

Cross-modal Semantic Priming: A Time-course Analysis Using Event-related Brain Potentials

Phillip J. Holcomb and Jane E. Anderson
*Department of Psychology, Tufts University, Medford,
Massachusetts, USA*

In two experiments, the time-course of behavioural and electrophysiological measures of semantic priming were examined between the visual and auditory modalities. In Experiment 1, auditory targets (words and pseudowords) were paired with visual prime words that onset either simultaneously with the target (0 msec stimulus onset asynchrony, SOA) or at one of two delays (200 and 800 msec SOA). Subjects made speeded lexical decisions to the auditory targets. Large priming effects were found across the three SOAs for reaction time and the N400 effect (the difference between related and unrelated target words). In Experiment 2, auditory primes were paired with visual targets. Here significant behavioural priming was found across the SOAs (larger for 0 and 800 msec), but the N400 effect was significant only for the 200 and 800 msec conditions. It is suggested that the data are most consistent with an amodal semantic system that is tapped by separate modality specific encoding processes.

INTRODUCTION

Over the past several decades, psycholinguists and cognitive psychologists have shown substantial interest in the processes and representations underlying language comprehension during reading and listening. However, comparatively little emphasis has been placed on determining the locus or extent of common language processes across the modalities (but see Bradley & Forster, 1987; Ellis & Young, 1988; Radeau et al., 1992; Shallice, 1988). On the one hand, it seems obvious that written and spoken words place unique demands on the reader/listener and that each modality must therefore enlist a set of its own "modality specific" processes during comprehension. However, it is equally clear that at some point after initial

Requests for reprints should be addressed to Phillip J. Holcomb, Department of Psychology, Tufts University, Medford, Massachusetts 02155, USA.

This research was supported by NIH Grant HD25889 to P.J.H.

encoding operations that a shared "common" set of processes and/or representations must be employed during reading and listening. The issue we wish to begin to address here is the locus of such common processes/ representations. The results from two experiments will be reported that directly examined the time-course of semantic priming between the modalities using event-related brain potentials (ERPs).

Although there is some question about the exact locus of semantic priming effects during word processing (e.g. see Neely, 1991, for a recent review), in the case of ERPs, there is at least partial consensus that the N400 component (a negative-going ERP that peaks at approximately 400 msec post-stimulus onset) is most sensitive to a relatively late post-recognition "integrative" process (e.g. Brown & Hagoort, 1993; Holcomb, 1993; Rugg, 1990). In a host of studies (see Osterhout and Holcomb, in press, for a review) it has been shown that the N400 is larger in amplitude to target words that are more difficult to integrate semantically with a prior context. In these studies, context is typically manipulated by the presence or absence of a prior semantically related word or sentence fragment that predicts or fits with the target word.

In one such study, Holcomb and Neville (1990) reported a similar, but non-identical, set of semantic priming effects for word pairs presented separately in either the visual or auditory modalities. Their study, like the experiments to be reported here, examined the effects of a single word context (prime) on the N400 component of a target item presented 1150 msec later. In both modalities, they found a robust difference in the amplitude of the N400 when a target word was preceded by a semantically related prime word compared to when the same word was preceded by an unrelated word. However, the time-course and scalp distribution of this "N400 effect" ¹ was different for the two modalities. In particular, the effect onset earlier (200 vs 300 msec) and lasted longer (800 vs 600 msec) for spoken than for written words. Also, written words, as in several previous studies (e.g. Kutas & Hillyard, 1980; 1984), tended to produce a slightly larger effect over the right hemisphere while spoken words resulted in a more bilaterally symmetrical N400. Holcomb and Neville interpreted the earlier onset of the N400 effect for spoken words, which was less than the duration of even the shortest words presented, as supporting the hypothesis that spoken word recognition can occur on-line, prior to the arrival of all of a word's acoustic information. They pointed out that this conclusion is consistent with the cohort model of Marslen-Wilson and colleagues (e.g. Marslen-Wilson, 1987; Marslen-Wilson & Tyler, 1980; Marslen-Wilson & Welsh, 1978).

¹In a semantic priming task, the "N400 effect" refers to the difference in the N400 components elicited by unprimed vs primed words-unprimed words elicit a more negative-going N400 compared to words that are primed.

In a second study, Holcomb and Neville (1991) demonstrated that the onset of the N400 can occur even earlier for spoken words in connected natural speech. In this experiment, the N400 effect between sentence final words that fit with the context of the sentence and final words that did not fit started as early as 50 msec post-word-onset (average final word duration was 561 msec). Holcomb and Neville attributed this even earlier auditory N400 effect to the influence of prosodic and co-articulatory cues that are usually present in connected natural speech. It should be noted that the 50 msec onset of the spoken sentence N400 effects contrasts with the findings from visually presented sentences where N400 effects do not usually start before 200 msec (e.g. Kutas & Hillyard, 1980).

The results discussed so far support the hypothesis that somewhat different mechanisms underlie semantic priming for spoken and written words and are consistent with the prediction that N400 priming *between* the modalities should either be absent or, at least, reveal a different pattern from within-modality priming. However, by at least one account, this prediction might not prove correct. Even if it is assumed that the modalities usually use different word recognition processes, they might, nevertheless, reveal robust between-modality priming due to some process that mediates between the modalities. There are at least three possibilities for such a process. The first two, collectively referred to here as the *conversion hypotheses*, argue that words are converted from one modality to the other during reading and possibly during listening as well. In the "recoding" version of this hypothesis, conversion presumably occurs early, prior to word recognition (e.g. Coltheart, 1978). In the "translation" version, conversion occurs only once a word has been recognised by a modality specific system. According to both of these views, between- and within-modality priming result from a somewhat different sequence of events. Within-modality priming results from a modality specific process (e.g. spreading activation within a unimodal lexicon and/or a post-lexical checking process that relies on semantic information from a modality specific system; see Neely, 1991, for a review of both types of priming mechanisms), and between-modality priming results from conversion of the prime into the target modality and the subsequent operation of a modality specific process. Therefore, it follows that between-modality priming should produce a different pattern of effects than within-modality priming, particularly if the prime and target words occur close together in time, that is, when the prime has not had time to be converted prior to the arrival of the target.

²Note that it is doubtful that the N400 could be used to differentiate between the recoding and translation hypotheses because of it being sensitive to a relatively late post-lexical priming process (Brown & Hagoort, 1993; Holcomb, 1993; Rugg, 1990).

A second possibility, the *common semantic system hypothesis*, suggests that while written and spoken words are processed in their own respective perceptual and lexical systems, they activate meanings in a common semantic or conceptual system. Although they did not discuss written and spoken words, Kroll and Potter (1984) have argued for such an amodal system in the case of written word and picture processing. According to this view, cross-modal priming takes place in an amodal semantic/ conceptual memory system (e.g. due to a process like spreading activation) that is shared by the modalities. This view also has the parsimonious advantage of using the same mechanism for accounting for within-modality priming and therefore predicts that a similar pattern of effects should be obtained for between- and within-modality conditions.

A number of studies have found evidence of between-modality priming using reaction time measures. These measures have been reported in both word pair tasks (Marslen-Wilson, 1987; Swinney, 1979) and in sentence tasks (Onifer & Swinney, 1981; Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, Onifer, Prather, & Hirshkowitz, 1979; Zwitserlood, 1989) where the sentence is usually presented in the auditory modality and a target word is presented visually. However, these findings are consistent with both of the above hypotheses about the source of between-modality priming, because in all of these reports the interval between the prime (context) and target items was relatively long, thus allowing time for a putative conversion process to intervene and possibly go unnoticed. Another problem with most of the prior cross-modal studies is that none of them used a truly on-line dependent measure, that is, one that can monitor a process as it occurs.

Recently, Anderson and Holcomb (submitted) compared the N400 effect in the visual and auditory modalities while manipulating the interval between the onset of the prime and target words (the stimulus onset asynchrony or SOA). They reasoned that changes in the N400 produced by varying the prime/target interval would reveal important information about the time-course of the processes underlying semantic priming. When both the prime and target words were presented in the visual modality (the prime just to the left of a fixation point and the target to the right), there were N400 priming effects present across the three SOAs (0, 200 and 800 msec), and when both the prime and target were presented in the auditory modality (the prime to the right ear and the target to the left), priming effects were found for the 0 and 800 msec conditions (they were not significant at 200 msec). These results demonstrate that in the case of simultaneously presented words (0 SOA), there is substantial temporal overlap in the processing of semantic information and suggests that the prime and target were being dealt with in parallel.

The primary purpose of the current experiments was to extend the

within-modality findings of Holcomb and Neville (1990; 1991) and Anderson and Holcomb (submitted) to the case where the prime and target words were in *different* modalities. Specifically, it was predicted that if between-modality priming (as measured by the N400) results from a conversion process, then there should be evidence of an N400 effect between modalities at relatively long prime/target intervals, but little if any evidence of such an effect at short intervals (i.e. prior to conversion). However, if between-modality priming results from activity in a common semantic system, then there should be evidence of an N400 effect between modalities at both short and long intervals (as was the case in the withinmodality conditions of Anderson and Holcomb).

Below we report the results of two experiments examining the time-course of between-modality priming. In the first experiment, the prime word was presented in the visual modality and the target item was presented auditorily (visual/auditory). In Experiment 2, the conditions were reversed and the prime was auditory and the target visual (auditory/visual). A lexical decision task in which one-third of the target items were pseudowords (e.g. doctor/teble) was used in both experiments. Among the word targets, half were semantically related to the prior prime word (doctor/ nurse) and half were unrelated (shoe/nurse). In such tasks, semantic priming effects are usually manifested by quicker and more accurate button presses to related target words compared to unrelated target words, and by smaller N400 amplitudes for related compared to unrelated targets. The interval between prime and target was also manipulated across three SOAs: long (800 msec), short (200 msec) and simultaneous onset (0 msec). The relatedness and SOA variables were mixed within a single experimental session so that the subjects did not know from trial to trial what level of each independent variable was coming next. Also, while they were told they were only to respond to the target items in both experiments, they were also instructed to read covertly (listen to) the prime word as well.

One unavoidable difference between the experiments was due to the very different temporal parameters of spoken and written words. In Experiment 1, even in the 0 SOA condition, the entire visual prime stimulus was available from the onset point of the auditory target, while in Experiment 2 only a small portion of even the shortest duration spoken prime was available at the same time as the entire visual target. However, we reasoned that this difference might not be as important as it appears because of the evidence for the onset of spoken word priming being earlier (e.g. Holcomb & Neville, 1990). Even though spoken words might have an average duration greater than 500 msec, it is clear that they access semantic information far earlier than this point (in fact, before written words!). As will be seen, this rationale did not prove to be totally correct.

EXPERIMENT 1: VISUAL/AUDITORY

The purpose of the first experiment was to determine if the same mechanisms supporting semantic priming within the auditory modality also mediate priming between visual and auditory words. It was predicted that if the same processes are involved, then there should be evidence of an N400 effect between modalities at the shortest SOAs. However, if between-modality priming is mediated via a conversion process, then only the longest prime-target interval (800 SOA) should show significant N400 effects.

Method

Subjects

Twelve right-handed Tufts University undergraduates (7 females, 5 males) with a mean age of 19.42 years ($SD = 1.68$ years) received partial course credit or \$10.00 for their participation. All of them were native speakers of English with normal visual and auditory acuity.

Stimuli and Procedure

Stimuli were presented on a 20-inch monitor (NEC model 5D) or binaurally through headphones (Sony MDR S30) under the control of an IBMPC compatible computer. The subject sat in a comfortable chair in a sound attenuating chamber. On each trial, the subject was presented with two stimuli. One (the prime) was a legal English word presented visually; the other (the target) was either a legal word or a pronounceable nonword (pseudoword) which was presented through headphones. Each subject was presented with a total of 360 visual-auditory pairs, comprised of equal proportions of semantically related, semantically unrelated and word/pseudoword pairs. This will be referred to as the *target type* variable. Examples of pairs for each of the three target type conditions are: SALT-PEPPER, MORE-TRUCK and NICKEL-PLONE. Unrelated pairs were formed by rearranging the related pairs so that the primes and targets did not have any semantic relationship. Pseudowords were constructed from legal words by altering one letter (phoneme) in such a way that it did not violate the orthographical or phonological rules of English. None of the pseudowords were pseudo-homophones. All visual stimuli were two to seven letters in length and all auditory stimuli were of one or two syllables.

Related and unrelated word pairs were selected from six similarly constructed lists of 40 related word pairs (see Appendix). The pairs of words and pseudowords were selected from three similarly constructed lists

of 40 word-pseudoword pairs. The word pairs were counterbalanced so that, across subjects, target words appeared in both the related and unrelated conditions and in each of the three SOA conditions (see below). However, within subjects, each list and therefore each stimulus was presented once.

A second within-subject variable was the stimulus onset asynchrony between items in each pair. Forty stimulus pairs in each of the three target type conditions (related, unrelated and pseudoword) were presented with an SOA of 0 msec, 40 others were presented with an SOA of 200 msec, and the remaining 40 were presented with an SOA of 800 msec. To summarise, each subject was presented with a total of 360 pairs of words (in a pseudorandom order) which were either related, unrelated or wordpseudoword pairs, and had an SOA of either 0, 200 or 800 msec, resulting in a total of 40 stimulus pairs in each of nine conditions (3 SOAs x 3 target types).

The visual stimuli were displayed as black lower-case letters on a white background. Each word subtended from 0.5° to 1.8° of horizontal and 0.4° of vertical visual angle. The auditory stimuli were spoken by a female member of our research team and were digitised (16 kHz, 24 pole 7.9 kHz Butterworth filter) by a Data Translations analogue-to-digital converter (12 bits, model DT2821). Each stimulus was edited using software that allowed us to listen to the stimulus while visually inspecting its waveform in order to store it from the time of onset. This was done so that the precise time of its onset could be time-locked with EEG digitisation. At the time of the experiment, the stimuli were output through a digital-to-analogue converter, then filtered (7.9 kHz) and sent to the subject's headphones. The average duration of auditory targets was 568 msec (range 300-862 msec).

Each trial began with a warning stimulus (a red "X") in the middle of the screen. Then, 500 msec later, the prime replaced the warning stimulus and remained on the screen for 200 msec. For the 0 msec SOA condition, the target onset was simultaneous with the onset of the prime; for the other two SOAs, the target onset was either 200 or 800 msec after the onset of the prime. Next, 1500 msec after the onset of the target, a green "X" appeared in the middle of the screen, indicating to the subject that it was alright to blink. Finally, after a 1250 msec inter-trial interval, the green "X" changed to a red "X" and the next trial began.

The subjects were instructed to respond as quickly and accurately as possible by pressing a button labelled "YES" with one thumb if the target was a real word, or a button labelled "NO" with their other thumb if it was not a real word. They were told to try to pay attention to the visual prime but not to make an overt response. The hand used for each re-sponse was counterbalanced across subjects. The subjects were told not to blink

or move their eyes while the stimuli were being presented. The experiment lasted about 35 min, including short breaks about every 60 trials. A practice block of eight trials preceded the experiment.

EEG Procedure

Tin electrodes were held in place on the scalp with an elastic cap (Electrode-Cap International). The scalp locations included standard International 10-20 system locations over the left and right hemispheres at the frontal (F7 and F8) and occipital sites (O1 and O2) and three locations on the midline: frontal (Fz), central (Cz) and parietal (Pz). In addition, six electrodes were placed at the following non-standard locations previously found to be sensitive to language manipulations (e.g. Holcomb, Coffey, & Neville, 1992; Holcomb & Neville, 1990; 1991): left and right temporal-parietal (Wernicke's area and its right hemisphere homologue, WL and WR: 30% of the interaural distance lateral to a point 13% of the nasion-inion distance posterior to Cz); left and right temporal (TL and TR: 33% of the interaural distance lateral to Cz); and left and right anterior-temporal (ATL and ATR: 50% of the distance between T3/4 and F7/8). To monitor for eye blinks, one electrode was placed below the left eye, and to monitor for horizontal eye movement, an electrode was placed lateral to the right eye. All the electrodes were referenced to the left mastoid, and the right mastoid was recorded from actively in order to determine if there were different experimental contributions to these two presumably neutral sites.

The electroencephalogram (EEG) was amplified by a Grass Model 12 amplifier system using a bandpass of 0.01 to 100 Hz (3 dB cut-off). The EEG was sampled continuously throughout the experiment (200 Hz), and off-line, separate ERPs were averaged (using a pre-target baseline of 100 msec) for each subject at each electrode site for the three target types (related, unrelated and pseudoword) at each of the three SOAs. Only correct response trials that were free of eye and muscle artifact were included. In addition, difference waves were formed by subtracting the ERPs of the related condition from the ERPs of the unrelated condition.

Data Analysis

The mean reaction times for correct responses between 200 and 2000 msec and the percentage of errors were calculated for each subject. ERPs to targets were quantified by measuring the mean amplitude in three latency windows: 300-550, 550-800 and 800-1150 msec. To examine the time-course of priming effects more closely, the mean amplitude measures of 100 msec epochs were also taken starting 100 msec post-target and

extending to 1100 msec. The use of multiple windows carries a greater risk of type 1 error; however, we utilise these analyses only as a supplementary measure to examine time-course effects.

Repeated measures analyses of variance (ANOVAs) were performed on the above dependent measures. A 2 x 3 ANOVA was done with target type (related vs unrelated: note that the pseudoword condition was not included in any of the analyses to be reported here) and SOA (0 vs 200 vs 800 msec) as the factors. For the ERP analyses, the midline and lateral sites were analysed separately. In addition to target type and SOA, for the midline analyses there was an electrode site factor [frontal (Fz) vs central (Cz) vs parietal (Pz)], and at the lateral sites there was an electrode site factor (frontal vs anterior-temporal vs temporal vs Wernicke's vs occipital) and a hemisphere factor (left vs right). Significant target type x SOA interactions were followed up with simple effects tests to help elucidate the source of the interaction. This involved analysing the effects of target type separately for each SOA. The Geisser-Greenhouse (1959) correction was applied to all analyses with more than one degree of freedom in the numerator.

Results

Behavioural Data

Across the SOA conditions, related targets were responded to more quickly than unrelated targets [main effect of target type: $F(1,11) = 74.89$, $P < 0.001$; see Table 1]. Reaction times for the 0 msec SOA were slightly longer than for the other SOAs; however, this difference only approached significance [main effect of SOA: $F(2,22) = 3.38$, $P < 0.06$]. The interaction between SOA and target type also approached significance [$F(2,22) = 3.80$, $P < 0.055$], indicating that the priming effect tended to become slightly larger as the SOA became longer. The subjects made more errors to the unrelated than to the related targets [main effect of target type: $F(1,11) = 42.19$, $P < 0.001$], and they made more errors to targets at the longer than at the shorter SOAs [main effect of SOA: $F(2,22) = 7.23$, $P < 0.009$].

Electrophysiological Data

The grand mean target ERPs are plotted in Fig. 1. Notice that these waveforms appear somewhat different at the three SOAs. This is due, in part, to the differential overlap of the visual prime and auditory target ERPs, particularly in the 0 and 200 msec SOA conditions. In the case of the 200 msec condition, the early P2 component from the prime-elicited

TABLE 1
(\pm SD) Reaction Times (msec) and Percent Errors

SOA		Related Words	Unrelated Words	Pseudowords
<i>Experiment 1: Visual/auditory</i>				
0	RT	822 \pm 91	889 \pm 100	985 \pm 98
	PE	1.9 \pm 1.9	4.0 \pm 2.2	8.6 \pm 6.7
200	RT	797 \pm 72	879 \pm 81	973 \pm 89
	PE	2.3 \pm 2.7	5.0 \pm 3.2	10.9 \pm 9.5
800	RT	779 \pm 82	892 \pm 74	954 \pm 77
	PE	2.3 \pm 3.1	8.6 \pm 4.3	7.7 \pm 6.1
<i>Experiment 2: Auditory/visual</i>				
0	RT	702 \pm 104	735 \pm 115	834 \pm 127
	PE	1.2 \pm 1.7	2.1 \pm 4.3	4.8 \pm 5.9
200	RT	670 \pm 119	686 \pm 137	813 \pm 141
	PE	1.7 \pm 3.6	1.9 \pm 3.0	4.2 \pm 5.1
800	RT	630 \pm 117	670 \pm 118	776 \pm 144
	PE	1.0 \pm 2.2	2.3 \pm 2.9	4.8 \pm 5.3

ERP occurred just as the auditory target stimulus onset. Thus the resulting target ERP is a summation of the activity generated by the target and the ongoing activity generated by the prime. Nevertheless, a large negativity, which peaked at approximately 100 msec (N100 or N1), can be seen at all three SOAs. The N1 was present at all but the most posterior sites (O1, O2) and was largest from the fronto-central electrodes. Following the N1 there was an equally large positive-going wave which peaked at approximately 200 msec (P200 or P2). The P2 had a similar scalp distribution to the N1.

The P2 component was followed by a broad negative-going wave peaking between 400 and 500 msec. This negativity, which overlaps the window usually associated with the N400, was largest (i.e. was most negative) at the more anterior sites. The broad negativity was followed at the more posterior sites by a late peaking positivity (P3), which continued through the end of the recording epoch (1180 msec).

Target Type Effects

300-550 msec. In this epoch, the unrelated targets elicited a significantly more negative-going ERP than the related targets [midline: $F(1, 11) = 18.34$, $P < 0.001$; lateral: $F(1, 11) = 17.6$, $P < 0.002$] and this "priming"

or N400 effect did not interact with the SOA variable. The interaction between priming and electrode site approached significance at the lateral sites [$F(4,44) = 3.79$, $P < 0.062$], indicating that target type differences were largest at the Wernicke's and temporal sites. Finally, there was no evidence for a lateral asymmetry in this epoch.

550-800 msec. Unrelated targets continued to be more negative-going than related targets in this epoch [main effect of target type, midline: $F(1,11) = 16.66$, $P < 0.002$; lateral: $F(1,11) = 24.39$, $P < 0.001$]. Also, the interaction between target type and electrode site was significant at the lateral sites [$F(4,44) = 6.37$, $P < 0.008$], indicating that priming was greatest at the Wernicke's and temporal sites. As in the previous epoch, there was no evidence of a significant difference in priming at the three SOAs (midline: $P > 0.15$; lateral: $P > 0.39$), nor was there a significant asymmetry in the priming effect across the hemispheres.

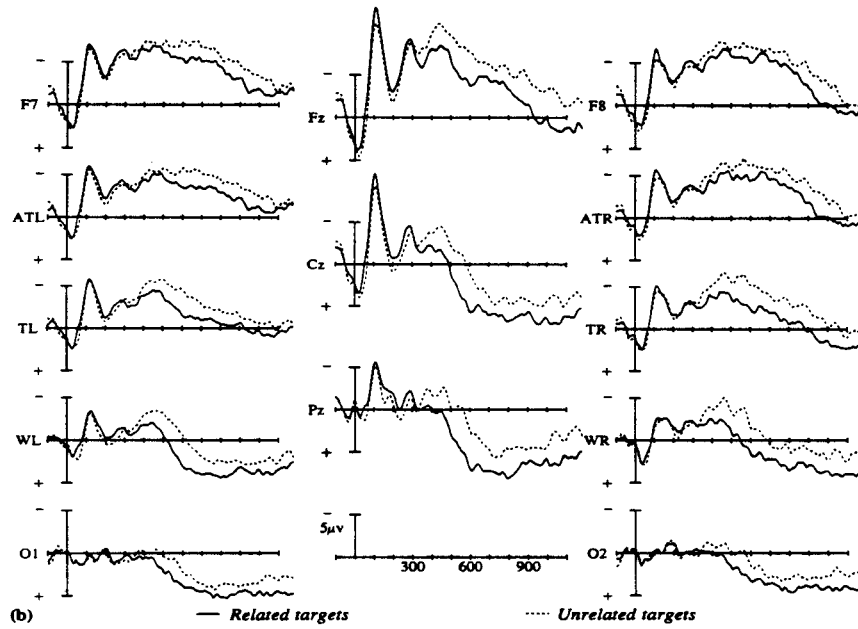
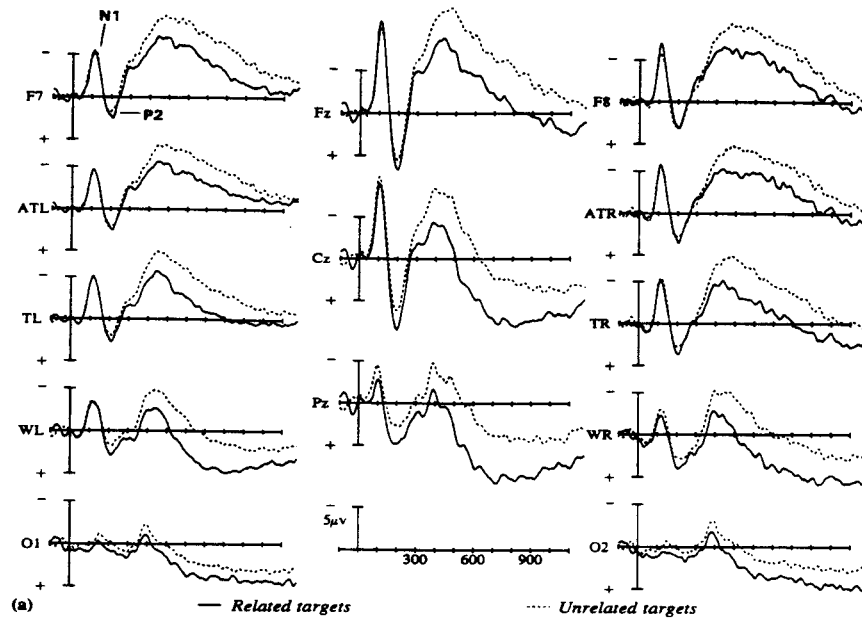
800-1150 msec. In the final epoch, the unrelated targets continued to produce more negative-going ERPs than related targets [main effect of target type, midline: $F(1,11) = 10.39$, $P < 0.008$; lateral: $F(1,11) = 9.87$, $P < 0.009$] and this effect did not differ across the three SOAs.

Time-course Analyses (100 msec Epochs). To examine the time-course of the priming effect, the waveform was divided into 100 msec epochs beginning with 100 msec and extending to 1100 msec. The differences in mean amplitude during each epoch are listed in Table 2. As can be seen from Table 2, the first reliable effects of relatedness occur starting in the 300-400 msec window and continue through to the end of the recording epoch. The only indication of a difference in priming between the SOAs is in the 200-300 msec window, where a significant SOA x target type interaction indicates that only the 0 SOA produced a priming effect.

Discussion

In Experiment 1, we examined semantic priming at different SOAs with the prime presented in the visual modality and the target in the auditory modality. Large effects, both behavioural and electrophysiological, were found across SOA conditions. The reaction time differences tended to be slightly larger as the SOA became longer (indicated by an interaction that approached significance). However, the magnitude of the ERP priming effect did not differ between the SOAs. This N400 effect began around 300 msec and continued to the end of the measuring epoch.

The fact that the visual primes were able to prime the auditory targets at the simultaneous (0 SOA) and 200 SOA conditions is most consistent



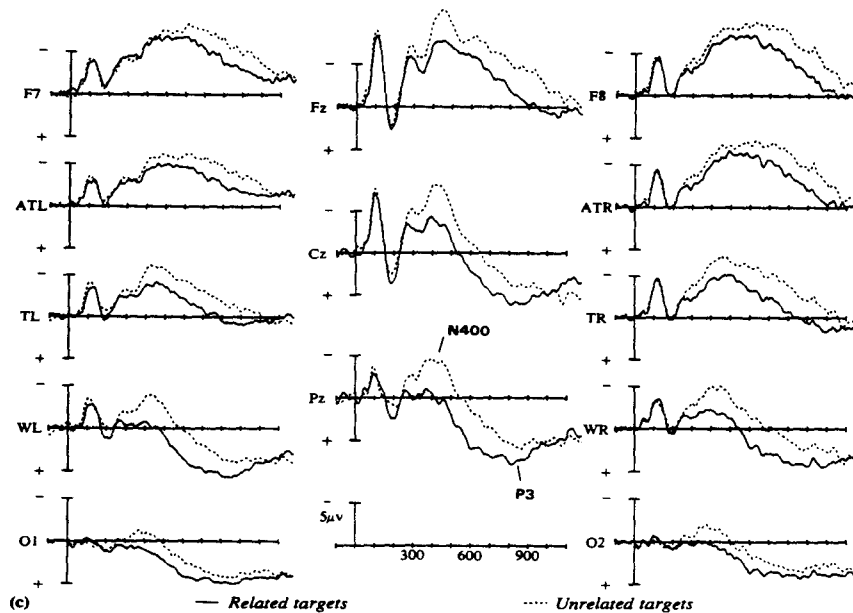


FIG. 1 Grand mean ERPs ($n = 12$) to related and unrelated auditory target words in Experiment 1: (a) 0 SOA condition; (b) 200 SOA condition; (c) 800 SOA condition. The ERPs in the left-hand column are from electrodes placed over the left hemisphere sites, the middle column is from the midline sites and the right-hand column is from the right hemisphere sites. Time is measured in msec, each tic mark representing 100 msec. Stimulus onset is the vertical calibration bar.

with the hypothesis that the two modalities share a common semantic process. If priming had been due to a conversion process, there should have been evidence of cross-modal priming effects only when there was sufficient time for such a process, that is, in the 800 SOA condition.

The pattern of results obtained in Experiment 1 was similar to that of Anderson and Holcomb (submitted). They found ERP evidence of short interval (0 SOA) priming when both the prime and target were auditory, although their effects were not as large or consistent as those in the present study. The similar early time-course of priming between these two studies is consistent with the hypothesis that within- and between-modality semantic priming (as measured here) rely on a common amodal semantic system.

The early onset of the N400 effect is also consistent with previous ERP findings (Holcomb & Neville, 1990; 1991) that auditory words can be recognised prior to their completion (Marslen-Wilson, 1987). The average length of the targets was 568 msec, with the shortest duration being 300 msec. The N400 effect began in the 300-400 msec window and approached

TABLE 2
The Size of the Semantic Priming Effect (Unrelated-Related) in μV at Each of the 100 msec Epochs for Each SOA in Experiment 1 (Visual Prime, Auditory Target)

<i>Epoch</i>	SOA			P-Values	
	<i>0</i>	<i>200</i>	<i>800</i>	<i>TT'</i>	<i>TTxSOA</i>
100-200 msec					
midline	-1.19	1.10	-0.42	NS	NS
lateral	-0.32	0.35	-0.09	NS	NS
200-300 msec					
midline	-1.58 ^a	1.03	1.00	NS	0.0267
lateral	-0.46	0.42	-0.48	NS	NS
300-400 msec					
midline	-2.89 ^c	-1.14	-2.50 ^b	0.0043	NS
lateral	-1.27 ^c	-0.64	-1.19 ^a	0.0073	NS
400-500 msec					
midline	-4.11 ^c	-2.60 ^b	-3.87 ^c	0.0014	NS
lateral	-2.28 ^d	-1.30 ^b	-1.83 ^c	0.0018	NS
500-600 msec					
midline	-5.57 ^c	-4.14 ^c	-2.97 ^b	0.0005	NS
lateral	-3.03 ^d	-2.14 ^c	-1.79 ^b	0.0002	NS
600-700 msec					
midline	-4.86 ^c	-2.69 ^b	-3.09 ^b	0.0024	NS
lateral	-2.75 ^c	-1.81 ^b	-2.17 ^c	0.0004	NS
700-800 msec					
midline	-4.88 ^c	-2.01	-2.73 ^b	0.0040	0.0914
lateral	-2.70 ^c	-1.47 ^a	-2.19 ^c	0.0015	NS
800-900 msec					
midline	-4.50 ^c	-2.33 ^a	-2.48 ^b	0.0038	NS
lateral	-2.69 ^c	-1.60 ^a	-1.89 ^b	0.0031	NS
900-1000 msec					
midline	-3.61 ^c	-2.34 ^b	-1.67	0.0153	NS
lateral	-2.11 ^c	-1.69 ^b	-1.80 ^b	0.0088	NS
1000-1100					
midline	-3.36 ^c	-3.05 ^c	-0.38	0.0128	0.0401
lateral	-1.82 ^b	-1.65 ^b	-0.81	0.0255	NS

Note: Superscripts indicate significance of separate analyses at each SOA. TT target type.

^aP < 0.1; ^bP < 0.05; ^cP < 0.01; ^dP < 0.001;

significance in the 200-300 msec window of the 0 SOA condition. This occurred even though in an auditory lexical decision task the subject should wait until the end of the word to make a behavioural response, since they cannot know for sure that an item is a real word until all of the acoustic information in that stimulus has been heard. This latter observation may account for the long duration of the N400 observed in this and other studies (e.g. Anderson & Holcomb, submitted; Holcomb & Neville, 1990). The scalp distribution of the N400 effect was also similar to Holcomb and Neville's (1990) auditory lexical decision study. The N400 effect was largest from more posterior lateral sites (temporal and Wernicke's) and was symmetrical across the hemispheres. Rugg et al. (this issue) report auditory repetition priming effects which began later than visual effects. In addition to task differences (repetition vs semantic priming), this may be due to the fact that their auditory stimuli had a longer average duration (about 659 msec) and lower frequency (see the General Discussion for a more thorough treatment of Rugg and coworkers' study).

EXPERIMENT 2: AUDITORY/VISUAL

The purpose of this experiment was to determine if the findings from Experiment 1 could be generalised to the case where the prime and target modalities are reversed (i.e. auditory/visual). Given the tentative conclusions outlined above for Experiment 1, it seems reasonable to predict a similar pattern of results for visual targets primed by auditory wordseven at short prime-target SOAs. That is, when an auditory prime onsets either simultaneously or shortly before a visual target, the processing of the initial sounds from the prime should influence the ongoing processing of the visual target. This prediction is based on the presence of semantic effects which onset as early as 200 msec in spoken word pairs (Holcomb & Neville, 1990) and in written/spoken pairs (Experiment 1). From these findings it was reasoned that if spoken words can be primed at this latency and if between-modality priming relies on the same mechanism as withinmodality priming, then a spoken word should also be able to prime a visual word at short intervals. It is noteworthy that the 0 SOA conditions in the two experiments are very similar, since in both cases a visual and an auditory stimulus are presented simultaneously. The major difference is in the instructions to the subject concerning which stimulus they should respond to.

Zwitserslood (1989) used a cross-modal procedure with auditorily presented sentence contexts and a sentence final word which was or was not semantically related to a visual target word. The visual probes were presented at the offset of auditory final word fragments which varied in

length. She found evidence of facilitation at short intervals (mean = 130 and 199 msec) of probes related to both the actual word to be presented and to a close "competitor" in the initial cohort, independent of the degree of biasing context. At longer intervals (mean = 278 and 410 msec), the pattern of activation changed, presumably reflecting the influence of contextual constraints and additional acoustic information on word selection. Zwitserlood's design, however, differed from that used in the current experiment in that the auditory prime word was terminated at the end of the SOA interval, so that in the shortest SOA condition the subjects heard, on average, only 130 msec of the prime word. In the current experiment, all prime words were fully presented. Another difference was that sentences were used in the study by Zwitserlood and word pairs were used in the present study.

Following the common semantic system hypothesis, it was predicted that a pattern of priming effects similar to those found in Experiment 1 would also be obtained in Experiment 2. That is, significant behavioural and ERP differences should be observed between the related and unrelated target types at all three SOAs. However, the conversion hypothesis predicts significant N400 effects only at longer intervals because of the additional time required for converting the prime or target to the other modality.

Method

Subjects

Twelve right-handed Tufts University undergraduates (7 females, 5 males) with a mean age of 18.5 ± 1.0 years received partial course credit for their participation. They were all native speakers of English with normal visual and auditory acuity. None of the subjects had participated in the first experiment.

Stimuli and Procedure

The lists of stimuli and the procedure were the same as those used in Experiment 1. The only difference between the experiments was that the modality of the prime and target were reversed. In Experiment 2, primes were presented in the auditory modality and targets in the visual modality. The average duration of the primes was 562 msec (range 375-812 msec).

Data Analysis

The data from Experiment 2 were analysed using the same procedures employed in Experiment 1.

Results

Behavioural Data

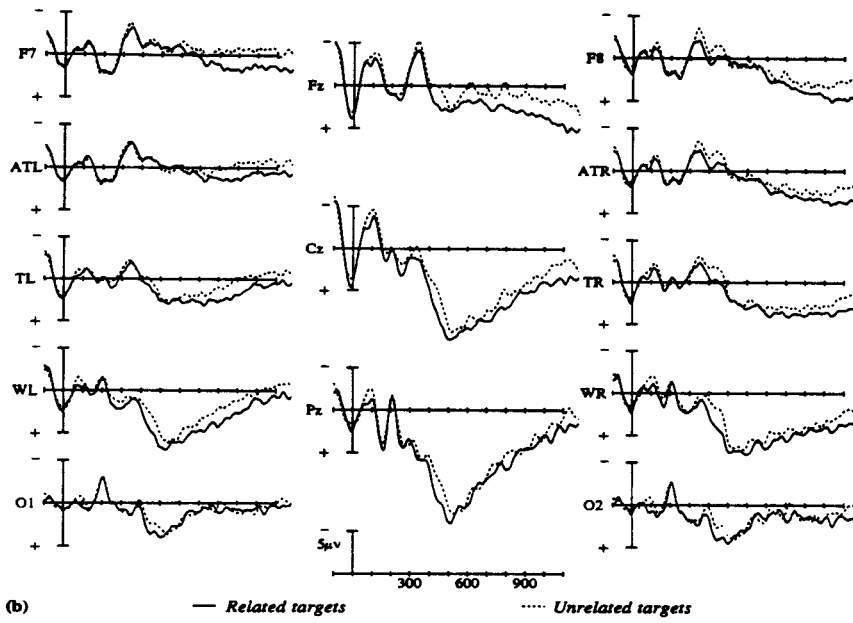
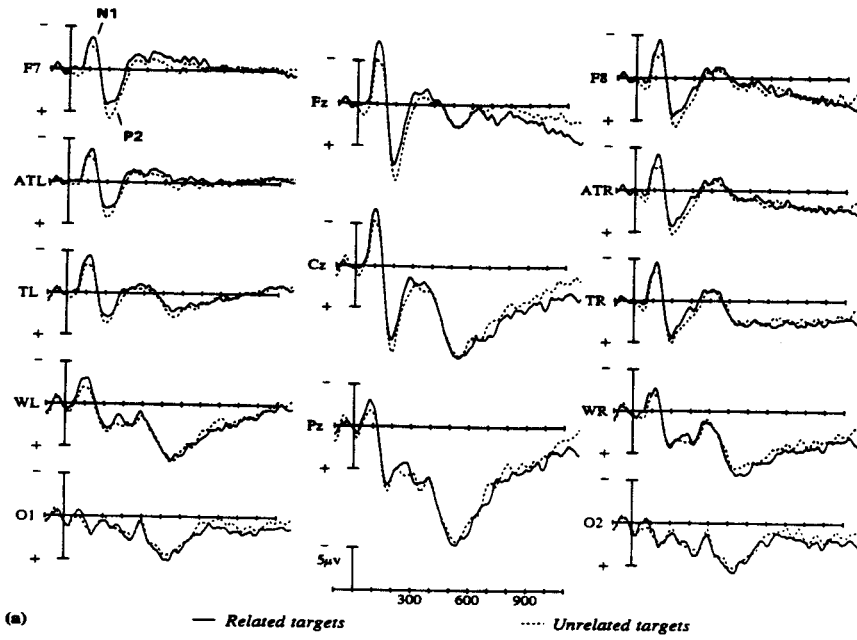
Across the SOA conditions, related targets were responded to more quickly than unrelated targets [main effect of target type: $F(1,11) = 31.86$, $P < 0.001$; see Table 1]. There was also a main effect of SOA [$F(2,22) = 34.91$, $P < 0.001$], indicating that the RTs became shorter as the SOA became longer. However, there was no significant interaction between target type and SOA ($P > 0.25$), indicating that priming was not significantly different in each of the SOA conditions.

The responses to the unrelated targets were only marginally less accurate than the related targets [$F(1,11) = 3.59$, $P < 0.085$] and there was no difference across SOAs ($P > 0.68$).

Electrophysiological Data

The grand mean ERPs are plotted in Fig. 2. As in Experiment 1, the differential overlap of visual and auditory stimuli made the early components of the ERPs appear slightly different for each SOA. In the 0 SOA condition, where auditory and visual stimuli onset at the same time, the early N1 and P2 components are similar to those seen in Experiment 1. Note that from a purely physical standpoint, this condition is very similar to the 0 SOA condition in Experiment 1 in that they both have a simultaneous visual and auditory stimulus. However, in the 200 and 800 SOA conditions, where the onset of the visual target is not simultaneous with the onset of the auditory prime, the distributions of the N1 and P2 are quite different from Experiment 1. At the anterior sites the N1 is small, and at the posterior sites (O1, WL, Pz, WR and O2) it peaks later (200 msec). Following the N1, there was a positivity (P2) around 200-250 msec, which was anteriorly distributed in the 200 SOA condition, but was more widely distributed in the 800 msec condition. From this point on, the waveforms were more positive relative to the baseline than they were in Experiment 1 (auditory target).

As in Experiment 1, the P2 in this experiment was followed by a prominent negative-going component (N400), peaking between 350 and 400 msec. This negativity was widely distributed and at the anterior sites was slightly larger over the left hemisphere. Following the negativity was a large positive wave which peaked between 500 and 600 msec (P3) at the posterior sites (note that the late positivity at the lateral anterior sites peaks closer to 900 msec). The P3 tended to be larger over the right hemisphere at anterior sites for all SOAs and at posterior sites for the 800 SOA.



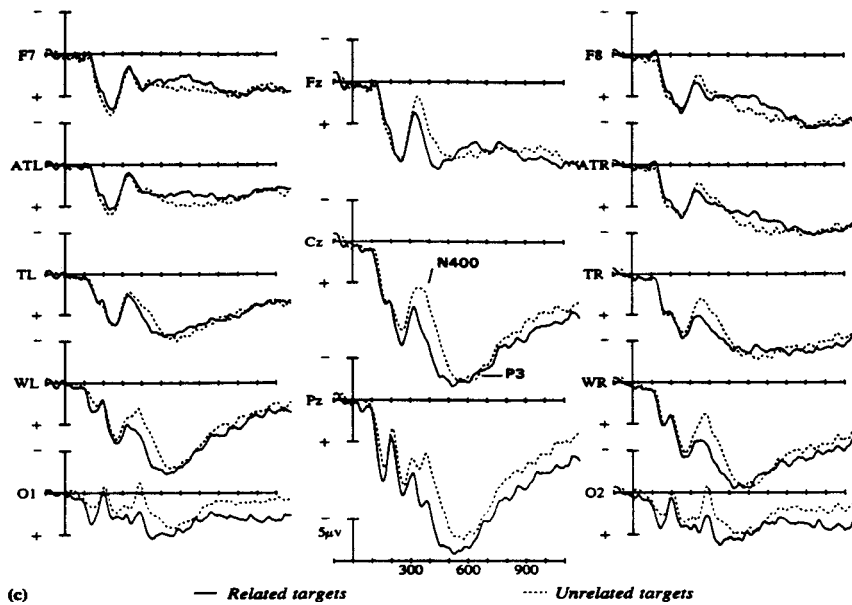


FIG. 2 Grand mean ERPs ($n = 12$) to related and unrelated visual target words in Experiment 2: (a) 0 SOA condition; (b) 200 SOA condition; (c) 800 SOA condition. For further information, see legend to Fig. 1.

Target Type Effects

300-550 msec. The unrelated targets elicited a more negative-going wave than did related targets over the midline sites [main effect of target type: $F(1,11) = 10.48$, $P < 0.008$], but only the more posterior sites produced a similar effect at the lateral sites [target type \times electrode site interaction: $F(4,44) = 9.27$, $P < 0.007$]. There was also a difference in the priming effect across SOAs [target type \times SOA interaction, midline: $F(2,22) = 6.69$, $P < 0.006$; lateral: $F(2,22) = 3.09$, $P < 0.077$]. Separate follow-up analyses at each SOA indicated that at the 0 SOA there was no significant difference between unrelated and related targets (see Fig. 2; P 's > 0.7); at the 200 SOA the difference was significant at the midline [$F(1,11) = 5.57$, $P < 0.038$; lateral: $P > 0.14$]; and at the 800 SOA the difference was significant in both analyses [midline: $F(1,11) = 18.04$, $P < 0.001$; lateral: $F(1,11) = 8.68$, $P < 0.013$].

550-800 msec. There was no significant difference between related and unrelated targets in this epoch (midline: $P > 0.3$; lateral: $P > 0.85$), nor were there any interactions of target type and SOA. At the lateral sites,

TABLE 3

The Size of the Semantic Priming Effects (Unrelated-Related) in uV at Each of the 100 msec Epochs for Each SOA in Experiment 2 (Auditory Prime, Visual Target)

<i>Epoch</i>	SOA			P-Values	
	<i>0</i>	<i>200</i>	<i>800</i>	<i>TT^e</i>	<i>TT x SOA</i>
100-200 msec					
midline	0.81	-0.63	-0.47	NS	NS
lateral	0.49	-0.27	0.00	NS	NS
200-300 msec					
midline	1.27 ^a	-0.47	-1.10 ^a	NS	0.0746
lateral	0.67	-1.23	-0.27	NS	NS
300-400 msec					
midline	0.35	-0.82	-3.56 ^d	0.0103	0.0053
lateral	0.23	-0.49	-1.23 ^c	0.1043	0.0803
400-500 msec					
midline	-0.10	-2.05 ^d	-3.45 ^c	0.0030	0.0092
lateral	0.12	-1.03 ^b	-1.37 ^b	0.0509	0.0408
500-600 msec					
midline	-0.41	-0.63	-0.61	NS	NS
lateral	0.13	-0.08	0.21	NS	NS
600-700 msec					
midline	-0.67	-0.75	-0.08	NS	NS
lateral	0.15	-0.41	0.63	NS	NS
700-800 msec					
midline	-1.17	-1.35	-0.80	NS	NS
lateral	-0.36	-0.86	0.11	NS	NS
800-900 msec					
midline	-0.93	-1.15	-1.38	NS	NS
lateral	-0.36	-1.08 ^a	-0.51	NS	NS
900-1000 msec					
midline	-1.01	-1.16	-1.63 ^b	0.0638	NS
lateral	-0.31	-0.90	-0.70	NS	NS
1000-1100					
midline	-1.40 ^a	-1.79 ^b	-1.82 ^b	0.0077	NS
lateral	-0.27	-1.25 ^b	-0.86	0.0750	NS

Note: Superscripts indicate significance of separate analyses at each SOA. TT, target type.

^aP < 0.1; ^bP < 0.05; ^cP < 0.01; ^dP < 0.001; ^eP-value for main effect of target type.

there was an interaction between target type and electrode site [$F(4,44) = 4.03, P < 0.05$], indicating that the unrelated targets were more negative going posteriorly, but anteriorly the related targets were more negative-going.

800-1150 msec. There was a main effect of target type at the midline sites across SOAs [$F(1,11) = 6.75, P < 0.025$], and at the lateral sites there was a significant interaction of target type, SOA and electrode site [$F(8,88) = 3.55, P < 0.036$]; for the 200 SOA the effect was larger anteriorly, but for the 800 SOA the effect was larger posteriorly (what little difference there was for the 0 SOA was largest posteriorly).

Time-course Analyses (100 msec Epochs). Table 3 reports the results of the 100 msec time-course analyses for Experiment 2. As can be seen, the effects of target type are much more restricted in time than in Experiment 1 and are significant only for the 200 and 800 msec SOAs during the traditional latency window for the N400. However, later (1000-1100 msec), the 0 SOA did show a difference that approached significance in the predicted direction.

Discussion

When the prime was auditory and the target visual, there was a significant RT priming effect across the SOAs. However, ERP priming (i.e. the N400 effect) was significant in the 200 (midline only) and 800 SOA conditions, but there was no hint of an N400 in the 0 SOA condition. Moreover, the effect was larger and began earlier in the 800 than the 200 SOA condition.

This pattern of effects is similar, but not identical, to that obtained by Anderson and Holcomb (submitted) for stimuli within the visual modality. While they found evidence of ERP priming in the 200 and 800 SOA conditions, they also obtained a significant N400 effect in the 0 SOA condition which onset between 300 and 400 msec. Therefore, the failure of the 0 SOA auditory-visual condition to show a similar effect suggests that cross-modality priming may not rely on the exact same processes as within-modality priming and calls into question the veracity of the common semantic system hypotheses offered at the end of Experiment 1. Further discussion of these findings and their implications will be presented in the General Discussion.

BETWEEN-EXPERIMENT COMPARISONS

Behavioural Data

In order to test for the existence of any effects due to the modality of presentation, analyses were done with Experiment as a between-subjects variable. Visual targets (Experiment 2) were responded to faster (161 msec) than auditory targets (Experiment 1) [main effect of experiment: $F(1,22) = 15.82$, $P < 0.001$]. Across experiments, targets were responded to faster as the SOA became longer [main effect of SOA: $F(2,44) = 28.88$, $P < 0.001$], but when the target was visual, this decrease had a steeper decline [experiment x SOA interaction: $F(2,44) = 8.15$, $P < 0.002$]. For both auditory and visual targets, the unrelated targets were responded to more slowly [main effect of target type: $F(1,22) = 105.66$, $P < 0.001$], but this effect was greater when the target was auditory [experiment x target type interaction: $F(1,22) = 25.97$, $P < 0.001$]. Across experiments, the priming effect was greatest in the 800 SOA [target type x SOA interaction: $F(2,44) = 3.9$, $P < 0.034$].

More errors were made in Experiment 1 (auditory target) than in Experiment 2 (visual target) [main effect of experiment: $F(1,22) = 12.22$, $P < 0.002$]. Across experiments, the subjects made more errors to unrelated targets than to related targets [main effect of target type: $F(1,22) = 40.85$, $P < 0.001$], and this effect was greater when the target was auditory [target type x experiment interaction: $F(1,22) = 17.59$, $P < 0.001$].

Difference Waves

In order to facilitate ERP comparisons between the experiments, difference waves are -formed by subtracting the related from the unrelated waveforms. This procedure tends to remove waveform features that the two conditions of interest have in common (e.g. modality-specific "exogenous" activity such as the N1 and P2 components); and permits an analysis of pure ERP priming differences between the experiments. The mean amplitude from 200 to 700 was calculated for each difference wave and the resulting measures from both experiments were entered into a mixeddesign ANOVA with one between-subject factor (experiment) and two (SOA and electrode site) or three (SOA, electrode site and hemisphere) within-subject factors (note that the difference wave technique collapses

³Another advantage of this procedure is that it reduces the contribution of differential prime-target ERP overlap for the three SOAs. As can be seen in Figs 1 and 2, the early part of the target ERPs in the 200 SOA condition were "contaminated" by the P2 and N400-like negativity produced by the prime. By subtracting the related from the unrelated ERPs, the prime P2s and N400s, which are similar for these two conditions, cancel each other out.

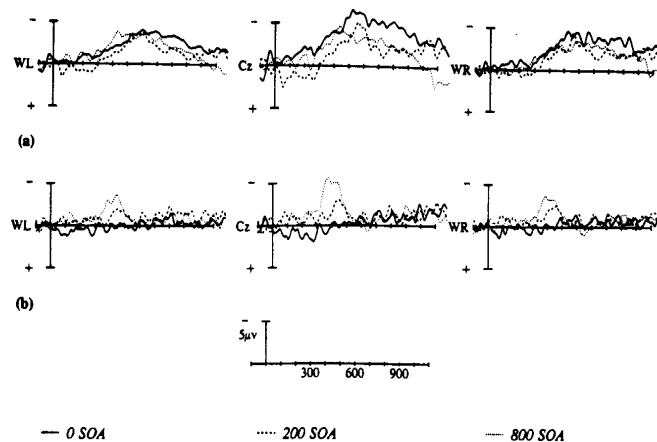


FIG. 3 Difference waves calculated by subtracting related from unrelated target ERPs at each of the three SOAs: (a) Experiment 1; (b) Experiment 2.

the target type factor). These difference wave analyses are intended to serve as supplementary analyses to the more conventional ones reported above.

As Fig. 3 illustrates, in Experiment 1 (visual prime and auditory target) the difference between unrelated and related targets (N400 effect) was large, peaked around 500-600 msec and extended through much of the measuring epoch in all three SOA conditions. However, in Experiment 2 (auditory prime and visual target), the difference was visible in only the 200 and 800 SOA conditions, peaked around 400-500 msec and lasted only until about 600 msec.

A single latency window (200-700 msec) was used to quantify the difference waves. ANOVAs on this measure indicated that the N400 effect was significantly greater in Experiment 1 than in Experiment 2 [main effect of experiment, midline: $F(1,22) = 5.61$, $P < 0.027$; lateral: $F(1,22) = 8.38$, $P < 0.008$]. The distribution of the effect was not significantly different between the two experiments (midline: $P > 0.90$; lateral: $P > 0.12$), although across experiments there was a difference in the distribution [midline: $F(2,44) = 3.95$, $P < 0.047$; lateral: $F(4,88) = 9.94$, $P < 0.001$], indicating that the N400 effect was greater at the more posterior sites.

The interaction of SOA and experiment was significant at the midline [$F(2,44) = 4.01$, $P < 0.033$] and approached significance at the lateral sites [$F(2,44) = 2.65$, $P < 0.088$]. This interaction reflects the finding reported earlier of statistically similar N400 effects of Experiment 1 (visual prime/ auditory target) but differential effects across SOA for Experiment 2 (auditory prime/visual target).

Since previous studies (e.g. Holcomb et al., 1992; Kutas, Van Petten, & Besson, 1988) have found a difference in the laterality of the visual N400

effect at the temporal-parietal locations (right hemisphere usually greater than left), separate analyses were done at Wernicke's sites. Unlike many previous studies using visual targets, there was no evidence of a significant difference in the size of the effect between the hemispheres ($P > 0.63$).

GENERAL DISCUSSION

Summary of Findings

The main purpose of this study was to examine the interaction of word processes between the visual and auditory modalities. This was done by comparing semantic priming effects in two cross-modal experiments in which the interval between the prime and target words was manipulated. It was predicted that if a common semantic system is shared in the processing of visual and auditory words, relatively consistent N400 effects would be seen across SOAs. However, if cross-modal priming is due to a word-level recoding process or to a post-recognition translation process, priming would be delayed (due to the extra time required for conversion) and should only occur for the 800 SOA condition.

When the prime was visual and the target auditory (Experiment 1), there were large behavioural and ERP priming effects observed at all three SOAs, and the ERP effects onset at a relatively early point after the onset of the target (between 200 and 400 msec in the 0 SOA condition). These findings are most consistent with the common semantic system hypothesis and would seem to contradict the alternative position that cross-modal priming results from the addition of a word-level recoding or postrecognition translation process. Further evidence in favour of the common semantic system hypothesis comes from two sources. First, while the auditory target-effects (Experiment 1) tended to be larger than the visual ones (Experiment 2), there were no reliable N400 differences across the scalp between the modalities. That is, the N400 had the same posteriormaximum, bilaterally symmetrical distribution regardless of whether the target was visual or auditory. This suggests that for cross-modality presentations, the N400 effect reflects little if any modality-specific processing.⁴

⁴However, this finding would seem to be at odds with that of Domalski, Smith and Halgren (1991), who reported a different scalp distribution for auditory-auditory and auditory-visual words. In their study, auditory targets elicited a relatively larger frontal N400 effect and visual targets a larger posterior effect. The most likely explanation for the discrepancies between the studies is differences in methodologies. Dolmalski et al. (1991) used repetition priming (as opposed to semantic priming), a long prime/target interval and an old/new judgement task (as opposed to a lexical decision task). Perhaps more important, their comparisons were not symmetrical, with auditory targets being a within-modality comparison and visual targets a between-modality comparison.

Second, the pattern of effects across SOAs in Experiment 1 was similar to the within-modality studies of Anderson and Holcomb (submitted). This suggests that the same mechanism was operating for between- and within-modality semantic priming. This is inconsistent with the conversion hypothesis, which argues that somewhat different mechanisms should mediate priming within and between modalities.

However, it would appear that the above conclusions should be tempered by the findings from Experiment 2, where the prime was auditory and the target visual. Although reaction time differences were significant in the 0 SOA condition, there was no semantic priming effect on the N400. In the 200 SOA condition there were small N400 effects, while in the 800 SOA condition there were quite robust effects. These results are quite different from Anderson and Holcomb's (submitted) findings of clear N400 effects in simultaneous auditory-auditory and visual-visual presentations. Taken together, the findings of short interval priming within modalities and its absence between modalities (Experiment 2) would seem to offer some support for the conversion hypotheses.

Additional support for this position comes from another cross-modal study by Rugg et al. (this issue). They found differences between the modalities using a repetition priming task in which the first presentation was in either the visual or auditory modality and the second presentation (six items later) was in the same or different modality. The ERP priming effects for auditory repetitions were very similar whether the prime was auditory or visual. However, the repetition effect for the visual targets onset later when the prime was auditory compared to when it was visual. They interpreted this as evidence that visual words are automatically converted to an auditory code, but that auditory words are not automatically converted to a visual code. This latter conclusion assumes that the delayed onset of the auditory/visual priming effect was due to the additional time required to convert the visual target word into an auditory representation (i.e. the conversion hypothesis). The failure to find evidence of N400 priming in the 0 SOA auditory/visual condition of Experiment 2 would appear to agree with Rugg and co-workers' conclusions. That is, in the 0 SOA condition, the completion of "visual" processing of the target might have preceded completion of auditory recoding of the target and therefore priming, as reflected by the N400, might not have had time to take place. However, this interpretation is at a loss in explaining the robust N400 effect in the 0 SOA condition of Experiment 1 (visual/ auditory). If the visual word has to be recoded to prime or be primed by the auditory word, it is difficult to see how this could have happened in time to support an N400 effect between 200 and 400 msec in Experiment 1, but not in Experiment 2.

However, there are at least two additional possibilities, both of which are consistent with the common semantic system hypothesis. The first

explanation focuses on the temporal dynamics of spoken and written words. While auditory words unfold over time, visual words are fully available at stimulus onset. Even if spoken word processing is "on-line", it still may be that, at short SOAs, insufficient acoustic information has reached the subject prior to processing of the visual target. What distinguishes this explanation from Rugg and co-workers' account is that it does not need to assume a conversion operation, but instead it suggests that visual and auditory word processing precede along distinct and separate routes, and then after recognition feed into a common semantic system (where semantic priming presumably takes place). According to this view, weak or non-existent priming could occur if there was an absence of temporal overlap in the processing of the prime and target by the semantic system. In the case of the 0 SOA auditory/visual condition, this could have happened if the semantic system received and processed target word information from the modality-specific visual system prior to the arrival of sufficient prime word information from the auditory system. This seems particularly plausible given the different temporal dynamics of spoken and written words.

A final possibility for the discrepant 0 SOA findings focuses on the role of attentional mechanisms. Even though it has been found that limitations of divided attention are reduced when stimuli are presented cross-modally rather than within modalities (e.g. Treisman & Davies, 1973), it is possible that in each of the two experiments reported here there were differences in the competition for attention resources. In support of this argument, it has been shown that in some situations there is an attentional bias for visual stimuli over auditory stimuli (Colavita, 1974; Colavita & Weisberg, 1979; Posner, Nissen, & Klein, 1976). For example, Colavita (1974) required subjects to respond rapidly to a tone with one hand and to a light with the other hand. He found that when there was an occasional simultaneously presented tone and light (of equal perceived intensity), the subjects tended to respond to the visual stimulus and often reported being unaware of the auditory stimulus. Similarly, Posner et al. (1976) reported a series of studies suggesting that visual stimuli tend to be less automatically alerting, resulting in a need for attention to be more "actively" directed towards them. According to this account, when there is competition between inputs from the two modalities, there is a reduction in the amount of attention allocated to the auditory modality. This explanation would be especially relevant in the 0 SOA condition. When both stimuli were presented simultaneously, the visual stimulus (as either a prime or a target) may have received preferential attention over the auditory stimulus. This would have resulted in greater attentional resources being allocated to the visual prime in Experiment 1 (visual/auditory) and to the visual target in Experiment 2 (auditory/visual). Since in Experiment 1

the task was to respond to the auditory word, which was being presented over time, there may have been less of a cost associated with the visual attention bias, since there was still time to process the auditory target. Alternatively, making the auditory stimulus the target might have demanded enough attentional resources to offset the visual bias. However, in Experiment 2, a response was also required to the visual target, which could have added to the visual attentional bias resulting in less processing of the auditory prime. This general notion of the N400 priming effect being affected by attentional variables is consistent with the findings of Holcomb (1988), who demonstrated that when attention was diverted from a prime word, the target N400 was attenuated.

Behavioural/ERP Differences

There was also evidence of differences in auditory and visual processing in the comparisons between the behavioural and ERP data. For example, although there were no ERP priming effects at the 0 SOA in Experiment 2, there was a significant (33 msec) reaction time priming effect. One possibility for these different findings is that the RT and N400 effects might reflect the operation of a somewhat different set of processes (Holcomb, 1993; Kounios & Holcomb, 1992). For example, it may be that RT is more sensitive to certain post-lexical decision processes such as Neely and Keefe's (1989) retrospective matching strategy. According to this account, some part of RT semantic priming in the lexical decision task is due to the relatedness of the prime and target being used to help make the appropriate word/nonword decision. In the case of related primes and targets, when a high degree of relatedness is detected, a rapid "word" decision can be made, but in the case of an unrelated prime and target, there is an initial tendency to decide "nonword" which delays the correct "word" response. Evidence that subjects use this strategy comes from the higher error rates for unrelated targets, which presumably result from subjects occasionally acting on their initial semantically based impulse to respond "nonword". All of the unrelated conditions in both experiments produced higher error rates than the related condition, suggesting that the subjects were using a retrospective semantic-matching strategy. Unfortunately, there has not been a study designed to look at the effect of the retrospective matching strategy on the N400. However, Kounios and Holcomb (1992) have shown that certain other late decision processes that influence RT in a sentence verification task do not seem to have much impact on the N400.

Conclusions

Most of the data from the current experiments seem to favour the interpretation that cross-modality semantic priming, as measured by the N400, is mediated by a common semantic system that receives input from separate modality-specific recognition systems. The data do not fit as well with either of the alternative interpretations (recoding or post-recognition translation) because neither of these can account for the presence of equivalent priming across SOAs in the visual/auditory experiment (Experiment 1). The seemingly most damaging finding for the common semantic system hypothesis was the absence of a robust ERP priming effect for the 0 SOA auditory/visual condition. However, neither of the most plausible explanations for this finding—namely, that visual target processing captured most of the available attentional resources leaving little for auditory prime processing and/or that visual target processing was fast enough to not benefit from the partial auditory information available at this short interval—are inconsistent with the common semantic system position.

One line of future studies will need to extend this research to other domains. For example, while it makes sense that language would maintain a common semantic system for spoken and written words, it is less clear why image-based processes important for picture recognition would necessarily tap the same semantic system. By examining the time-course of word/picture and picture/word priming, it should be possible to determine if there is a similar or different pattern of priming between words and pictures.

Manuscript received December 1991

Revised manuscript received April 1993

REFERENCES

- Anderson, J.E., & Holcomb, P.J. (submitted). Auditory and visual semantic priming using different stimulus onset asynchronies: An event-related brain potential study.
- Bradley, D.C., & Forster, K.I. (1987). A readers view of listening. *Cognition*, 25, 103-134.
- Brown, C., & Hagoort, P. (1993). The processing nature of the N400: Evidence from masked priming. *Journal of Cognitive Neuroscience*, 5, 34-44.
- Colavita, F.B. (1974). Human sensory dominance. *Perception and Psychophysics*, 16, 409-412.
- Colavita, F.B., & Weisberg, D. (1979). A further investigation of visual dominance. *Perception and Psychophysics*, 25, 345-347.
- Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing*. London: Academic Press.
- Domalski, P., Smith, M.E., & Halgren, E. (1991). Cross-modal repetition effects on the N4. *Psychological Science*, 2, 173-178.
- Ellis, A.W., & Young, A.W. (1988). *Human cognitive neuropsychology*. Hove: Lawrence Erlbaum Associates Ltd.

- Geisser, S., & Greenhouse, S. (1959). On methods in the analysis of profile data. *Psychometrika*, *24*, 95-112.
- Holcomb, P.J. (1988). Automatic and attentional processes: An event-related brain potential analysis of semantic priming. *Brain and Language*, *35*, 66-85.
- Holcomb, P.J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology*, *30*, 47-61.
- Holcomb, P.J., & Neville, H.J. (1990). Semantic priming in visual and auditory lexical decision: A between modality comparison. *Language and Cognitive Processes*, *5*, 281-312. Holcomb, P.J., & Neville, H.J. (1991). The electrophysiology of spoken sentence processing. *Psychobiology*, *19*, 286-300.
- Holcomb, P.J., Coffey, S., & Neville, H. (1992). The effects of context on visual and auditory sentence processing: A developmental analysis using event-related brain potentials. *Developmental Neuropsychology*, *8*, 203-241.
- Kounios, J., & Holcomb, P.J. (1992). Structure and process in semantic memory: Evidence from event-related brain potentials and reaction times. *Journal of Experimental Psychology: General*, *121*, 459-479.
- Kroll, J.F., & Potter, M.C. (1984). Recognizing words, pictures and concepts: A comparison of lexical, object and reality decisions. *Journal of Verbal Learning and Verbal Behavior*, *23*, 39-66.
- Kutas, M., & Hillyard, S.A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, *207*, 203-205.
- Kutas, M., & Hillyard, S.A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature*, *307*, 161-163.
- Kutas, M., Van Petten, C., & Besson, M. (1988). Event-related potential asymmetries during reading of sentences. *Electroencephalography and Clinical Neurophysiology*, *69*, 218-233.
- Marslen-Wilson, W. (1987). Functional parallelism in spoken word-recognition. *Cognition*, *25*, 71-102.
- Marslen-Wilson, W.D., & Tyler, L.K. (1980). The temporal structure of spoken language understanding. *Cognition*, *8*, 1-71.
- Marslen-Wilson, W.D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive Psychology*, *10*, 29-63.
- Neely, J.H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner & G.W. Humphreys (Eds), *Basic processes in reading: Visual word recognition*, pp. 264-336. Hillsdale, NJ: Lawrence Erlbaum Associates Inc.
- Neely, J.H., & Keefe, D.E. (1989). Semantic context effects on visual word processing: A hybrid prospective/retrospective processing theory. In G.H. Bower (Ed.), *The psychology of learning and motivation*, pp. 207-248. *Advances in Research and Theory*, Vol. 24. New York: Academic Press.
- Onifer, W., & Swinney, D.A. (1981). Accessing lexical ambiguities during sentence comprehension: Effects of frequency of meaning and contextual bias. *Memory and Cognition*, *9*, 225-236.
- Osterhout, L., & Holcomb, P.J. (in press). Event-related potentials and language comprehension. In M.D. Rugg & M.G.H. Coles (Eds), *Electrophysiological studies of human cognition*. Oxford: Oxford University Press.
- Posner, M.I., Nissen, M.J., & Klein, R.M. (1976). Visual dominance: An information processing account of its origins and significance. *Psychological Review*, *83*, 157-171.
- Radeau, M., Morais, J., Mousty, P., Saerens, M., & Bertelson, P. (1992). A listener's investigation of printed word processing. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 861-871.

- Rugg, M. (1990). Event-related brain potentials dissociate repetition effects of high- and low-frequency words. *Memory and Cognition*, 18, 367-379.
- Seidenberg, M.S., Tanenhaus, M.K., Leiman, J.M., & Bienkowski, M. (1982). Automatic access of the meanings of ambiguous words in context: Some limitations of knowledgebased processing. *Cognitive Psychology*, 14, 489-537.
- Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.
- Swinney, D.A. (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning and Verbal Behavior*, 14, 645-660.
- Swinney, D.A., Onifer, W., Prather, P., & Hirshkowitz, M. (1979). Semantic facilitation across sensory modalities in the processing of individual words and sentences. *Memory and Cognition*, 7, 159-165.
- Treisman, A.M., & Davies, A. (1973). Divided attention to ear and eye. In S. Kornblum (Ed.), *Attention and performance 1V*, pp. 101-117. New York: Academic Press.
- Zwitserslood, P. (1989). The locus of the effects of sentential-semantic context in spoken word processing. *Cognition*, 32, 25-64.

