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CONCEPTUAL RELATIONSHIPS BETWEEN SPOKEN WORDS AND ENVIRONMENTAL SOUNDS: EVENT-RELATED BRAIN POTENTIAL MEASURES

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Abstract—Identifiable nonspeech sounds were paired with spoken words. In Experiment 1, words preceded by related sounds yielded faster lexical decision times than those preceded by unrelated sounds. In Experiment 2, subjects were presented with sound/word and word/sound pairs while event-related potentials were recorded. Words preceded by related sounds elicited smaller N400 components than those preceded by unrelated sounds; this N400 context effect was slightly larger at electrode sites over the right hemisphere. A context effect similar in latency and morphology was observed for sounds—a smaller negative wave for related than unrelated sounds. The context effect for sounds was significantly larger at left than right recording sites, suggesting differential hemispheric involvement in the processing of word meanings than the "meanings" of environmental sounds.

INTRODUCTION

The distinction between "sign" and "symbol" has a long tradition in philosophy and linguistics. The sound pattern of words bears an arbitrary relationship to mental concepts and real-world objects or events—this symbolic relationship may vary across languages and across time as languages change. Some nonlinguistic sounds and visual patterns serve as signs because of natural correspondences between the sign and a real-world object or event—the sound of a dog barking bears a natural relationship to the visual image of a dog. Humans can clearly process both symbolic and natural relationships. It is also clear that we can translate among stimulus modalities to appreciate the relationship between a visual image, a nonlinguistic sound, and a word, whether it be spoken or printed. Less clear is how the translation between sensory modalities, and between linguistic and nonlinguistic formats is accomplished. At the extremes, we can imagine an amodal conceptual representation tapped by a variety of access routes, or modality-specific stores combined with processes which allow transfer from one to another. These issues have stimulated a large literature comparing picture and word processing with results favoring both amodal and modality-specific stores, as well as results best accommodated by more complex models [31, 32, 52, 85, 98].

In the present study, we examine the processing of conceptual relationships between spoken words and environmental sounds. With the exception of music, nonlinguistic sounds

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have received less experimental attention than other sorts of sensory stimuli which convey information or activate concepts. The auditory system clearly does provide information about our immediate surrounds, and about events that are out of view. Ballas has noted that when subjects are asked to identify sounds, they typically provide a name for the source or cause of the sound rather than describing its acoustic characteristics [4]. He defines an environmental sound as one that is produced by a real event, and has meaning by virtue of its causal relation to that event, in contrast to the social conventions defining the meanings of words. However, Ballas and colleagues [3, 5] have gone on to describe some abstract similarities between the processing of sounds and words: (1) commonly-heard sounds are easier to identify than less common sounds, analogous to the word frequency effect, (2) the identification of sounds can be facilitated by the prior presentation of "related" sounds (e.g. an explosion paired with the sound of a fuse burning), and (3) that acoustically similar sounds produced by different sources may be analogous to homonymous words. These characteristics suggest that environmental sounds are particularly well-suited to the question of whether the analysis of linguistic and nonlinguistic concepts involve overlapping or distinct neural mechanisms.

With noninvasive techniques in normal subjects, the surest means of establishing that a stimulus has been processed for meaning is to demonstrate a context effect—faster or more accurate performance for related than unrelated items. In a number of laboratory tasks including naming, distinguishing words from nonwords, verbal report of briefly presented or degraded words, and monitoring for the occurrence of a target item, words which are semantically related to previous words receive faster and more accurate responses than unrelated items [11, 69, 74, 89, 109, 110]. This context effect is also evident in event-related potentials (ERPs) recorded from the scalp. ERPs are small voltage fluctuations in the EEG that are time locked to sensory, motor, or cognitive events; these potentials are the scalp reflections of synaptic activity associated with informational transactions in the brain, including specific cognitive processes such as spatial attention, memory, motor preparation, and linguistic processes [19, 33, 39, 53]. The present experiment uses the ERP as a means of comparing the conceptual analysis of spoken words and environmental sounds. The remainder of the introduction reviews the sensitivity of the ERP to contextual information delivered in different modalities.

The component of the ERP which has been mostly closely tied to language processing is a late negative wave peaking at about 400 msec post-stimulus onset, the N400 [64, 66]. When pairs or lists of words are presented visually, the amplitude of the N400 is smaller if the eliciting word is semantically related rather than unrelated to the prior word [13, 34, 41, 59, 93]. For words in sentences, the amplitude of the N400 is determined by the amount of contextual constraint imposed by the preceding portion of the sentence; highly predictable final words elicit smaller N400s than congruent but unlikely words, which in turn elicit smaller N400s than completely anomalous final words [58, 61]. Sentence-intermediate words elicit N400s of graded amplitude depending on their position in the sentence; early words elicit relatively large N400s, later words elicit smaller N400s as they can benefit from a larger amount of preceding context [101, 103, 104]. Despite large differences in the earlier sensory components of the ERP, auditory words yield similar semantic context effects to those observed in the visual modality [12, 20, 21, 36, 42, 44, 45, 70, 78]. The N400 semantic context effect is thus relatively independent of sensory modality for linguistic input, and has even been observed during sentences in American Sign Language [63].

The auditory N400 literature consists of many fewer studies than the visual data base, but these are suggestive of subtle differences between the two modalities, so that the N400 may not prove to be completely modality-neutral. It has been fairly clear that there are differences in both the onset latency and duration of the N400 across modalities, but these may be attributed to temporal differences between spoken and printed words. In auditory sentences, the N400 context effect has been apparent at a shorter latency than that for visual sentences, but spoken words may also be identified quite early in the presence of co-articulatory information from the preceding word. Similarly, the duration of the auditory N400 is typically longer than that of the visual N400, but this may be related to the variable durations of spoken words and variability in the point at which a word may be uniquely identified [79, 112].*

From scalp-recorded data alone, evidence that the auditory and visual N400s were produced by different populations of neurons or synapses would consist of differences in scalp distribution. While it is difficult or impossible to infer the location of the neurons generating an ERP component only from analyses of its distribution across multiple recording sites, such analyses can suggest whether or not two components are generated by identical or different neuronal populations [6, 24, 48, 111]. In the visual modality, the N400 is typically larger at scalp sites over the right than left hemisphere [55, 57, 67]. This asymmetry is not always large and not always observed, but a survey of published studies shows that perhaps two-thirds report a significant right-sided asymmetry, the remainder report bilaterally symmetric N400s, and none that we are aware of report left-sided asymmetries. In contrast, the smaller literature on auditory N400s has suggested little in the way of asymmetry; most studies report no statistically significant difference between the impact of semantic context over the right vs left scalp. The interpretation of this modality difference and the relationship between asymmetric ERPs and their neural generators is taken up in the Discussion.

A handful of studies have examined whether or not nonlinguistic stimuli also elicit N400-like potentials, and whether these are modulated by context. Two studies have used the analogy between familiar melodies (e.g. *Mary Had a Little Lamb*) and cliches (e.g. "Roses are red and violets are blue"). However, incongruous words in cliches elicit large N400s [57] while ill-formed notes in melodies do not [14, 81]. Similarly, unexpected numbers or letters in arithmetic or alphabetic progressions produce larger late positive waves than the expected endings, rather than N400s [84]. These studies suggest that the contextual sensitivity of the N400 is specifically linguistic or semantic in nature. However, other results have shown modulations of late negative waves in response to contextual manipulations. Barrett and Rugg [8] presented famous faces which had been sorted into occupational categories (e.g. politicians, actors, etc.) and assigned the task of deciding whether sequentially presented faces belonged to the same category. Faces preceded by a face in a different category elicited a larger late negative wave than those paired with faces from the same category. This result can be accommodated within a language-specific view of the N400 by postulating that subjects performed the task by semantically recoding the faces into verbal labels. Other experiments combining pictures and words are amenable to a similar explanation. Kutas [65] used visually-presented sentence fragments terminated by either semantically congruous words, incongruous words, line drawings depicting objects

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*Because ERPs are the average of EEG activity across a number of single trials, the duration of an effect in the ERP will depend on both the earliest and latest effect in the set of trials comprising the average. Latency variability across trials will thus tend to create a broader, longer duration effect in the average than in any single trial corresponding to the congruous word, or incongruous line drawings. Despite the overall differences between the ERP waveforms elicited by words and line drawings, there was a remarkable similarity in the relative difference between congruent and incongruent endings consisting of words and line drawings. A similar experimental design was employed by Nigam and colleagues [77], who reported no difference between the congruity effects for words and line drawings.

Both of the initial picture-word studies used a fairly small number of recording sites so that the scalp distribution of the two congruity effect on words and pictures could be only roughly mapped. A more recent study by Ganis and Kutas [30] using a greater number of recording sites has suggested that the incongruity effect for line drawings has a more anterior distribution than that for words. This last result is important in suggesting that the impact of context on picture processing is not identical to word processing, so that a semantic recoding hypothesis does not provide a complete account of the picture incongruity effect. In a study using only line drawings, Holcomb and McPherson [43] have reported a context effect for pictures which was both anteriorally-distributed and larger over the left than right scalp, in contrast to the typical right-greater-than-left asymmetry of the N400 elicited by visual words.

A summary of the literature comparing informational modalities would suggest that (1) printed, spoken and signed words elicit N400s whose amplitude is modulated by semantic context, (2) not all forms of context are capable of influencing late negative components of the ERP, and (3) at least under some circumstances, pictures of faces and objects produce N400-like potentials which are modulated by context, and (4) there may be a family of N400 or N400-like potentials sensitive to different modalities of input, as indicated by different scalp distributions in the responses to visual words, auditory words, and line drawings. The present study examines a new modality—meaningful but nonlinguistic sounds. The first experiment uses a reaction time measure to verify that a context effect can be obtained in sound/word pairs; Experiment 2 examines the ERPs to both words and sounds in related and unrelated pairs.

EXPERIMENT 1

METHODS

Subjects

Ten males and eight females ranging from 20 to 40 years in age (mean = 28 years) participated as paid volunteers. All subjects reported that they were native English speakers, and had normal hearing sensitivity bilaterally. All subjects were right-handed by self-report. Eleven reported exclusively right-handed family members; seven subjects reported at least one left-handed parent or sibling.

Materials

Nonspeech sounds. A total of 99 nonspeech sounds were obtained from commercially available compact disks and live recordings. These consisted of 14 animal vocalizations (e.g. meow, bark, whinny), 12 nonspeech human sounds (e.g. sneeze, cough, gargling), three musical instruments (e.g. piano), and 70 sounds best described as "events" (e.g. helicopter rotor, glass breaking, stream flowing, horses hooves striking pavement).

The nonspeech stimuli were selected from a larger set of 159 sounds as being readily identifiable to most listeners in a pilot study. Thirty-seven (18 male, 19 female) subjects with a mean age of 20 (range 18–38 years) participated in the pilot study for course credit. They were asked to listen carefully to each sound, and to write down the first three words that came to mind on a response sheet. Responses were scored according to whether, in the judgement of both experimenters, they referred to the actual sound presented. For example, a response of "horse/police/parade" was considered to indicate accurate identification of the sound of horse hooves while "walking/person/ground" was scored as inaccurate. Unclear or idiosyncratic responses such as "New York/park/Christmas" were also scored as inaccurate. Stimuli that could be identified by at least 80% of the pilot subjects (mean identification accuracy = 93%) were included in the final set of 99 sounds. Three sounds were consistently misidentified by the pilot subjects: most thought that a mosquito whine was a fly, a punching bag in use was a basketball being dribbled, and that a manual typewriter with a bell was a cash register. These sounds were included in the experimental set, but were recoded as referring to the dominant perception of the pilot subjects. Seventeen stimuli with identification scores of 68–79% were used as practice items.

Audio recording and presentation procedures. The live sound samples obtained by the experimenters were initially recorded onto analogue tape (ElectroVoice RE16 microphone, MCS series 2277 tape deck). Together with the stimuli from commercial compact disks, these were low pass filtered at 9 kHz (Butterworth 6-pole) and digitized at a sampling rate of 20 kHz by an analogue/digital card (DT 2821) under the control of a PC computer. Each digital audio file was edited to ensure good synchronization between the beginning of the file and the acoustic onset of the sound, and trimmed to have a duration of 2500 msec. The intensity levels of all stimuli were scaled to equate the maximum peak-to-peak values across sounds. During the experiment, the stimuli were played back through the same A/D card and filter used during acquisition to an audio monitor (Yamaha MS202). Volume levels were set at a comfortable listening level of approximately 72 dB.

Words and nonwords. Responses from the pilot study were also used to choose a related word for each nonspeech sound. In most cases, the word used by the largest number of pilot subjects was selected as the related word for a particular sound. In a few cases, the second most frequent response was selected because two sounds elicited the same word as the most typical response. Mean frequency of usage [27] was 77 per million, with a range of 0–509 (sum of all regularly inflected forms). Mean word duration was 629 msec (range 352–939). Pronounceable nonwords were constructed to have the same initial phonemes and roughly the same durations as the words (mean = 579 msec, range 414–939). Words and nonwords were recorded and digitized as above for the nonspeech sounds.

Procedure

Three stimulus lists were constructed, each containing all 99 of the nonspeech sounds, 66 words, and 33 nonwords. In each list, 1/3 of the sounds were followed by related words, 1/3 by unrelated words (which were related to some other sound in the list), and 1/3 by nonwords. Six subjects were assigned to each stimulus list, so that each subject heard a stimulus only once, but across subjects each word and each sound appeared equally often in a related and an unrelated pair. The stimulus-onset-asynchrony (SOA) between the sounds and words within a trial was 3000 msec, with an intertrial interval of 5000 msec.

Subjects were tested individually during a 1 hr session. Each subject was seated in a comfortable chair facing the audio monitor approximately 4 feet away in a sound attenuated chamber. They were instructed to listen to each stimulus, and to indicate if the second stimulus in the pair was a word or a nonword by using response buttons held in both hands. Half of the subjects used the right hand for word decisions and the left for nonword decisions, half used the reverse. A practice list consisting of 17 sounds paired with related, unrelated and nonwords preceded the experimental block of trials. Accuracy and response times were recorded.

RESULTS AND DISCUSSION

Accuracies in the lexical decision task averaged 99.5%, 98.0%, and 94.3% for related words, unrelated words, and nonwords. Mean reaction times (RTs) for correct responses were computed for each subject after excluding outlying trials with RTs greater than 2 S.D. above the individual's mean in that condition. Mean RTs across subjects were 867 msec for related words (S.E. = 43 msec), 956 msec for unrelated words (S.E. = 34), and 994 msec for nonwords (S.E. = 35). A repeated measures analysis of variance (ANOVA) showed that the 89 msec difference between related and unrelated words was significant [$F(1, 17) = 33.6$, $P < 0.0001$].

To our knowledge, this is the first demonstration of a context effect on words produced by nonlinguistic sounds. It is worth noting that the facilitatory effect was a large one for the lexical decision task, as large as those typically obtained for pairs of highly related words. It is difficult to compare the size of the effect to those obtained between pictures and words because those have used a naming latency measure with visually presented words [31]; even with word pairs the impact of semantic manipulations is usually much larger in lexical decision than in naming latencies.

The primary purpose of Experiment 1 was to verify that our stimulus set would yield a robust context effect with a behavioral measure. The second experiment was designed to determine whether or not this reaction time effect would be accompanied by a pattern of brain activity similar to that reported for pairs of spoken words—a smaller amplitude N400 for related than unrelated words. A second goal was to determine if the ERPs elicited by nonspeech sounds would also differ according to whether they were preceded by a related or unrelated word.

We use a different behavioral task in the ERP study to avoid using any of the limited set of nonspeech sounds on nonword trials and thus optimize the signal to noise ratio for averaged ERPs in the word trials. A second motivation for avoiding the lexical decision task is that stimuli requiring a binary decision elicit large P300 potentials in the same latency range as the N400. The amplitude and latency of the P300 can vary with task difficulty and reaction time, making it difficult to determine whether variation in the N400, P300 or both is responsible for a difference between two experimental conditions [59, 62, 64]. We thus selected a task which requires that subjects listen attentively, but postpones any task-related decisions until beyond the recording epoch for the related or unrelated words. Following the second stimulus of a pair (either a word or a sound) we presented a brief acoustic fragment drawn from that stimulus or a different stimulus and asked subjects to indicate whether or not it was a part of the second stimulus. This task requires no overt response or decision based on the related or unrelated stimulus pairs, thus avoiding the elicitation of a decision-related P300. We have little reason to expect that relationships between the paired stimuli will influence the RTs to the acoustic fragments, given that an analogous letter-search task for visual word pairs shows no effect of semantic relationship [59]. In ERP language paradigms, the influence of semantic relationships on the N400 has proved to be fairly independent of the task assigned to subjects; semantic N400 effects can be observed in the absence of any overt task [66]. Word pair experiments which have included a lexical decision task have yielded both smaller N400s and faster reaction times to related than unrelated words, but the presence of a temporally overlapping P300 engendered by the decision component of the lexical decision task has made such results more difficult to analyze than data sets without an overlapping P300 [13, 44, 59, 64, 66].

EXPERIMENT 2

METHODS

Subjects

Twenty-four subjects participated as paid volunteers; 12 were presented with sound/word pairs and 12 with word/sound pairs. Both groups included 11 females and one male. The mean ages were 25 years (range 19–38) for the sound/word group and 26 years (range 22–40) for the word/sound group. All subjects were native English speakers with normal hearing sensitivity bilaterally by self-report. In the sound/word group nine subjects were right-handed, two were left-handed, and one was ambidextrous according to self-report and the Edinburgh Handedness Inventory. Four of the right-handers reported a parent or sibling to be left-handed. The subjects in the word/sound group were matched for handedness and family history of left-handedness, except that the ambidextrous subject was matched with a left-hander. Data from two additional subjects were collected but not analyzed due to high artifact rejection rates for eyeblinks. Data from a third additional subject were lost due to a computer malfunction.

Materials

The words and nonspeech sounds from Experiment 1 were used in the ERP study. Target stimuli were formed by excising portions from the beginning, middle, or end of each of the stimuli. The word "fragments" had a mean duration of 211 msec (range 74–394); the sound fragments had a mean duration of 213 msec (range 80–400). For the sound/word subjects, a single trial consisted of a sound, a word, and a word fragment; for the word/sound subjects a single trial consisted of a word, a sound, and a sound fragment. Two stimulus lists were constructed for both groups of subjects, each containing all of the nonspeech sounds and all of the words, but half in related and half in unrelated pairs.* Half of the related and half of the unrelated pairs were followed by a target fragment that matched the second stimulus; other pairs were followed by a mismatching fragment drawn from some other word or sound. Each subject thus heard all of the sounds, words, and fragments (word or sound for the different subject groups) once, but across subjects each sound and word appeared in both related and unrelated pairs, and each fragment occurred as both a "match" and a "mismatch".

General procedure

Auditory presentation procedures were much as in Experiment 1. For the sound/word trials, stimulus-onset-asynchrony (SOA) between the sounds and words was 3000 msec (500 msec silent interval); SOA between words and word fragment targets was 3000 msec; intertrial interval of 5000 msec. For the word/sound trials, SOA between words and sounds was 1500 msec (duration of silent interval contingent on duration of the word); SOA between sounds and sound fragment targets was 3000 msec; intertrial interval 5000 msec. Subjects were instructed to listen to all three stimuli and indicate with a right or left button press if the target stimulus matched or mismatched the full stimulus. Response hands for "match" and "mismatch" were counterbalanced across subjects. A practice block of 17 trials preceded the experimental block.

Electrophysiological methods

Electroencephalograms (EEG) were recorded via tin electrodes mounted in a commercially available cap (Electrocap International). Recording sites included midline frontal (Fz), central (Cz), and parietal (Pz) scalp sites, in addition to lateral pairs of electrodes over frontal (F7, F8), temporal (T3, T4, T5, T6), parietal (P3, P4), and occipital (O1, O2) scalp regions as defined by the 10–20 system [46]. The scalp electrodes and an electrode on the right mastoid were referenced to the left mastoid during data collection. The scalp sites were then re-referenced to an average of the two mastoids off-line. Vertical eye movements and blinks were monitored using an electrode placed below the right eye and referenced to the left mastoid; a pair of electrodes placed near the external canthus of each eye were used to monitor horizontal eye movements.

The EEG was amplified with a Grass Model 12 polygraph with half-amplitude cutoffs at 0.01 and 100 Hz, digitized at a sampling rate of 250 Hz and stored on optical disk for subsequent averaging. Trials contaminated by electro-oculographic, muscle, or amplifier saturation artifacts were rejected prior to averaging.

Average ERPs were formed for each subject in each condition, over an epoch beginning 100 msec before stimulus onset and extending 924 msec post-onset. The waveforms were quantified by measuring mean amplitudes within selected latency windows, relative to the prestimulus baseline. Statistical analyses were performed with analyses of variance (ANOVAs) with repeated measures. For interactions involving more than a single degree of freedom in the numerator, we use the Huynh–Feldt correction for violations of sphericity [107]. In these cases, we report the original degrees of freedom, the epsilon correction factor, and the corrected probability level.

RESULTS

Words and sounds without context: the first stimulus

The ERPs elicited by the words and nonspeech sounds when they served as the first stimulus of the pairs are shown in Fig. 1. Both included components characteristic of most auditory ERPs: a frontocentral N1 (peaking at about 100 msec poststimulus onset), P2 (peaking at about 190 msec) and N2 (peak latency at about 280 msec). These were followed by a long duration negative wave which also reached greatest amplitude at frontal and central scalp sites. The broad negative wave may not be a unitary component, but receive contributions from a number of sources: the "sustained potential" observed for other acoustic stimuli of long duration [38, 40], the Contingent Negative Variation typically elicited by anticipation of the second stimulus in paired stimuli [37], and/or an N400.

Figure 1 suggests that the broad negative wave shows a different distribution across the scalp for words vs sounds: frontally, it is larger for sounds while at parietal, posterior temporal, and occipital sites it is larger for words. The broad negativity was quantified as the mean amplitude from 300 to 700 msec. The values from the lateral scalp sites were

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*More precisely, List 1 contained 50 related pairs and 49 unrelated pairs, while List 2 had 49 related pairs and 50 unrelated pairs.

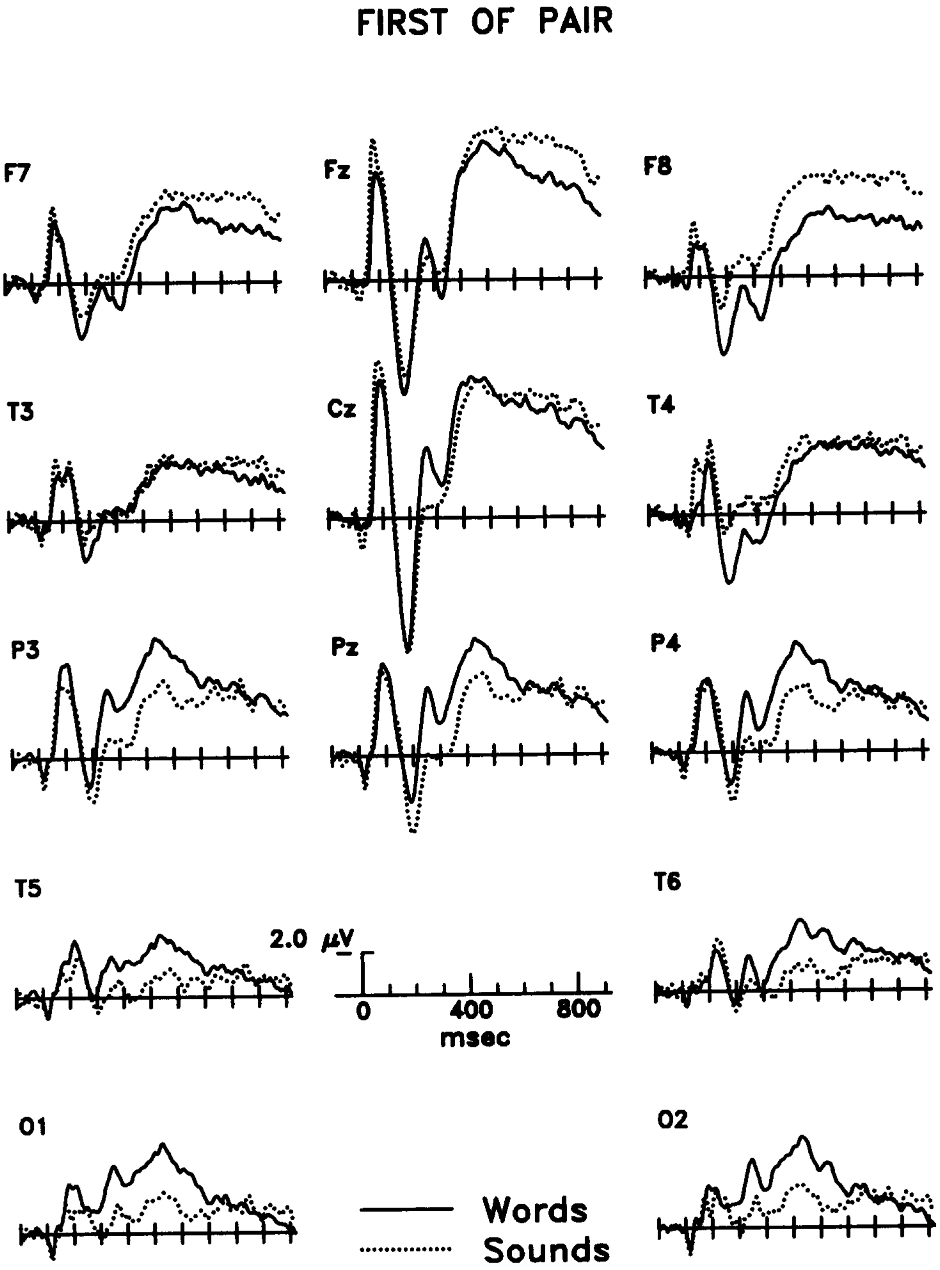

Fig. 1. Grand average ERPs elicited by words and sounds when they were the first member of a stimulus pair.

subjected to an ANOVA taking stimulus type (word vs sound), relationship (first member of a related or unrelated pair), laterality, and electrode location along the anterior–posterior axis as factors. A significant interaction between stimulus type and anterior–posterior electrode location verified the observation above [$F(4, 88) = 3.60$, $P < 0.05$, epsilon $= 0.42$]. None of the main effects of stimulus type, relationship, laterality, or the interactions among them were significant.

Context effects

Words. The ERPs elicited by words when they occurred second in the stimulus pairs are shown in Fig. 2. Beginning at about 200 msec poststimulus onset, related words differ from unrelated in eliciting a smaller late negative wave. At lateral sites, the context effect is smallest at frontal and anterior temporal sites, largest parietally, and of intermediate amplitude at posterior temporal and occipital sites. Overall, the context effect is similar in latency, amplitude and scalp distribution to the N400 effects previously reported for spoken words preceded by single words or sentences. The N400 was quantified as mean amplitude from 300 to 700 msec and subjected to an ANOVA taking relationship and scalp site as factors. The main effect of relationship was significant across all of the electrodes [$F(1, 11) = 14.1$, $P < 0.005$]. The lateral electrodes were subjected to a second analysis to evaluate the scalp distribution of the effect, taking relationship, laterality, and anterior–posterior (five levels) as factors. The ERPs were generally more negative over the right than left hemisphere, yielding a main effect of laterality [$F(1, 11) = 6.58$, $P < 0.03$], but the context effect was not asymmetric [relationship × laterality, $F(1, 11) = 0.81$]. The anterior–posterior differences in the context effect did not reach significance [relationship × anterior/posterior: $F(4, 44) = 3.35$].

Sounds. The ERPs elicited by sounds when they occurred second in the stimulus pair are shown in Fig. 3. Relationship to the preceding word influenced the response to sounds in a manner somewhat similar to that observed for the words: a late negative wave was reduced in amplitude for related as compared to unrelated sounds. The context effect was quantified and analyzed as above. Across all electrodes, there was a significant main effect of relationship [$F(1, 11) = 19.3$, $P < 0.002$]. As before, we analyzed the lateral sites alone to better describe the scalp distribution of the effect. Like the ERPs elicited by the words, those elicited by sounds tended to be more negative over the right than the left hemisphere, but this overall laterality effect was weaker and did not reach statistical significance [$F(1, 11) = 3.97$, $P < 0.10$]. In contrast to the words, the difference between related and unrelated sounds was significantly larger at left than right scalp sites [relationship × laterality: $F(1, 11) = 11.6$, $P < 0.01$]. None of the interactions involving the anterior–posterior dimension were significant [$F < 1.5$].

Words vs sounds. The results above indicate that the ERPs elicited by words and sounds are both influenced by conceptual relationships between them. In this section we explicitly evaluate the similarities and differences between the two context effects. ERPs elicited by the second stimulus at the midline electrode sites were subjected to an ANOVA taking stimulus type (word vs sound) as a between-subject factor, with relationship and electrode site as repeated measures. The main effect of relationship was significant [$F(1, 22) = 40.4$, $P < 0.0001$], but the size of this context effect was not influenced by stimulus type [main effect of stimulus type: $F(1, 22) = 0.01$; stimulus type × relationship: $F(1, 22) = 1.38$].

Figure 4 and the analyses above suggest that while the context effects for words and sounds were similar in overall amplitude, they showed different patterns of asymmetry: the context

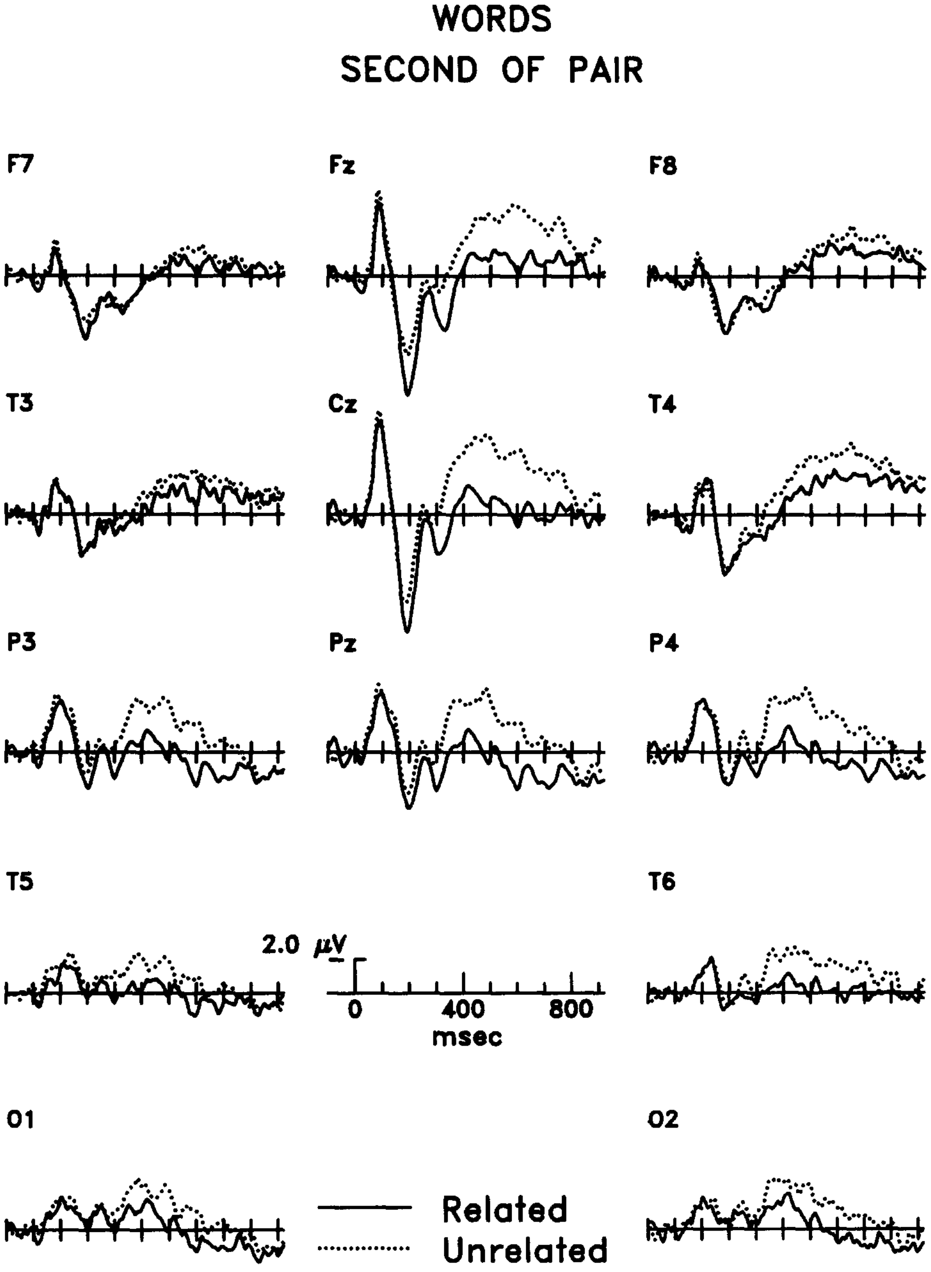

Fig. 2. Grand average ERPs elicited by words which were preceded by related or unrelated sounds.

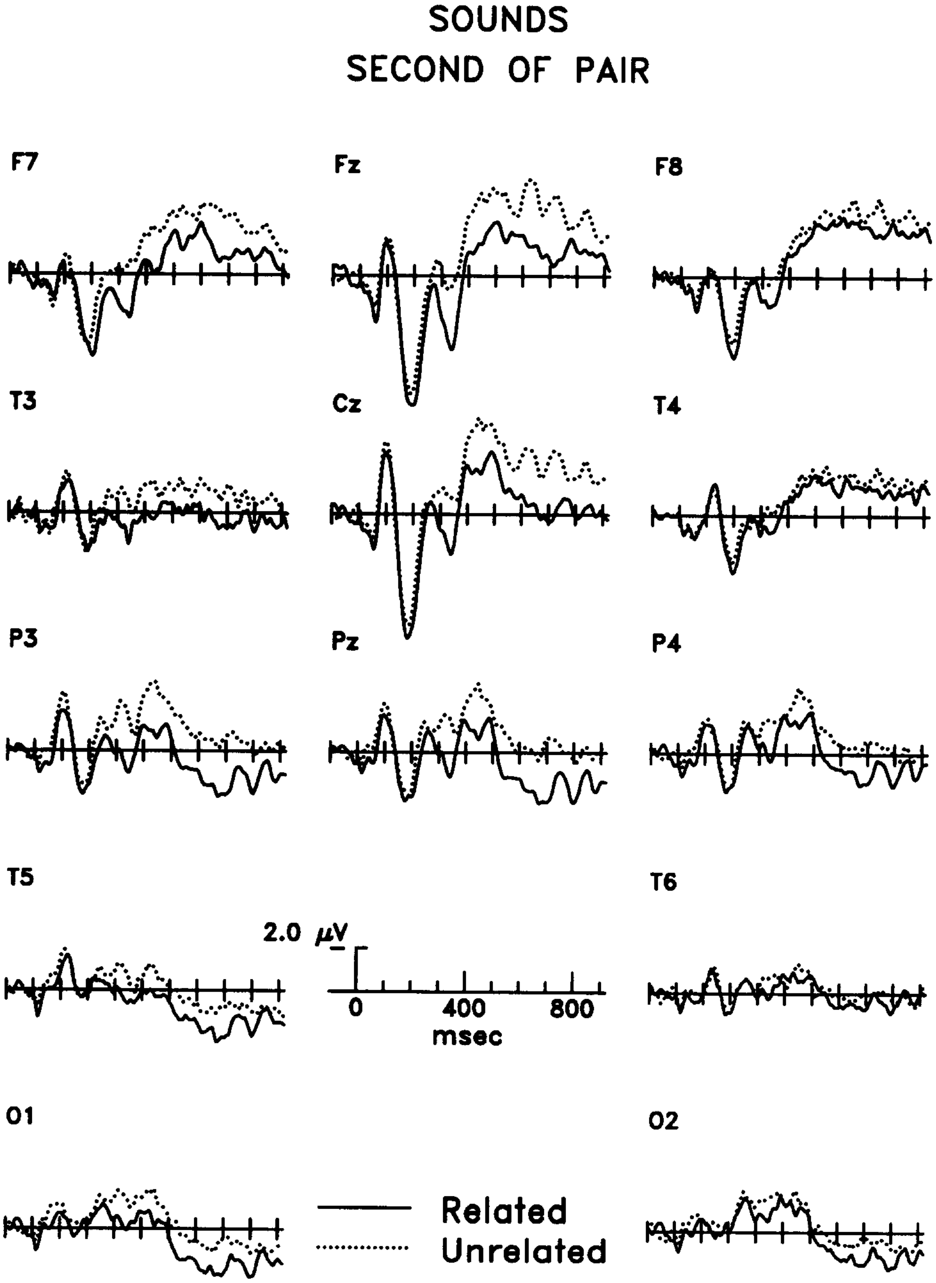

Fig. 3. Grand average ERPs elicited by sounds which were preceded by related or unrelated words.

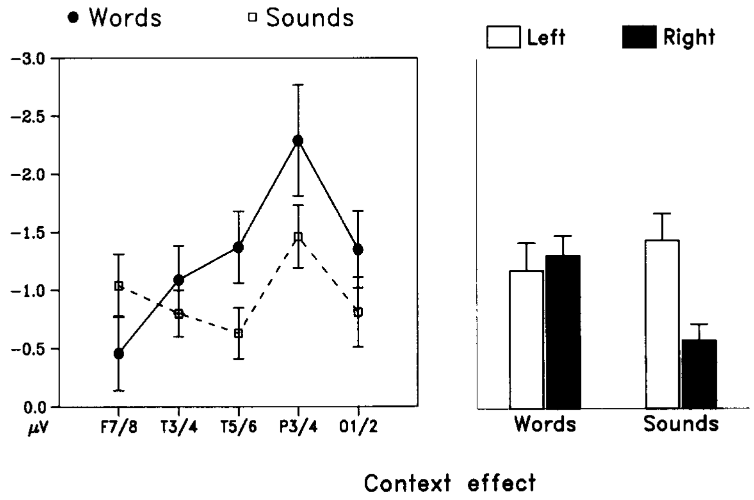

Fig. 4. Scalp distribution of the difference between related and unrelated items, quantified as the mean voltage from 300 to 700 msec after stimulus onset relative to a 100 msec pre-stimulus baseline. The left panel collapses across right and left recording sites to show distribution from the front to the back of the head (but note that some sites are further from the midline than others, T5/6 is lateral to T3/4). The right panel compares all recording sites over the right side of the head to all recording sites over the left side of the head. Error bars show standard error of the mean.

effect for words was slightly, though not significantly, larger over the right hemisphere while the analogous effect for sounds was larger over the left. These distributional differences were analyzed via an ANOVA on the lateral electrode sites taking stimulus type, relationship, laterality and anterior–posterior as factors. As for the midline sites, the main effect of relationship was significant [$F(1,22)=29.1$, $P<0.0001$] while stimulus type and the interaction were not [$F<1$]. None of the interactions involving the anterior–posterior axis were significant [$F<2.5$]. There was no evidence of an overall difference in hemispheric asymmetry between words and sounds [stimulus type × laterality: $F(1,22)=0.01$]. In contrast, the context effects for the two types of stimuli showed a different pattern of laterality [stimulus type × relationship × laterality: $F(1,22)=7.59$, $P<0.02$].*

The latencies of the two context effects are also of some interest. Figures 1 and 2 suggest that both context effects began at nearly the same time, approximately 200 msec poststimulus onset. The onset latency of the difference between related and unrelated items was evaluated by first forming difference waves for each subject: a point-by-point subtraction of the ERP

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*It is important to note that the differential asymmetry of the two context effects occurred in the absence of an overall amplitude difference. When two effects are not of equivalent amplitude, the additive nature of the ANOVA may yield interactions between factors representing an experimental manipulation and scalp site in the absence of any true difference in scalp distribution of the two effects [69]. Equating overall amplitudes via some normalization procedure serves to correct this problem when it exists. In the present data, we derived difference waves reflecting the context effects on words and sounds (a point-by-point subtraction of the waveforms, unrelated minus related) and normalized the mean amplitudes in the 300–700 msec latency window according to the method recommended by McCarthy and Wood [69]. The normalized measures were subjected to an ANOVA taking stimulus type (word vs sound), laterality (left vs right electrode sites) and anterior–posterior (five levels) as factors. This yielded the same results as the analysis of the raw data reported in the text: a significant interaction between stimulus type and laterality [$F(1,22)=8.58$, $P<0.01$], with nonsignificant interactions involving the anterior–posterior factor [stimulus type by anterior–posterior: $F(4,88)=1.02$; stimulus type by laterality by anterior–posterior: $F(4,88)=1.05$].

elicited by related items from that elicited by unrelated items. The onset latencies of the difference waveforms were estimated by measuring the point at which they first reached 15% of their maximal amplitude. An ANOVA taking stimulus type and electrode site as factors yielded no significant differences in these latencies nor any interactions involving scalp site [$F<1$].

Targets

ERPs. The results from the stimulus pairs show striking similarities between the ERPs elicited by speech and nonlinguistic sounds. The sole difference is in the pattern of hemispheric asymmetry for the context effect. Two questions need to be resolved before interpreting these results. First, the word/sound and sound/word pairs were presented to different groups of subjects. Although the groups were matched for handedness, it is possible that the apparent differences between stimulus types are actually differences between subjects. A second issue is whether the lateralized effects are related to perceptual processing of words vs sounds, or to analysis of the "meaning" of the stimuli. For the first stimulus of the pairs, we observed no lateralized difference between words and sounds; the asymmetries were observed only at the second stimulus, in the interaction between stimulus type and conceptual relationship. However, the ERPs elicited by the first stimulus are difficult to interpret because the broad late negativity shown in Fig. 1 may be composed of several overlapping components indexing different neural generators and different psychological processes. It is possible that overlapping components with opposing asymmetries could cancel each other. The ERPs elicited by the target stimuli may provide a better way of addressing both issues. The word-fragment and sound-fragment targets were also presented to separate groups of subjects, so that any lateralization of these ERPs can be used to evaluate overall differences between the subject groups. In contrast to the conceptual relationships (or lack thereof) between the first and second members of the stimulus pairs, the relationships between the second stimuli and the targets were perceptual—each target was either an acoustic fragment of the second stimulus or not.

Figures 5 and 6 show the ERPs elicited by the word and sound fragments. All of the target types elicited a large late positivity, with largest amplitudes parietally and a peak latency at about 500 msec. This scalp distribution, latency, and elicitation by task-relevant stimuli are all consistent with labeling the late positivity a P300. Although the matching and mismatching targets were presented with equal probability, the matching targets elicited a larger P300 than mismatching targets. Other paradigms with equiprobable stimuli calling for "yes" and "no" responses (the stimulus fits the specifications the subject is asked to look for, or doesn't) have also yielded larger P300s for the positive class of targets [47]. In the present experiment, the difference between match and mismatch targets is a result of the subjects' perceptual comparisons between the second paired stimulus and the target. The ERP effects of match/mismatch for the targets can thus be contrasted with the related/unrelated effects based on conceptual comparisons of the words and environmental sounds. Our main interest is thus in determining whether the match/mismatch effect yields differential patterns of hemispheric asymmetry for words and sounds.

The ERPs from the lateral electrode sites were quantified in the same manner as the paired stimuli, as the mean amplitude from 300 to 700 msec poststimulus. An ANOVA taking stimulus type as a between-subject factor and match/mismatch, laterality, and electrode location in the anterior/posterior dimension as within-subject factors yielded a significant main effect of match/mismatch [$F(1, 22)=49.7$, $P<0.0001$], a main effect of anterior/

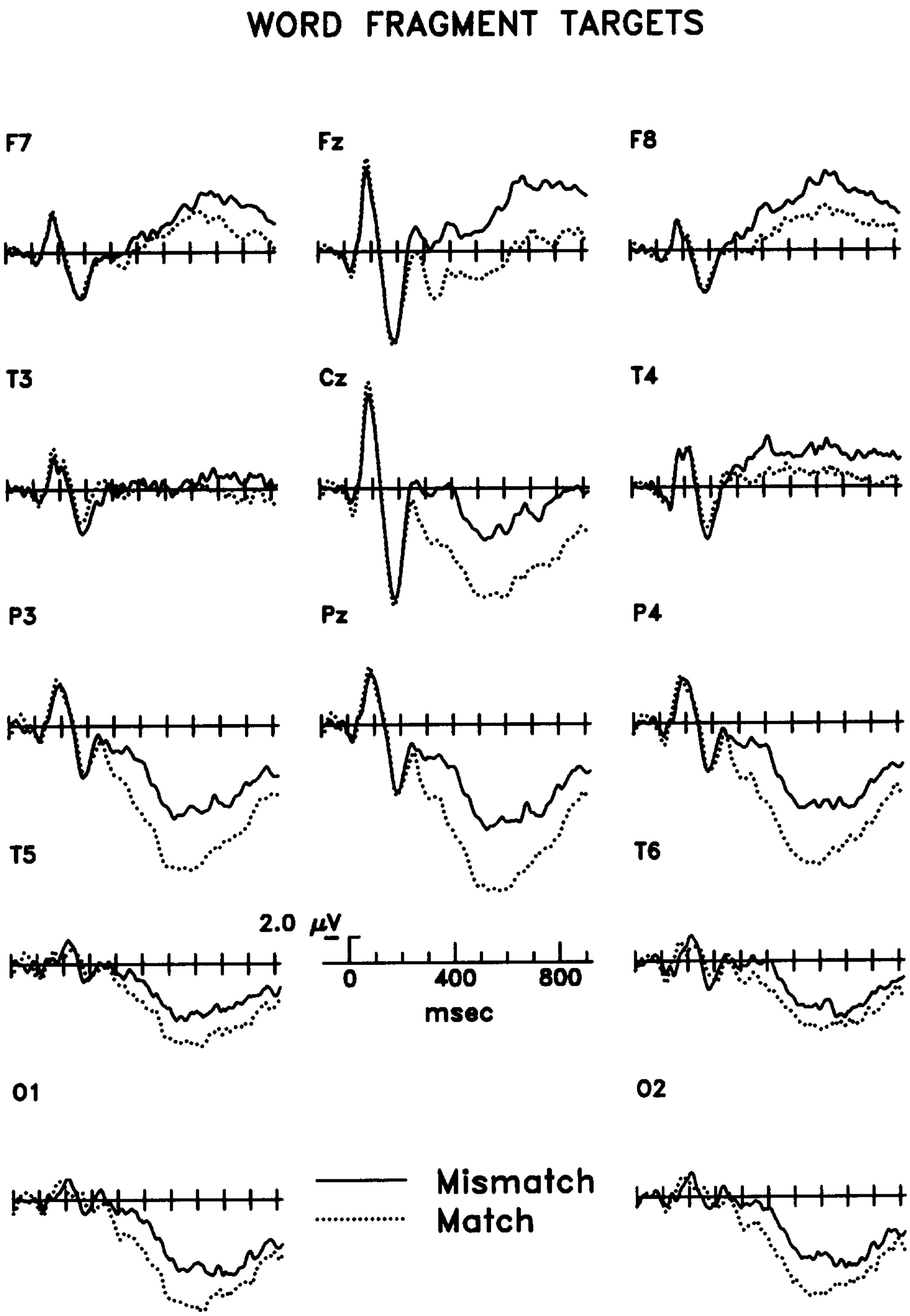

Fig. 5. Grand average ERPs to the third stimulus in each trial, for trials consisting of sound/word/word-fragment. "Match" trials are those in which the fragment was a portion of the preceding word, "mismatch" trials are those in which the fragment was drawn from a different word.

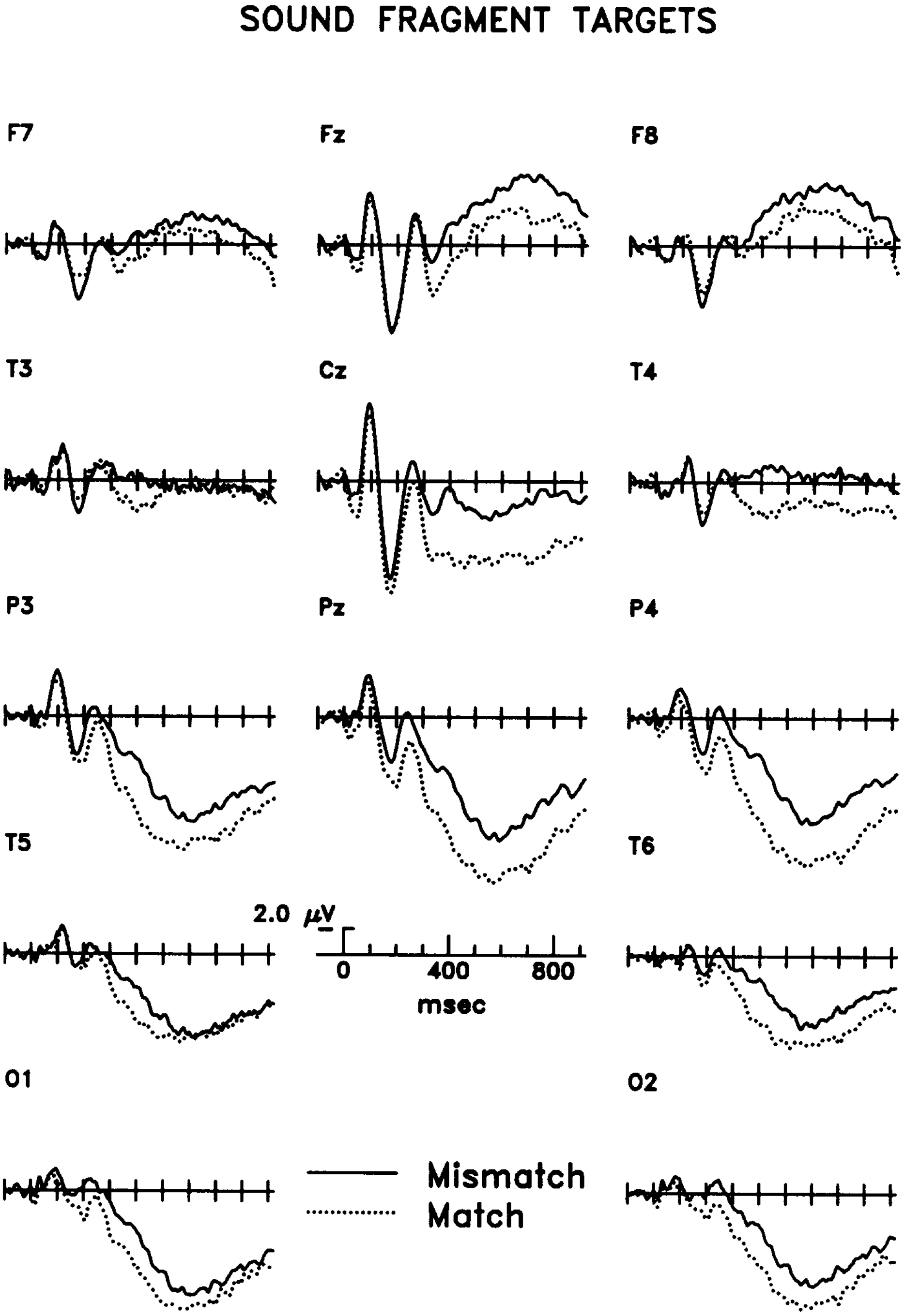

Fig. 6. Grand average ERPs to the third stimulus in each trial, for trials consisting of word/sound/sound-fragment. "Match" trials are those in which the fragment was a portion of the preceding sound, "mismatch" trials are those in which the fragment was drawn from a different sound.

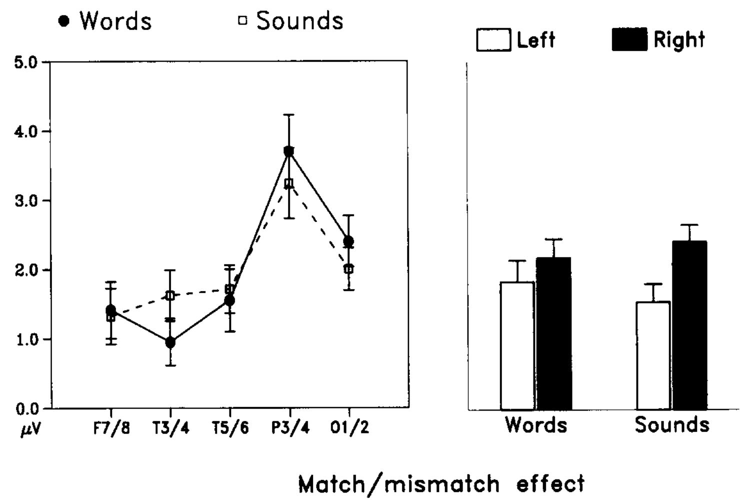

Fig. 7. Scalp distribution of the difference between matching and mismatching target fragments, quantified as the mean voltage from 300 to 700 msec after stimulus onset relative to a 100 msec pre-stimulus baseline. The left panel collapses across right and left recording sites to show distribution from the front to the back of the head (but note that some sites are further from the midline than others, T5/6 is lateral to T3/4). The right panel compares all recording sites over the right side of the head to all recording sites over the left side of the head. Error bars show standard error of the mean.

posterior reflecting the parietal maximum of the P3 [$F(4, 88)=100.2$, $P<0.0001$], and an interaction of match/mismatch by anterior/posterior [$F(4, 88)=10.6$, $P<0.0001$, epsilon $=0.49$]. The overall amplitude of the P300 and the match/mismatch effect were not influenced by stimulus type [$F<2.8$]. P300 amplitude was generally larger over the right than left, as was the match/mismatch effect [main effect of laterality: $F(1, 22)=5.1$, $P<0.05$; laterality × match/mismatch: $F(1, 22)=7.4$, $P<0.02$; laterality × match/mismatch × anterior/posterior: $F(4, 88)=4.2$, $P<0.005$, epsilon $=0.93$]. There was no indication that the scalp distribution of the overall P300 or the match/mismatch effect differed between the word and sound fragment targets [interactions between stimulus type and electrode factors, all $F<1$]. The scalp distributions of the match/mismatch effect are shown in Fig. 7.

Behavioral performance. Table 1 summarizes the subjects' performance in the task of indicating whether or not an acoustic fragment presented after the second stimulus formed a part of that stimulus. Accuracies were generally high. Reaction times showed more variability, and were submitted to an ANOVA taking stimulus type (word vs sound), match/mismatch, and relationship (targets following related vs unrelated pairs) as factors. Reaction times were faster for matching than mismatching targets for both speech and nonspeech sounds [match/mismatch: $F(1,22)=30.3$, $P<0.0001$; stimulus type × match/mismatch, $F<1$]. The main effects and interactions of stimulus type and relationship were not significant [$F<2$].

GENERAL DISCUSSION

The results of the two experiments demonstrate that conceptual relationships between spoken words and meaningful nonspeech sounds influence the processing of both words and sounds. Lexical decisions to words showed a substantial reaction time benefit when preceded by related sounds; ERPs elicited by both words and sounds showed an attenuation of a late

Table 1. Target performance

	Word fragments		Sound fragments	
	RT	Accuracy	RT	Accuracy
Match related	921 (58)	98.3 (0.7)	866 (49)	83.9 (4.6)
Match unrelated	901 (49)	97.7 (0.7)	859 (51)	96.7 (1.0)
Mismatch related	1060 (75)	97.0 (1.0)	1017 (66)	95.7 (0.9)
Mismatch unrelated	1082 (69)	93.2 (1.2)	959 (62)	98.3 (0.7)

"Match" and "mismatch" refer to whether the fragment was or was not a portion of the preceding stimulus. "Related" and "unrelated" refer to whether the target fragment followed a related or unrelated pair. Reaction times in msec, accuracies in percent. Standard errors in parentheses.

negative wave when preceded by related items of the other modality. The ERP context effects elicited by words and sounds were similar in general morphology, latency, and scalp distribution in the anterior–posterior dimension, but differed in lateral asymmetry. The N400 modulation in ERPs elicited by words as a consequence of their relationship to a preceding sound was indistinguishable from prior results using word/word pairs. This N400 context effect for auditory words was slightly larger over the right than left hemisphere, but, like previous reports, the asymmetry was not statistically significant. In contrast, the contextual modulation of a late negative wave in the ERPs elicited by sounds was larger over the left hemisphere, an asymmetry not reported for either visual or auditory words in previous studies. This pattern of results is consistent with the idea that the two context effects received differential contributions from the two cerebral hemispheres. Below, we take up the question of what functional processes were lateralized in this paradigm. But first, we briefly discuss the interpretation of asymmetric ERPs in language paradigms.

Over the last 10 years, a variety of asymmetries have been reported in the ERPs elicited by words [67, 76, 94, 102]. These have included both standing asymmetries—differences between left and right recording sites independent of experimental manipulations, and asymmetric effects of particular experimental variables. Standing asymmetries in the ERP are not easily interpretable as reflecting greater activity in one hemisphere or the other; lacking knowledge of the exact synaptic events producing a scalp potential, either greater positivity or greater negativity may indicate greater activity. Lateralized effects of particular experimental manipulations are more interpretable; larger amplitude effects over one hemisphere are most readily accounted for by differential hemispheric involvement in the experimental task. The present results showed a standing asymmetry in the ERPs to both words and sound when they were the second member of a stimulus pair; both elicited greater negativity over the right hemisphere. However, the effect of prior context showed differential asymmetries for words and sounds.

As noted in the introduction, the influence of semantic context on the N400 elicited by visual words has shown a reliable asymmetry of being larger over the right side of the head. In a series of experiments using a rhyme-matching task, Rugg and Barrett [9, 10, 91, 92] also observed a right-greater-than-left difference between rhyming and nonrhyming words. The asymmetry of this "rhyme N400" for visual words appears to be larger and more robust than the semantic N400 effect, but is less apparent when rhyming and nonrhyming words are presented acoustically and do not require grapheme to phoneme conversion [86]. The right-sided asymmetry of a component sensitive to semantic processing is counterintuitive. Right-sided dominance in a rhyming task is even more surprising given other evidence that the left hemisphere is superior at phonological analysis in general, and grapheme to phoneme conversion in particular [68, 82, 88]. But because the scalp distribution of an ERP component is determined not only by the location but the orientation of neurons with respect to the skull, a right-sided asymmetry at the scalp need not indicate right-hemisphere generation. For motor potentials whose neural generators have been well-characterized, unilateral hand movements produce larger potentials over the contralateral hemisphere, as expected from the organization of the motor system [54, 80]. Foot movements, however, produce larger potentials ipsilateral than contralateral. This "paradoxical lateralization" is attributable to the fact that the cortical representation of the foot is near the medial surface of the hemisphere and the neurons are oriented such that current flow is greatest toward the opposite side of the head [16, 17]. A similar argument based on the mapping of the visual fields in calcarine cortex has been used to explain the paradoxical lateralization of the visual P1 component elicited by reversing checkerboard stimuli [7, 15].

The evidence to date is far from conclusive, but suggests that the N400 semantic context effect on words is dependent on a left hemisphere dominance for language processing despite its predominance over the right scalp. The right-sided asymmetry is most evident in right-handed subjects without left-handed family members, and much reduced or absent in right-handers with a family history of sinistrality [56, 67]. On the basis of less reliable or smaller asymmetries in visual hemifield or dichotic listening tasks, others have suggested that the right-handers with left-handed relatives have a more bilateral representation of language than those without [1, 49, 72, 83, 100]. Somewhat stronger evidence comes from a study of commissurotomy patients in which Kutas and colleagues [60] restricted sentence-final words to one or the other hemisphere by presenting them in the left or right visual field. Right visual field presentations (left hemisphere) resulted in N400 context effects for all of the patients. Left visual field presentations (right hemisphere) resulted in N400 effects for only those patients whose right hemisphere also had productive language capability and could control the vocal tract. Words presented to a "speaking hemisphere" resulted in N400 context effects over both the right and left scalp, while words presented to a mute right hemisphere resulted in no context effect. Bilateral control of the vocal tract is an unusual state of affairs; in most normal individuals the "speaking hemisphere" is the language-dominant or left hemisphere. The commissurotomy data thus suggest that in the majority of normal individuals, the N400 is more dependent on the left than right hemisphere. Additional data about the neural generators of the N400 come from intracranially recorded field potentials showing larger amplitude responses to visual words from the left than right temporal lobe [97].

The commissurotomy and intracranial studies used visual words as stimuli. We have no corresponding data concerning the semantic context effect on auditory words, but the most parsimonious working hypothesis is that both effects are dependent on a left hemisphere language system. The similarity between the influence of environmental sound context and the word contexts used in previous studies argues that the context effect on words in the present study is likely to result from left hemisphere activity as well. What of the context effect in the ERPs elicited by sounds? Given the complex geometrical relationships between scalp asymmetries and neural asymmetries described above, this is a topic for further research. The impact of familial sinistrality on the asymmetry of the N400 elicited by visual words suggests that it will be of some interest to determine whether this factor also influences the asymmetry of the context effect observed for environmental sounds. The subjects participating in the present study were not selected for handedness or family history of handedness, and the sample sizes were too small to subdivide for additional analyses.

Assuming that the differential asymmetries obtained for words and environmental sounds do index differential contributions from the two cerebral hemispheres, the results would be consistent with other data suggesting that the processing of speech and nonspeech sounds received larger contributions from the left and right hemispheres, respectively. With dichotic listening tasks in normal individuals, speech sounds typically show a right ear advantage, while environmental sounds show a left ear advantage [18, 23, 50, 51]. The neuropsychology literature presents a dissociation between speech and other sounds which suggests relative rather than absolute hemispheric specializations. Most brain-damaged patients with deficits in the recognition of environmental sounds have left hemisphere lesions and also suffer aphasic symptoms [105, 106, 108]. However, there are reports of unilateral right hemisphere lesioned patients with deficits in environmental sound recognition and preserved recognition of speech [26, 29, 90, 99]. In contrast, the syndrome of pure word deafness, in which recognition of environmental sounds is spared, is thought to require damage which disrupts auditory input to a speech area in the left hemisphere [2, 22, 83].

The asymmetric context effects observed in ERPs from normal subjects is thus in accord with data from patients in suggesting a greater right hemisphere involvement in the processing of environmental sounds than words. However, it is worth examining in greater detail exactly what process was lateralized in our contrast between speech and nonspeech sounds. One prominent theory is that the special acoustic characteristics of speech underly the left hemisphere specialization for speech perception [95]. In particular, consonants are distinguished from one another by acoustic signals of very brief duration, and the auditory system of the left hemisphere is superior at discriminating brief acoustic events [87]. Thus, the right ear advantage in dichotic listening is restricted to consonants, rather than vowel sounds of longer duration [18]. The syndrome of pure word deafness has been attributed to defective temporal processing, given that these patients can discriminate vowels and artifically slowed consonant sounds, but not normal consonants [2, 22, 83]. In contrast, patients with auditory deficits after right hemisphere lesions are more likely to be impaired at pitch discriminations which do not require recognition of rapid temporal changes [87, 96].

The nonspeech sounds used here were not selected on the basis of their acoustic characteristics, which vary widely. But on average, identification of the sounds was less likely to depend on rapid temporal changes than the identification of the spoken words. An initial hypothesis might then be that the differentially asymmetric context effects observed for sounds and words were based purely on their different acoustic characteristics. It would be surprising, however, if purely acoustic differences were responsible for the observed asymmetries. A number of ERP studies conducted in the 1970s and early 1980s compared speech and nonspeech sounds in search of hemispheric asymmetries, with largely negative results [25, 35, 75]. Of these, Friedman and colleagues [28] used stimuli which were the most comparable to those here: five spoken words and five nonspeech produced by a human (e.g. cough). Each stimulus was presented with an equal probability in several blocks of 100 trials, and subjects were asked to respond to one item in each block whenever it occurred. The target items elicited bilaterally symmetric P300s whether they were words and sounds. The differences between the present study and earlier ERP studies are thus not in the contrast between speech and nonspeech, but in the use of a larger nonrepeating stimulus set, and the inclusion of both conceptual and perceptual relationships among stimuli.

Two aspects of the current data also argue against the interpretation that the differential asymmetries were due solely to the differing acoustic properties of speech vs environmental sounds. First, subjects needed to process both the first and second members of each stimulus pair in order to analyze the conceptual relationship between them. We did not, however, observe asymmetric differences between words and sounds when they served as the first member of a stimulus pair. Second, the ERPs elicitied by the target items showed the same pattern of asymmetry regardless of whether they were fragments of words or fragments of sounds. Recording sites over the right hemisphere showed a generally larger P300 to the targets, and a larger P300 modulation depending on whether or not the fragment matched the prior word or sound. The relationships between the first and second stimuli in each trial were conceptual in nature; the relationships between the second stimuli and subsequent targets were perceptual in nature. The pattern of observed asymmetries thus cannot be accounted for by either the purely acoustic properties of the items or by the nature of the relationship (conceptual vs perceptual) between two stimuli. Instead, the interaction between stimulus modality and type of relationship suggests that the hemispheres were differentially engaged by words and other sounds only when the meaning of the stimulus needed to be analyzed. A prerequisite of conceptual analysis is the unique identification of an item, picking out one memory representation which corresponds to the current item. This is likely to be more demanding than the fragment matching task, and thus more likely to engage specialized hemispheric processors.

Our working hypothesis has been that the observed asymmetries in an N400-like wave are specific to the modality of the eliciting stimulus rather than to the crossmodal nature of the paradigm. However, it will be important to test this hypothesis in future research by comparing word/word and sound/sound pairs.

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REFERENCES

1. Andrews, R. J. Aspects of language lateralization correlated with familial handedness. *Neuropsychologia* **15,** 769–778, 1977.
2. Auerbach, S. H., Allard, T., Naeser, M., Alexander, M. and Albert, M. Pure word deafness: Analysis of a case with bilateral lesions and a defect at the prephonemic level. *Brain* **105,** 271–300, 1982.
3. Ballas, J. A. Common factors in the identification of an assortment of brief everyday sounds. *J. exp. Psychol.: Hum. Percept. Perform.* **19,** 250–267, 1993.
4. Ballas, J. A. and Howard, J. H. Interpreting the language of environmental sounds. *Environ. Behav.* **19,** 91–114, 1987.
5. Ballas, J. A. and Mullins, R. T. Effects of context on the identification of everyday sounds. *Hum. Perform.* **4,** 199–219, 1991.
6. Balish, M. and Muratore, R. The inverse problem in electroencephalography and magnetoencephalography. *Adv. Neurol.* **34,** 79–88, 1990.
7. Barrett, G., Blumhardt, L., Halliday, A. M., Halliday, E. and Kriss, A. A paradox in the lateralization of the visual evoked response. *Nature* **261,** 253–255, 1976.
8. Barrett, S. E. and Rugg, M. D. Event-related potentials and the semantic matching of faces. *Neuropsychologia* **27,** 913–922, 1989.
9. Barrett, S. E. and Rugg, M. D. Asymmetries in event-related potentials during rhyme matching: Cofirmation of the null effects of handedness. *Neuropsychologia* **27,** 539–548, 1989.
10. Barrett, S. E. and Rugg, M. D. Event-related potentials and the phonological matching of picture names. *Brain Lang.* **38,** 424–437, 1990.
11. Becker, C. A. and Killion, T. H. Interaction of visual and cognitive effects in word recognition. *J. exp. Psychol.: Hum. Percept. Perform.* **3,** 389–401, 1977.
12. Bentin, S., Kutas, M. and Hillyard, S. A. Electrophysiological evidence for task effects on semantic priming in auditory word processing. *Psychophysiology* **30,** 161–169, 1993.

13. Bentin, S., McCarthy, G. and Wood, C. C. Event-related potentials associated with semantic priming. *Electroencephalogr. clin. Neurophysiol.* **60,** 343–355, 1985.
14. Besson, M. and Macar, F. An event-related potential analysis of incongruity in music and other nonlinguistic contexts. *Psychophysiology* **24,** 14–25, 1987.
15. Blumhardt, L. and Halliday, A. M. Hemisphere contributions to the composition of the pattern-evoked waveform. *Exp. Brain Res.* **36,** 53–69, 1979.
16. Boschert, J., Brickett, P., Weinberg, H. and Deecke, L. Movement-related potentials preceding toe plantarflexion and dorsiflexion. *Hum. Neurobiol.* **2,** 87–90, 1983.
17. Boschert, J. and Deecke, L. Cerebral potentials preceding voluntary toe, knee and hip movements and their vectors in human precentral gyrus. *Brain Res.* **376,** 175–179, 1986.
18. Bradshaw, J. L., Burden, V. and Nettleton, N. Dichotic and dichaptic techniques. *Neuropsychologia* **24,** 79–90, 1986.
19. Coles, M. G. H., Gratton, G. and Fabiani, M. Event-related brain potentials. In *Principles of Psychophysiology: Physical, Social, and Inferential Elements*, J. T. Cacioppo and L. G. Tassinary (Editors). Cambridge University Press, Cambridge, 1990.
20. Connolly, J. F., Phillips, N. A., Stewart, S. H. and Brake, W. G. Event-related potential sensitivity to acoustic and semantic properties of terminal words in sentences. *Brain Lang.* **43,** 1–18, 1992.
21. Connolly, J. F., Stewart, S. H. and Phillips, N. A. The effects of processing requirements on neurophysiological responses to spoken sentences. *Brain Lang.* **39,** 302–318, 1990.
22. Coslett, H. B., Brashear, H. R. and Heilman, K. M. Pure word deafness after bilateral primary auditory cortex infarcts. *Neurology* **34,** 347–352, 1984.
23. Curry, F. K. W. A comparison of left-handed and right-handed subjects on verbal and non-verbal dichotic listening tasks. *Cortex* **3,** 343–352, 1967.
24. Dale, A. M. and Sereno, M. I. Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: A linear approach. *J. cognit. Neurosci.* **5,** 162–176, 1993.
25. Donchin, E., McCarthy, G. and Kutas, M. Electroencephalographic investigations of hemispheric specialization. In *Language and Hemispheric Specialization in Man: Cerebral ERPs*, J. E. Desmedt (Editor), pp. 212–242. Karger, Basel, 1977.
26. Eustache, F., Lechevalier, B., Viader, F. and Lambert, J. Identification and discrimination disorders in auditory perception: A report on two cases. *Neuropsychologia* **28,** 257–270, 1990.
27. Francis, W. N. and Kucera, H. *Frequency Analysis of English Usage: Lexicon and Grammar.* Houghton Mifflin, Boston, 1982.
28. Friedman, D., Simson, R., Ritter, W. and Rapin, I. Cortical evoked potentials elicited by real speech words and human sounds. *Electroencephalogr. clin. Neurophysiol.* **38,** 13–19, 1975.
29. Fuji, T., Fukatsu, R., Watabe, S., Ohnuma, A., Teramura, K., Saso, S. and Kogure, K. Auditory sound agnosia without aphasia following a right temporal lobe lesion. *Cortex* **26,** 263–268, 1990.
30 Ganis, G. and Kutas, M. The search for "common sense": An electrophysiological investigation of semantic analysis of words and pictures in sentences. Presentation at Cognitive Neuroscience Society, San Francisco, March 1993.
31. Glaser, W. R. Picture naming. *Cognition* **42,** 61–105, 1992.
32. Glucksberg, S. Commentary: the functional equivalence of common and multiple codes. *J. verb. Learn. verb. Behav.* **23,** 100–104, 1984.
33. Halgren, E. Insights from evoked potentials into the neurophysiological mechanisms of reading. In *Neurobiology of Higher Cognitive Function*, A. B. Scheibel and A. F. Weschler (Editors), pp. 103–149. Guilford Press, New York, 1990.
34. Harbin, T. J., Marsh, G. R. and Harvey, M. T. Differences in the late components of the event-related potential due to age and to semantic and non-semantic tasks. *Electroencephalogr. clin. Neurophysiol.* **59,** 489–496, 1984.
35. Hansen, J. C., Dickstein, P. W., Berka, C. and Hillyard, S. A. Event-related potentials during selective attention to speech sounds. *Biol. Psychol.* **16,** 211–224, 1983.
36 Herning, R. I., Jones, R. T. and Hunt, J. S. Speech event related potentials reflect linguistic content and processing level. *Brain Lang.* **30,** 116–129, 1987.
37. Hillyard, S. A. The CNV and human behavior: a review. *Electroencephalogr. clin. Neurophysiol. Supplement* **33,** 161–171, 1973.
38. Hillyard, S. A. and Picton, T. W. ON and OFF components in the auditory evoked potential. *Percept. Psychophys.* **24,** 391–398, 1978.
39. Hillyard, S. A. and Picton, T. W. Electrophysiology of cognition. In *Handbook of Physiology: The Nervous System, Vol. V*, F. Plum (Editor), pp. 519–584. American Physiological Society, Bethesda, MD, 1987.
40. Hillyard, S. A. and Woods, D. L. Electrophysiological analysis of human brain function. In *Handbook of Behavioral Neurobiology, Vol.* 2, M. S. Gazzaniga (Editor), pp. 345–378. Plenum, New York, 1979.
41. Holcomb, P. J. Automatic and attentional processing: An event-related brain potential analysis of semantic processing. *Brain Lang.* **35,** 66–85, 1988.

42. Holcomb, P. J. and Anderson, J. E. Cross-modal semantic priming: A time-course analysis using event-related brain potentials. *Lang. Cognit. Process.* **8,** 379–412, 1993.
43. Holcomb, P. J. and McPherson, W. B. Event-related brain potentials reflect semantic priming in an object-decision task. *Brain Cognit.* **24,** 259–276, 1994.
44. Holcomb, P. J. and Neville, H. J. Auditory and visual semantic priming in lexical decision: A comparison using event-related brain potentials. *Lang. Cognit. Process.* **5,** 281–312, 1990.
45. Holcomb, P. J. and Neville, H. J. Natural speech processing: An analysis using event-related brain potentials. *Psychobiology* **19,** 286–300, 1991.
46. Jasper, H. H. The ten-twenty electrode system of the International Federation. *Electroencephalogr. clin. Neurophysiol.* **10,** 371–375, 1958
47. Johnson, R., Jr. The amplitude of the P300 component of the event-related potential: Review and synthesis. In *Advances in Psychophysiology, Vol.* 3, P. K. Ackles, J. R. Jennings and M. G. H. Coles (Editors), pp. 69–138. JAI Press, Greenwich, CN, 1988.
48. Johnson, R., Jr. On the neural generators of the P300 component of the event-related potential. *Psychophysiology* **30,** 90–97, 1993.
49. Kee, D. W., Bathurst, K. and Hellige, J. B. Lateralized interference of repetitive finger tapping: Influence of familial handedness, cognitive load, and verbal production. *Neuropsychologia* **21,** 617–624, 1983.
50. King, F. L. and Kimura, D. Left-ear superiority in dichotic perception of vocal nonverbal sounds. *Can. J. Psychol.* **26,** 111–116, 1972.
51. Knox, C. and Kimura, D. Cerebral processing of nonverbal sounds in boys and girls. *Neuropsychologia* **8,** 227–237, 1970.
52. Kroll, J. F. and Potter, M. C. Recognizing words, pictures, and concepts: A comparison of lexical, object, and reality decisions. *J. verb. Learn. verb. Behav.* **23,** 39–66, 1984.
53. Kutas, M. Review of event-related potential studies of memory. In *Perspectives in Memory Research*, M. S. Gazzaniga (Editor), pp. 181–218. MIT Press, Cambridge, MA, 1988.
54. Kutas, M. and Donchin, E. Studies of squeezing: Handedness, responding hand, response force, and asymmetry of readiness potential. *Science* **186,** 545–548, 1974.
55. Kutas, M. and Hillyard, S. A. Reading between the lines: Event-related potentials during natural sentence processing. *Brain Lang.* **11,** 354–373, 1980.
56. Kutas, M. and Hillyard, S. A. Event-related potentials to semantically inappropriate and surprisingly large words. *Biol. Psychol.* **11,** 99–116, 1980.
57. Kutas, M. and Hillyard, S. A. The lateral distribution of event-related potentials during sentence processing. *Neuropsychologia* **20,** 579–590, 1982.
58. Kutas, M. and Hillyard, S. A. Brain potentials during reading reflect word expectancy and semantic association. *Nature* **307,** 161–163, 1984.
59. Kutas, M. and Hillyard, S. A. An electrophysiological probe of incidental semantic association. *J. cognit. Neurosci.* **1,** 38–49, 1989.
60. Kutas, M., Hillyard, S. A. and Gazzaniga, M. S. Processing of semantic anomaly by right and left hemispheres of commissurotomy patients. *Brain* **111,** 553–576, 1988.
61. Kutas, M., Lindamood, T. and Hillyard, S. A. Word expectancy and event-related brain potentials during sentence processing. In *Preparatory States and Processes*, S. Kornblum and J. Requin (Editors), pp. 217–238. Lawrence Erlbaum, Hillsdale, NJ, 1984.
62. Kutas, M. McCarthy, G. and Donchin, E. Augmenting mental chronometry: the P300 as a measure of stimulus evaluation time. *Science* **197,** 792–795, 1977.
63. Kutas, M., Neville, H. J. and Holcomb, P. J. A preliminary comparison of the N400 response to semantic anomalies during reading, listening, and signing. *Electroencephalogr. clin. Neurophysiol. Supplement* **39,** 325–330, 1987.
64. Kutas, M. and Van Petten, C. Event-related brain potential studies of language. In *Advances in Psychophysiology, Vol.* 3, P K. Ackles, J. R. Jennings and M. G. H. Coles (Editors), pp. 139–187. JAI Press, Greenwich, CN, 1988.
65. Kutas, M. and Van Petten, C. Electrophysiological perspectives on comprehending written language. In *New Trends and Advanced Techniques in Clinical Neurophysiology*, P. M. Rossini and F. Mauguiere (Editors), pp. 155–167. Elsevier, New York, 1990.
66. Kutas, M. and Van Petten, C. Psycholinguistics electrified: Event-related brain potential investigations. In *Handbook of Psycholinguistics*, M. Gernsbacher (Editor). Academic Press, New York, in press.
67. Kutas, M., Van Petten, C. and Besson, M. Event-related asymmetries during the reading of sentences. *Electroencephalogr. clin. Neurophysiol.* **69,** 218–233, 1988.
68. Levy, J. and Trevarthan, C. Perceptual, semantic, and phonetic aspects of elementary language processes in split-brain patients. *Brain* **100,** 105–118, 1977.
69. Massaro, D. W., Jones, R. D., Lipscomb, D. and Scholz, R. Role of prior knowledge on lexical decisions with good and poor stimulus information. *J. exp. Psychol.: Hum. Learn. Mem.* **4,** 498–512, 1978.

70. McCallum, W. C., Farmer, S. F. and Pocock, P. K. The effects of physical and semantic incongruities on auditory event-related potentials. *Electroencephalogr. clin. Neurophysiol.* **59,** 477–488, 1984.
71. McCarthy, G. and Wood, C. C. Scalp distribution of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalogr. clin. Neurophysiol.· Evoked Potentials* **62,** 203–208, 1985.
72. McKeever, W. F. and Hoff, A. L. (1982). Familial sinistrality, sex, and laterality differences in naming and lexical decision latencies of right handers. *Brain Lang.* **17,** 225–239, 1982.
73. McKeever, W. F. Interacting sex and familial sinistrality characteristics influence both language lateralization and spatial ability in right handers. *Neuropsychologia* **21,** 661–668, 1983.
74 Meyer, D. E. and Schvaneveldt, R. W. Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *J. exp. Psychol.* **90,** 227–234, 1971.
75. Molfese, D. L. Event-related potentials and language processes. In *Tutorials in ERP Research: Endogenous Components,* A. W. K. Gaillard and W. Ritter (Editors), pp. 345–367. North Holland Press, Amsterdam, 1983.
76 Neville, H. J. Whence the specialization of the language hemisphere? In *Modularity and the Motor Theory of Speech Perception,* I. G. Mattingly and M. Studdert-Kennedy (Editors), pp. 269–294. Lawrence Erlbaum, Hillsdale, NJ, 1991.
77. Nigam, A., Hoffman, J. E. and Simons, R. F. N400 to semantically anomalous pictures and words. *J. cognit Neurosci.* **4,** 15–22, 1992.
78. O'Halloran, J. P., Isenhart, R., Sandman, C. A. and Larkey, L. S. Brain responses to semantic anomaly in natural continuous speech. *Int. J. Psychophysiol.* **6,** 243–254, 1988.
79. O'Rourke, T. B. and Holcomb, P. J. Electrophysiological evidence for the time course of spoken word recognition. *Psychophysiology* **29,** S54, 1992.
80. Osman, A., Bashore, T. R., Coles, M. G. H., Donchin, E. and Meyer, D. E. On the transmission of partial information: Inferences from movement-related brain potentials *J. exp. Psychol. Hum. Percept. Perform* **18,** 217–232, 1992.
81. Paller, K. A., McCarthy, G. and Wood, C C. Event-related potentials elicited by deviant endings to melodies. *Psychophysiology* **29,** 202–206, 1992.
82. Patterson, K. and Besner, D. Is the right hemisphere literate? *Cognit. Neuropsychol.* **1,** 315–341, 1984.
83. Phillips, D. P. and Farmer, M. E. Acquired word deafness, and the temporal grain of sound representation in the primary auditory cortex. *Behav. Brain Res.* **109,** 85–94, 1990.
84. Polich, J. Semantic categorization and event-related potentials. *Brain Lang.* **26,** 304–321, 1985.
85. Potter, M. C., Kroll, J. F., Yachzel, B., Carpenter, E. and Sherman, J. Pictures in sentences: understanding without words. *J. exp. Psychol.: Gen.* **115,** 281–294, 1986.
86. Praamstra, P. and Stegeman, D. F. Phonological effects on the auditory N400 event-related brain potential. *Cognit. Brain Res.* **1,** 73–86, 1993.
87. Robin, D. A., Tranel, D. and Damasio, H. Auditory perception of temporal and spectral events in patients with focal left and right cerebral lesions. *Brain Lang.* **39,** 539–555, 1990.
88. Rodel, M., Dudley, J. G., and Bourdeau, M. Hemispheric differences for semantically and phonologically primed nouns: A tachistoscopic study in normals. *Percept. Psychophys.* **34,** 523–531, 1983.
89. Rouse, R. O. and Verinis, J. S. The effect of associative connections on the recognition of flashed words. *J verb. Learn. verb. Behav.* **88,** 454–462, 1962.
90. Rubens, A. R. Agnosia. In *Clinical Neuropsychology,* K. M. Heilman and E. Valenstein (Editors), pp. 233–267. Oxford University Press, New York, 1979.
91. Rugg, M. D. Event-related potentials and the phonological processing of words and nonwords. *Neuropsychologia* **22,** 435–443, 1984.
92. Rugg, M. D. Event-related potentials in phonological matching tasks. *Brain Lang.* **23,** 225–240, 1984.
93. Rugg, M D. The effects of semantic priming and word repetition on event-related potentials. *Psychophysiology* **22,** 642–647, 1985.
94. Rugg, M., Kok, A., Barrett, G. and Fischler, I. ERPs associated with language and hemispheric specialization. In *Cerebral Psychophysiology: Studies in Event-Related Potentials,* W. C. McCallum, R. Zappoli and F. Denoth (Editors). Elsevier, Amsterdam, 1986.
95. Schwartz, J. and Tallal, P. Rate of acoustic change may underlie hemispheric specialization for speech perception. *Science* **207,** 1380–1381, 1980.
96. Sidtis, J. J. and Volpe, B. T. Selective loss of complex-pitch or speech discrimination after unilateral lesion. *Brain Lang.* **34,** 235–245, 1988.
97. Smith, M. E., Stapleton, J M. and Halgren, E. Human medial temporal lobe potentials evoked in memory and language tasks. *Electroencephalogr. clin. Neurophysiol.* **63,** 145–159, 1986.
98. Snodgrass, J. G. Concepts and their surface representation. *J. verb. Learn. verb. Behav.* **23,** 3–22, 1984.
99. Spreen, P , Benton, A. L. and Fincham, R. W. Auditory agnosia without aphasia. *Arch. Neurol.* **13,** 84–92, 1965
00. Springer, S. P. and Searleman, A. The ontogeny of hemispheric specialization: Evidence from dichotic listening in twins. *Neuropsychologia* **16,** 269–281, 1978.

101. Van Petten, C. A comparison of lexical and sentence-level context effects and their temporal parameters. *Lang. Cognit. Process.* **8,** 485–532, 1993.

102. Van Petten, C. and Kutas, M. The use of event-related potentials in the study of brain asymmetries. *Int. J. Neurosci.* **39,** 91–99, 1988.

103. Van Petten, C. and Kutas, M. Interactions between sentence context and word frequency in event-related brain potentials. *Mem. Cognit.* **18,** 380–393, 1990.

104. Van Petten, C. and Kutas, M. Influences of semantic and syntactic context on open and closed class words. *Mem. Cognit.* **19,** 95–112, 1991.

105. Varney, N. Sound recognition in relation to aural language comprehension in aphasic patients. *J. Neurol. Neurosurg. Psychiat.* **43,** 71–75, 1980.

106. Varney, N. R. and Damasio, H. CT scan correlates of sound recognition deficit in aphasia. *Cortex* **22,** 483–486, 1986.

107. Vasey, W. V. and Thayer, J. F. The continuing problem of false positives in repeated measures ANOVA in psychophysiology: A multivariate solution. *Psychophysiology* **24,** 479–486, 1987.

108. Vignolo, L. Auditory agnosia. In *Contributions to Clinical Neuropsychology*, A. L. Benton (Editor). Aldine, Chicago, 1969.

109. Warren, R. E. Association, directionality, and stimulus encoding. *J. exp. Psychol.* **102,** 151–158, 1974.

110. Warren, R. E. Time and the spread of activation in memory. *J. exp. Psychol.: Hum. Learn. Mem.* **3,** 458–466, 1977.

111. Wood, C. C. and Allison, T. Interpretation of evoked potentials: A neurophysiological perspective. *Can. J. Psychol.* **35,** 113–135, 1981.

112. Woodward, S. H., Owens, J. and Thompson, L. W. Word-to-word variation in ERP component latencies: Spoken words. *Brain Lang.* **38,** 488–503, 1990.