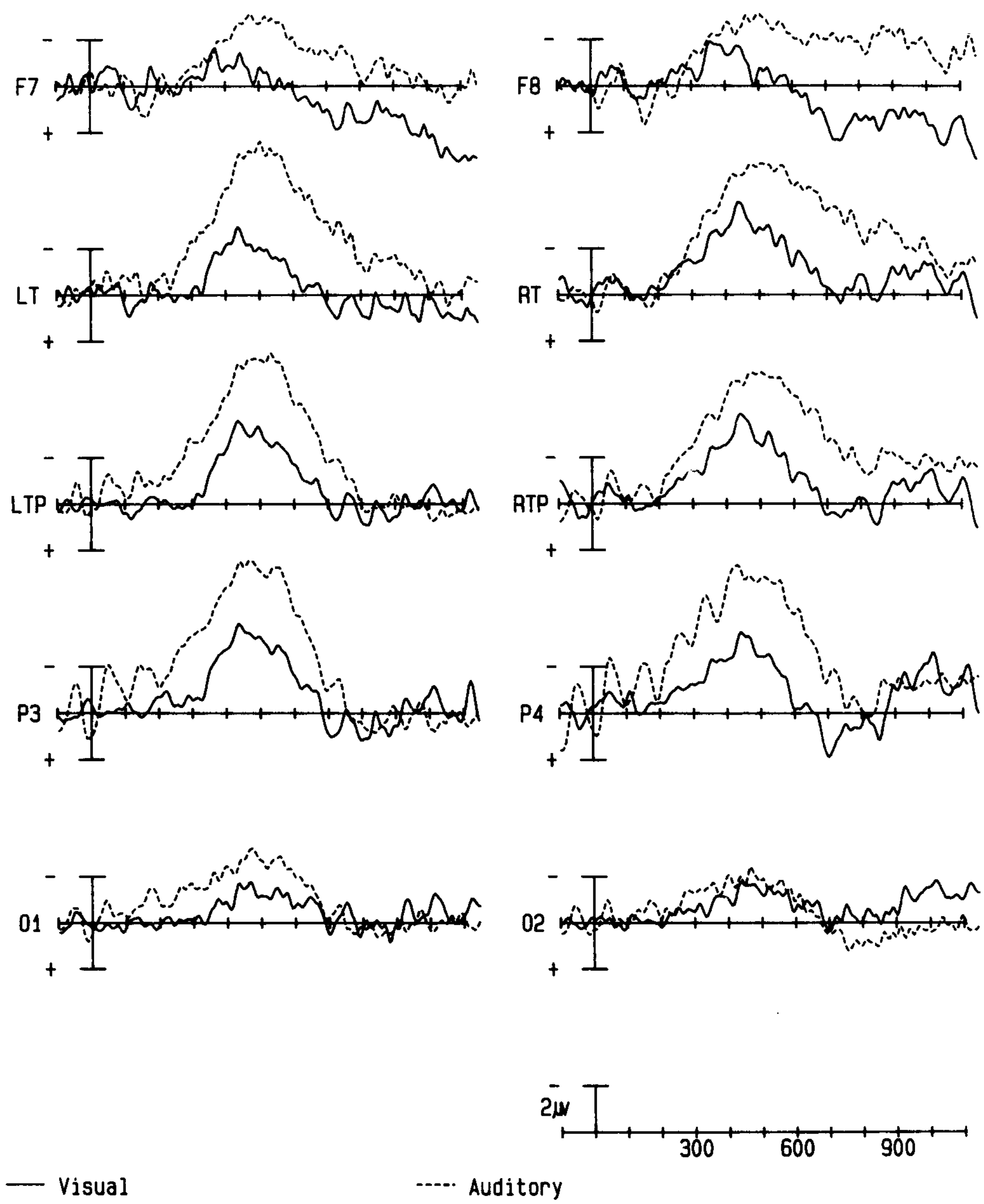


FIG. 3. Difference waves calculated by subtracting (a) related from unrelated ERPs and (b) related from pseudoword ERPs. Time in msec, each tic mark is 100 msec. Stimulus onset is the vertical calibration bar.

(b) Difference Waves PNs – RWs



effect of modality: $F(1,15) = 12.03$, $P < 0.0034$; see Table 2] and was larger in the pseudoword-related than the unrelated-related waveforms [main effect of target type: $F(1,15) = 4.20$, $P < 0.05$].

Figure 3b indicates that the pseudoword-related waves in the two modalities had similar distributions with parietal to temporal maxima [main effect of electrode site: $F(4,60) = 11.35$, $P < 0.0001$; modality x electrode site: $P > 0.13$]. However, an examination of Fig. 3a indicates there were differences in the scalp distribution of the N400 effect between the modalities for the unrelated-related condition [modality x electrode site interaction: $F(4,60) = 3.62$, $P < 0.02$]. The differences in distribution appear to be due to N400 having been largest at the parietal, temporoparietal, and temporal sites in both modalities, but having decreased relatively more at the frontal and occipital sites in the auditory waveforms. However, it is difficult to determine if this interaction reflects a true difference in the anterior-posterior distribution of the N400 effect between the modalities or was the result of a larger overall unrelated-related effect

TABLE 2

Mean N400 Amplitude in Difference Waves

	Unrelated Word-Related Word	*Pseudo word-Related Word*
Visual		
F7	-0.26(2.5)	-0.19 (3.3)
F8	-0.34(l.5)	-0.51(l.7)
LT	-0.13(l.8)	-1.03 (2.3)
RT	-0.67(l.7)	-1.95 (1.7)
WL	-0.27(l.9)	-1.51(2.1)
WR	-1.04(l.9)	-1.78 (1.4)
P3	-0.81(2.7)	-1.74 (2.3)
P4	-0.97(2.7)	-1.41 (1.9)
01	-0.47(2.2)	-0.73(l.8)
02	-0.57(2.4)	-0.85 (1.6)
Auditory		
F7	-1.39 (2.3)	-1.61(2.1)
F8	-0.93 (2.5)	-1.87(2.9)
LT	-2.87(2.6)	-3.91(2.5)
RT	-2.77 (2.0)	-3.91 (1.9)
WL	-3.01(l.8)	-3.97 (2.5)
WR	-2.49(l.9)	-3.95 (2.6)
P3	-3.36 (2.4)	-4.27(3.4)
P4	-3.35 (2.8)	-4.28(4.2)
01	-1.44(l.6)	-1.89(2.2)
02	-0.89(t.5)	-1.21 (2.0)

Standard deviations are in parentheses.

in the auditory modality. McCarthy and Wood (1985) have noted that the use of analysis of variance to evaluate interactions between scalp distribution (electrode site) and other variables (e.g. modality) can result in an increase in type 1 errors. This is because distributional effects can be multiplicative and analysis of variance assumes additivity. For this reason, the unrelated-related difference waves were re-analysed after first normalising the average amplitude between 200 and 700 msec separately within each modality (see McCarthy & Wood, 1985, for details). Using this procedure, the unrelated-related modality x electrode site interaction was no longer significant ($P < 0.64$).

As previous studies have reported that the N400 effect is larger over the right than the left parietal areas (see Kutas & Hillyard, 1984; Kutas & Van Petten, 1988; Neville et al., 1982), separate analyses were performed using only the tempoao-parietal electrodes. As in the previous studies, in the unrelated-related ERPs for visual stimuli, the N400 effect was larger over the right hemisphere, whereas in the auditory modality this effect was slightly larger over the left hemisphere [hemisphere x modality interaction: $F(1,15) = 4.48$, $P < 0.0515$; see Table 2]. By contrast, in the pseudoword-related difference waves, this interaction was not significant ($P > 0.68$). Also, at the temporal-parietal electrodes, N400 was clearly larger in the pseudoword-related than the unrelated-related waveforms for both auditory and visual modalities [main effect of target type: $F(1,15) = 10.94$, $P < 0.005$].

DISCUSSION AND SUMMARY

One of the goals of this study was to better characterise the processes underlying semantic priming within the auditory modality and to determine if these processes are similar to those in the visual modality. A secondary goal was to distinguish between two competing accounts of the processes underlying late ERP negativities that occur in semantic priming tasks.

Priming

With regard to the first goal, the results of this study reveal behavioural and electrophysiological evidence of auditory and visual semantic priming, corroborating and extending previous work by others (Bentin et al., 1985; McCallum et al., 1984). In both modalities, the subjects responded significantly slower and less accurately and produced significantly larger ERP negativities to target words preceded by semantically unrelated prime words than to target words preceded by related primes. This pattern of results is consistent with the hypothesis that similar mechanisms underlie semantic priming for visual and auditory words.

However, there were also several differences in the priming effect between the modalities. The ERP and behavioural (RT) priming effects were significantly larger in the auditory than the visual task, and while mean RTs were slower overall in the auditory task, the onset of the ERP effects were earlier and lasted longer in the auditory modality. In addition, while the overall pattern of the ERP scalp distribution was similar between the modalities, there was one notable difference in laterality. These differences would seem to weaken the argument for similar priming mechanisms between the modalities.

The results of this study also support previous suggestions (e.g. Kutas & Van Petten, 1988) that the late negativity recorded in this and other priming tasks was specific to linguistic events. While there was no evidence of a negative component in the 300-700 msec time range for nonwords in either modality, there was a large negativity that peaked near 400 msec for unrelated words and pseudowords in both modalities.

The polarity (negative), anterior-posterior distribution (larger over parietal and temporo-parietal sites), and direction of the difference between unrelated and related targets (unrelated more negative than related) suggests that the negativity peaking near 400 msec in the waveforms from both modalities is similar to the N400 component which several other investigators have reported to be sensitive to semantic priming in the visual modality (e.g. Bentin et al., 1985; Holcomb, 1986; 1988; Kutas & Hillyard, 1984; Kutas et al., 1984). For these reasons, we have referred to this negative component as the N400 and to the difference between related and unrelated words as the N400 effect.

Between-modality Comparisions of Priming

The ERPs to related and unrelated words started to differentiate between 200 and 290 msec in the auditory modality, whereas the analogous visual waves did not differ until 300-360 msec. This suggests that as early as 200 msec and certainly no later than 290 msec after target onset, information activated by the presentation of the prime affected the processing of auditory targets. As none of the auditory target stimuli in this experiment had durations shorter than 270 msec, these data support the work of Marslen-Wilson and colleagues (e.g. Marslen-Wilson & Welsh, 1978; Marslen-Wilson & Tyler, 1980) and Zwitserlood (1989), which has suggested that auditory word recognition can be achieved based on information available to the listener prior to the occurrence of the final sounds of a word. These data also support the hypothesis that this process can occur more quickly when semantically constraining information is provided to the listener. It should be noted that the 200-290 msec onset range for the ERP auditory priming effect is very close to the average latency (278 msec) Zwitserlood (1989) found for the earliest facilitation effects of spoken sentence contexts on word recognition.

The later onset of the ERP priming effect for visual words suggests that, although all the information contained in a written word is available at stimulus onset, the process required to differentiate related and unrelated words does not begin until some relatively later point in time. Although controversial, there is a class of theories that makes predictions consistent with the modality differences seen here. In these models, visually presented words undergo an initial process where their features are translated into an auditory code (so-called phonological recoding) prior to making contact with the lexicon (e.g. Coltheart, 1978, for a review, see McCusker, Hillinger, & Bias, 1981). This additional translation might delay the initial lexical processing of visual words. Spoken words, on the other hand, do not need to engage such a translation process and therefore may begin to activate their lexical entries sooner (but see Humphreys & Evett, 1985; Seidenberg, 1985).

The above formulation can account for the difference in the onset latency of the N400 between the modalities but appears to run into trouble in trying to account simultaneously for the later mean RT and later N400 offset for auditory targets. How could the process of differentiating between related and unrelated words start so much earlier in the auditory modality and yet finish, on average, so much later? There are at least two possible reasons.

First, it seems clear that information available early in an auditory word can, under normal listening conditions, initiate and in some cases lead to the completion of the word recognition process prior to all sounds in that word becoming available (Marslen-Wilson, 1987; Zwitserlood, 1989). However, in an auditory lexical decision task, where a portion of the target stimuli are, in a sense, catch-trials (pseudowords that sound much like real words up until late in the utterance), the listener cannot in many cases be sure of the status of an item until the final sounds arrive (as long as 700 msec in this experiment). This could conceivably have led subjects to postpone their behavioural lexical decision response and may have led to a more prolonged N400. This possibility suggests that the N400 may be sensitive to subject-controlled or "strategic" factors (Holcomb, 1988).

A second possibility for the longer duration of the N400 effect and later RT to auditory words may reflect the variability and longer average duration of auditory words. That is, the early onset of the auditory N400 may have been due to short duration words, while the late offset may have been due to that subset of words with long durations. Similarly, the longer auditory RT may have been due to the longer average duration of auditory words (there was no difference in visual word durations). However, if RT bears a relationship to auditory word duration, then the variability in RT across items should have been greater in the auditory session. Although auditory words had a greater average standard deviation than visual words (201 vs 177 msec), this difference was not significant ($P < 0.19$), suggesting that item variability cannot account for the differences seen for the two modalities. Because of the design of the study and equipment limitations, we were unable to look for word duration effects on ERPs and therefore cannot be sure that these did not contribute to the broad base of the N400. In future studies, we intend to explore this possibility more carefully.

The N400 and RT priming effects were also larger in the auditory than the visual modality. The reasons for this are not clear, but at least two possibilities exist. First, although there was no difference in the prime onset to target onset interval (SOA) between the two modalities, the interval between recognition of primes and targets may have been different due to the greater importance of temporal factors in auditory word processing. Previous studies have shown that priming in the visual modality is affected by relatively small changes in the interval between prime and target onset (e.g. Neely, 1977). However, because no similar work has been done with spoken language stimuli, it is unclear what effect similar changes in intervals would have in this modality. A second possibility is that the modality differences in priming were due to the visual effect being smaller than expected. Previous work by Holcomb (1988) and others (e.g. Bentin et al., 1985), using similar stimuli and procedures, have shown visual priming effects of similar size to those seen for auditory stimuli in the current study. However, it is difficult to see why this would be the case as the order of sessions and stimulus materials were carefully counterbalanced between the modalities.[5]

Functional Significance of N400

Pseudowords produced an N400-like negativity that was larger (both modalities) and longer in duration (auditory only) than that produced by unrelated words. There was no evidence in either modality of a similar negativity to nonwords. The auditory waveforms at certain sites did reveal nonwords to be more negative than pseudowords between 150 and 300 msec, however. This latter difference is

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[5]To explore the possibility that the order of modality may have played a role in the larger auditory N400 effect, we ran several follow-up analyses. There were no reliable statistical differences nor visible trends apparent in ERP plots between those subjects run in the visual modality first vs those run in the auditory modality first.

clearly not related to the N400 because it is maximal at anterior sites (N400 is larger at more posterior sites) and peaks at about 225 msec (Fig. 2b). Given its latency, this negativity to nonwords seems more likely to be an N2 mismatch effect (Naatanen, Simpson, & Loveless, 1982), possibly due to the physical deviation between word primes and subsequent nonwords. In both modalities, nonwords produced a large late positive component during the period when pseudowords and unrelated words were elicting N400s (Fig. 2). Similar large late positivities, usually referred to as the P3 component, have been reported in previous studies for stimuli perceived by the subject to be in a low-probability category (e.g. Johnson & Donchin,1980). As nonwords were the only truly non-linguistic stimuli and occurred on only 25% of the trials, they qualify as low-probability events.

One problem with the above interpretations is that the time course of the N400 is overlapped by the P3 component. The occurrence of a larger P3 component to nonwords could explain the absence of an N400 to these stimuli, as the larger P3 might have obscured an otherwise normal N400. This explanation seems unlikely, however, because unless the temporal coincidence is perfect, there should be some residual effect of the smaller (N400) component visible in the nonword waveforms. Figures 1 and 2 indicate that the P3 to nonwords has a later peak and time course than the N400s in the other three conditions. Therefore, if the N400 was masked in the nonword condition, there should have been some evidence of this in the initial phase of the positivity. Close examination of Figs 1 and 2 suggests that the nonword waveforms had the least N400-like activity of all four conditions-even less than related words.

Using similar logic, the presence of a later P3 to pseudowords than to unrelated words might explain the larger N400 to pseudowords (a later P3 might unmask more of the underlying N400). This does not seem to be a viable explanation in the current study, as the N400 difference between pseudowords and unrelated words had a different scalp distribution than the P3 component. The largest N400 difference was at more anterior sites, whereas P3 had its largest effects at more posterior sites.

The above findings have a number of implications for interpretations of the putative processes indexed by the N400. The occurrence of a large N400 to unprimed words and word-like pseudowords and its absence to nonwords is strong evidence that this component cannot be included in the category of generic negativities that reflect a general process of ". . . evaluation of stimulus similarity or dissimilarity", as argued by Polich (1985). If this were true, then N400 should have been larger to nonwords, because nonwords were dissimilar from the preceding prime on physical as well as lexical and semantic dimensions. Instead, these results suggest that N400 may be specific to linguistic events that are a member or a potential member of the subject's language system. The behavioural data are in agreement with this interpretation. Subjects were able to classify more quickly nonwords as non-English stimuli than pseudowords.

Further, these data raise the hypothesis that the N400 indexes some aspect of word recognition, possibly lexical access, and that its amplitude in some way reflects the amount of activity produced during this process. According to this account, N400 was small when the target was semantically related to the preceding prime word because the amount of activity required for accessing the target within the lexicon was reduced by residual activity associated with the prime. N400 was larger to unrelated words because these words did not benefit from the facilitating effects of a prior word and thus the amount of activity required to access the target item was greater. N400 was even larger and of longer duration to pseudowords, even though they do not have an entry in the lexicon. Perhaps this was because their word-like characteristics also produce lexical activation, but because no complete match was achieved the amount of activation produced was greater and more prolonged.

The major difficulty with this pre-lexical characterisation of the N400 is that previous work with the lexical decision task has shown that behavioural measures (RT) in this paradigm are sensitive to both pre- and postlexical influences, particularly at longer SOAs (e.g. Seidenberg et al., 1984). Is it possible that the N400 reflects activity in some post-lexical process (e.g. the integration of lexical information with other knowledge sources)? The largest problem for post-lexical accounts of the N400 is the presence of a large negativity to pseudoword stimuli. The term "postlexical" would seem to imply that the target item has been located in the lexicon, and that its lexically based information has been activated and passed on to stages further up-stream. What type of information is being passed further on for non-existent entries? One possibility is that partial lexical information is cascaded (e.g. McClelland, 1979) to post-lexical stages prior to a unique entry being selected at the lexical stage. On this account, the N400 to pseudowords could result from lexical information from a look-alike or sound-alike real word(s) being passed along to the post-lexical process responsible for the N400.

Another problem with a pre-lexical interpretation of the N400, at least in the visual modality, is its relatively late time course (greater than 300 msec for onset, mean latency 400 msec). Some behavioural studies have indicated that lexical access occurs on the order of 200-300 msec under normal reading conditions (e.g. Carroll & Slowiaczek, 1986). However, even in studies using eye gaze measures of reading time, it is diffiuclt to rule out the possibility that access is taking longer, but due to cascaded transmission of information successive eye fixations are only on average 250 msec apart. Unfortunately, the current study was not designed to settle the issue of prevs post-lexical explanations of the N400, and therefore this question must await the outcome of future research.

N400 Scalp Distribution

An important element of the argument for similar or the same processes underlying semantic priming between the modalities relies on the finding of similar scalp distributions for the N400 effect. Although the overall pattern of the effect was similar between the modalities, in auditory unrelatedrelated waveforms, there was a larger difference between the parietal, temporo-parietal, and temporal sites (those sites where N400 was largest) and the frontal and occipital sites (where it was smallest), i.e. modality x electrode site interaction. However, after normalising the ERPs within each modality (McCarthy & Wood, 1985), this effect disappeared suggesting that the anterior-posterior differences between the modalities were due to the overall larger auditory N400 and not to a genuine modality difference.[6]

Further evidence of similar N400 generators for the two modalities comes from looking at the pseudoword-related waves. These conditions did not produce a significantly different scalp pattern between the modalities either before or after normalisation.

Evidence supporting non-identical neural sources of the N400 in the two modalities comes from the significant difference in lateral (left vs right) distribution of this component in the unrelated-related waveforms. Visual waveforms were more negative over the right hemisphere and auditory waveforms were slightly more negative over the left hemisphere in the temporo-parietal electrode placements. In most previous work, in the visual modality there has been a small but reliable right greater than left N400 asymmetry (see Kutas, Van Petten, & Besson, 1988). In the only other auditory study that explored N400 laterality, there were no significant differences between the hemispheres (McCallum et al., 1984).

The scalp data suggest that while there is substantial overlap in the overall anterior-posterior distribution of the N400 between modalities, the difference in the lateral distribution of this ERP indicates non-identical sources of semantic priming in the two modalities. The goal of future studies should be to examine more carefully differences and similarities in the distribution of the N400 and other language-sensitive ERPs under a wider variety of conditions.

In summary, this study provides convincing behavioural and ERP evidence that semantic priming occurs in both the visual and auditory systems, indicating that it is a general manifestation of language processing across modalities. The current study also further demonstrates that the N400

[6]Simulation studies by McCarthy and Wood (1985) have shown that certain types of neural sources for scalp ERPs can propagate to the scalp in a multiplicative fashion. Because analysis of variance assumes additivity of variables, it can spuriously indicate a significant interaction between a scalp site and other variables.

component is specifically sensitive to linguistic events that are potential words in the lexicon of the reader/listener and raises the possibility that N400 may reflect some similar, but non-identical aspect of the word recognition process that goes on during reading and listening.

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APPENDIX

Related Pairs

List 1	*List 2*	*List 3*	*List 4*
BOTTOM-TOP	ASSIST-HELP	EAT-DRINK	UNCLE-AUNT
WAG-TAIL	KIND-MEAN	SHIRT-PANTS	UP-DOWN
COLOR-RED	OCEAN-SEA	MONEY-BANK	BACON-EGGS
TINY-SMALL	WIN-LOSE	SLEEP-DREAM	ICE-COLD

SKIRT-DRESS	SERPENT-SNAKE	SATIN-SILK	ALIVE-DEAD
KITTEN-CAT	TIME-CLOCK	STOVE-COOK	NO-YES
WILD-TAME	DIRTY-CLEAN	NEEDLE-THREAD	BLANKET-SHEET
BUTTER-BREAD	START-STOP	MOM-DAD	SPICE-HERB
SING-SONG	DOCTOR-NURSE	EAGLE-HAWK	JEWEL-GEM
HAMMER-NAIL	SPEND-SAVE	WET-DRY	ROCK-STONE
SICK-WELL	WAGON-CART	EARLY-LATE	PUPPY-DOG
MILDEW-MOLD	HUG-KISS	TEACH-LEARN	POTS-PANS
ONE-TWO	SAUCER-CUP	EVEN-ODD	CURTAIN-DRAPE
MONTH-YEAR	SHOE-SOCK	JOG-RUN	RICH-POOR
SNOW-RAIN	DINNER-LUNCH	KNIT-SEW	ARM-LEG
PUSH-PULL	SHIP-BOAT	RIP-TEAR	NEAR-FAR
JELLY-JAM	OPEN-CLOSE	FENCE-GATE	EMPTY-FULL
BEER-WINE	WAR-PEACE	READ-WRITE	LOST-FOUND
HEAVEN-HELL	ROBIN-BIRD	FLOWER-ROSE	HARD-SOFT
PORK-BEEF	MIX-STIR	PIG-HOG	HOME-HOUSE
HUNGER-THIRST	NICKEL-DIME	MAGIC-TRICK	MUD-DIRT
OLD-NEW	LIVE-DIE	PEA-POD	MIDGET-DWARF
RAZOR-SHAVE	MURDER-KILL	SCISSOR-CUT	WOMAN-MAN
MOON-STAR	LAMB-SHEEP	BLACK-WHITE	FROWN-SMILE
TABLE-CHAIR	SODA-POP	QUIET-LOUD	MANY-FEW
STAB-KNIFE	KING-QUEEN	TASTE-SMELL	HANDS-FEET
ANGRY-MAD	CIRCLE-SQUARE	SILVER-GOLD	AUTO-CAR
PEPPER-SALT	INK-PEN	ONCE-TWICE	FLOAT-SINK
KEY-LOCK	MINUS-PLUS	RIVER-STREAM	FUTURE-PAST
INSECT-BUG	HIDE-SEEK	BIG-LARGE	FLAME-FIRE
FRESH-STALE	SHOVEL-SPADE	FATHER-SON	MITTEN-GLOVE
NARROW-WIDE	COFFEE-TEA	LAKE-POND	FIRST-LAST
HALF-WHOLE	LEASE-RENT	BRONZE-BRASS	BEGIN-END
INCH-FOOT	SAD-CRY	CARPET-RUG	EYES-NOSE
GUN-SHOOT	HER-HIM	CAP-HAT	DIM-BRIGHT
FAIL-PASS	GOOD-BAD	MORE-LESS	SIT-STAND
CALF-COW	GOOSE-DUCK	CUB-BEAR	DUMB-SMART
TRUE-FALSE,	LONG-SHORT	FISH-SWIM	HOT-WARM
SCRATCH-ITCH	HOP-SKIP	COMB-HAIR	STING-HURT
BEST-WORST	FAST-SLOW	FAT-THIN	STEP-STAIR

Word-Pseudoword Pairs		Word-Nonword Pairs[7]	
List 1	*List 2*	*List 1*	*List 2*
ROW-NARF	ELK-ROOP	PLUG-NLPS	BOOT-SKSR
WASTE-LURID	FLASH-KLOIT	SHARK-GNRRP	DUMP-PLHP
PEG-JANK	ROOT-SELK	PONY-HGH	MONDAY-SRN
SCALE-MARG	HEAVY-GOID	BOX-DRPB	BURP-KNSKD
SEX-LAZ	EIGHT-RAB	SUMMER-LNDS	CAN-TNRS
TAPE-ROIP	PURPLE-RALT	POLE-TSRW	PERSON-DGPQS

[7] The primes and targets from these two lists were used in the visual nonword condition. Only the prime words were used in the auditory modality. Auditory nonwords were constructed by reversing targets from related lists 1 and 2.

COWBOY-GEFT	SHAPE-TROCH	ENTER-TCBWS	EAR-DDRT
COURT-YAD	JERK-FLOT	TRAIL-DRBH	BROWN-SRNKT
ORGAN-KACK	DART-JOP	ROPE-SLFB	STUPID-KCDR
ONLY-HAN	MESS-HAP	POOL-SPSR	BAKER-TRCP
OFFICE-BLOFT	CURL-NANE	CORNER-TBBHS	PUPPET-PKSL
NICE-LIERD	RESERVE-COIST	CHEST-LHWD	MOP-WLSN
PUBLIC-PLUT	CRUEL-SCROPT	FAITH-HGLS	PICTURE-MWSP
RHYME-BIX	FOLD-YOINT	LAW-RBLP	CATTLE-KCBG
STUMP-ROD	WINTER-GAT	CHERRY-MJLNR	TRADE-KCTSP
NYLON-COGE	PAGE-LOIF	BEND-ELT	MIND-YCW
TEAM-HALB	DIRECT-PIBE	REMIND-LHLR	ERROR-KSTS
NAP-NAS	BLAST-BURBS	YARD-KCLPQ	MODEL-NPR
SKIN-FRUCK	EITHER-FAZ	PLEASE-FNKR	BOW-PCSWGT
TAG-FELP	COUNT-CRID	BLOCK-TSRHT	MILE-HCNLP
BONNET-HERM	GLASS-RUNKS	FIVE-RTSP	ORDER-NUQ
PANEL-FRANT	MEAT-GRAG	SHINY-WHN	DECK-PHSLM
RICE-FLART	CREEK-ULG	YELLOW-FRRB	THREE-DRP
SKI-FARS	FILE-KARF	MOOD-CPBTP	BLADE-RTSK
PILLOW-MULT	GARDEN-POIT	BLOOD-DRD	THINK-NWXR
AWAKE-BARG	SERVE-SKALT	CALL-PTS	DIVE-SLCV
BARGAIN-HURPS	DRAG-DARSK	TIGER-DRCZVR	GRAPE-DRB
PARK-DIND	HANG-MARN	RABBIT-WCPN	TIMBER-MOPQ
TANK-NAR	FEMALE-MECH	POLICE-LPLR	PUNISH-TBBS
MAMMAL-BRUVE	MATTER-POLF	TWIG-NRDT	WINDOW-KCSP
SIZE-FRINK	COVER-CULF	FAKE-WTS	FADE-DNTSP
ROBOT-LARP	SHOCK-DULK	BULB-VHSP	NAME-LNLSP
AUTHOR-GROIDS	CRAZY-DAFE	FINISH-LSLW	MISTER-PPR
CELLAR-FLIG	DRUM-OIF	SHIVER-GNSVH	EQUAL-VSLM
ROCKET-JOOB	HAM-CHOF	ALLEY-GNSWQ	BIRTH-PTST
REWARD-GRUSP	LIFT-DALFT	STRIKE-RHL	BEANS-KCLCW
DEN-MARB	ENJOY-FUNTS	PLANT-MTPSN	FANCY-RQSPT
ROOF-SAR	HEEL-SOND	BARLEY-TLSG	GOAT-SLNV
PAY-LARMP	JELLO-TOR	ADD-GBR	RESULT-NMR
SCORE-GRUPH	CREATE-LOINK	SHADE-SRSDP	CAMP-SCSHP