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The Mechanism Underlying Backward Priming in a Lexical Decision Task: Spreading Activation versus Semantic Matching

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Koriat (1981) demonstrated that an association from the target to a preceding prime, in the absence of an association from the prime to the target, facilitates lexical decision and referred to this effect as "backward priming". Backward priming is of relevance, because it can provide information about the mechanism underlying semantic priming effects. Following Neely (1991), we distinguish three mechanisms of priming: spreading activation, expectancy, and semantic matching/ integration. The goal was to determine which of these mechanisms causes backward priming, by assessing effects of backward priming on a language-relevant ERP component, the N400, and reaction time (RT). Based on previous work, we propose that the N400 priming effect reflects expectancy and semantic matching/ integration, but in contrast with RT does not reflect spreading activation. Experiment 1 shows a backward priming effect that is qualitatively similar for the N400 and RT in a lexical decision task. This effect was not modulated by an ISI manipulation. Experiment 2 clarifies that the N400 backward priming effect reflects genuine changes in N400 amplitude and cannot be ascribed to other factors. We will argue that these backward priming effects cannot be due to expectancy but are best accounted for in terms of semantic matching/ integration.

When a word (the target) is preceded by an associated word (the prime) in word recognition tasks, performance is facilitated. For instance, subjects respond faster to the word "doctor" when it is preceded by "nurse" than when it is preceded by an unrelated word like "carrot". This *semantic priming effect* has been observed in a variety of tasks, ranging from sentence verification (Loftus, 1973) to lexical decision (e.g. Meyer & Schvaneveldt, 1971) and naming (e.g. Balota & Lorch, 1986; De Groot, 1985). The general phenomenon has been much studied, and we will review several possible mechanisms below. Koriat

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(1981) was the first to make the more specific observation than an association from the target to the prime, in the absence of an association from the prime to the target, facilitates lexical decision. For example, subjects in free association tests frequently respond "baby" to "stork" but almost never respond "stork" to "baby". But in spite of the fact that "baby" does not, by this measure, evoke "stork", "baby" reliably primes a following lexical decision to "stork". Koriat referred to this as "backward priming".[1]

Backward priming is of interest both because of what it might tell us about the representation and processing of semantic and associative relationships and because of what it tells is about the mechanism of the semantic priming effect, which is widely used as a tool for indexing semantic activation. For example, the observation that in sentence context an ambiguous word cross-modally primes lexical decision to a word related to either of its meanings has been taken as evidence that even the contextually irrelevant meaning is active at that point (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, 1979). Others, however, have interpreted the same finding as resulting from backward priming of the contextually irrelevant meaning resulting from the presentation of the probe (Glucksberg, Kreuz, & Rho, 1986).

It is generally agreed that there are mutliple causes or loci of semantic priming. In this paper, we attempt to localize backward priming with respect to these using the N400—that is, an Event-Related Brain Potential (ERP) component—alongside RT measures. Following De Groot (1985) and Neely (1991), we first distinguish three different mechanisms for priming: spreading activation, semantic matching/ integration, and expectancy. We will argue that existing ERP evidence indicates that the N400 component is sensitive only to semantic matching/ integration and expectancy. We will then report data demonstrating that the N400 is sensitive to backward priming in the same way as RT, even in conditions that rule out expectancy as a mechanism. We will conclude that some form of semantic matching or integration mechanism must be responsible for effects of backward priming.

Mechanisms for Semantic Priming

The mechanism of spreading activation as described by Collins and Loftus (1975) has often been used to explain the semantic priming effect. Spreading activation is based on the assumption that in semantic memory strong or direct links exist between the representations of words that are closely related in meaning. Presentation of a word activates the corresponding node in semantic memory, and via the links to nearby nodes part of this activation automatically spreads to the nodes representing words that are related in meaning. As a consequence, the recognition of nodes representing related words takes less time. Spreading activation has all the characteristics of an automatic process. It is fast-acting, of short duration, does not require attention or awareness, and presupposes no or only

[1] The term "backward priming" has also been used in a different sense. Kiger and Glass (1983) reversed the temporal sequence — that is, they presented the prime (e.g. "baby") very soon (SOA = −65, −130 msec) after the target (e.g. "stork") to which a lexical decision was required. They found a facilitation for the short −65 msec SOA and called it "backward priming".

minimal demands on resource capacity (Posner & Snyder, 1975; Shiffrin & Schneider, 1977).

In his review on semantic priming, Neely (1991) concluded that no single mechanism is able to account for the full spectrum of RT priming effects. One basic problem for any single mechanism is to account for the differences in priming effects that are observed between tasks, in particular between naming and lexical decision. According to Neely, at least two additional priming mechanisms are needed to give a comprehensive account of the RT priming literature.

The first of these is expectancy-induced priming (Becker, 1980; 1985; Posner & Snyder, 1975) in which the subject uses the information provided by the prime to generate an expectancy set for related target words. The resulting RT pattern is dependent upon the size of the expectancy set. If the expectancy set is small, as is the case for antonyms (e.g. "black–white"), then a facilitation-dominant pattern is observed. In contrast, if the expectancy set is large, as is the case for category relationships (e.g. "fish–shrimp"), then an inhibition-dominant pattern is obtained. The generation of an expectancy set takes time, so that the effects of this mechanism are usually only obtained at intervals that are longer than approximately 500 msec (De Groot, 1984; Neely, 1977). Moreover, this mechanism can be influenced by instruction or by the list structure of the material, for example by the proportion of related word pairs (e.g. Fischler, 1977). Expectancy-induced priming has been characterized as a controlled process.

The second additional mechanism is semantic matching (Neely & Keefe, 1989) also called post-lexical meaning integration by De Groot (1985). According to both models, subjects in the lexical decision task match primes and targets post-lexically for semantic similarity. The presence versus absence of a semantic relationship provides information about the lexical status of the target word. As a semantic match is only found on word trials, the detection of a relationship leads to a bias to respond "word", whereas the absence of such a relation invokes a bias to respond "nonword". When the nonword ratio (i.e. the proportion of trials with a nonword target and a word prime out of all trials in which targets are unrelated to their word primes) is high, the use of the semantic matching strategy will be particularly helpful, and thus it should be used more often, as indeed the results of Neely, Keefe, and Ross (1989) have shown.

Neely (1991) and De Groot (1985) differ in their view on the nature of the integration process. According to Neely, semantic matching is a time-consuming process that can only be effective with relatively long intervals between primes and targets. De Groot (1985), however, has proposed that the post-lexical meaning integration process reflects a fast-acting process that can be observed even at very short stimulus-onset asynchronies (SOAs).

In summary, three mechanisms are supposed to underlie semantic priming. We assume that two of these mechanisms share core characteristics with processes involved in ordinary language comprehension. Spreading activation is an automatic by-product of the process of lexical access—that is, the process of accessing the mental lexicon and activating a subset of all the words in the lexicon.[2] Semantic matching shares characteristics with

[2] Here it is assumed that the mental lexicon is comprised of a well-defined word–meaning component in systematic relationship with linguistic word-forms. This implies that associative and semantic relationships are represented at the level of word meaning.

post-lexical integration processes, that is, integrating a lexical element into a higher-order representation of the entire sentence or discourse.

More recently, alternative models of semantic priming have been presented (Ratcliff & McKoon, 1988, Masson, 1991 and 1995). For simplicity, we frame the present research within the Neely framework and return to these other models in the General Discussion Section.

The Event-Related Potential Method

ERPs are stimulus-bound voltage fluctuations in the scalp-recorded spontaneous electro-encephalogram (EEG). Because ERPs are much smaller in amplitude (5–10 μV) than the spontaneous EEG (50–100 μV), they have to be extracted from the background EEG by averaging across several stimulus presentations. The ERPs elicited by a stimulus consist of a series of positive and negative peaks. These peaks are typically labelled according to their polarity (P for positive and N for negative), and their latency is measured from stimulus onset. It has been established that one particular ERP component, called "the N400"—that is, a negative peak with a mean latency of about 400 msec—is especially sensitive to semantic processing (see for reviews Kutas & Van Petten, 1988, 1994). A distinction needs to be made between the presence or absence of the N400 as opposed to modulations in N400 amplitude. Each open-class word evokes an N400, so that the elicitation of this component is a default response to words. In addition, the amplitude of the N400 is very sensitive to semantic relations between words, both in word-word and in sentential contexts. In particular, the N400 amplitude is smaller when a word is preceded by a semantically related word than when it is preceded by an unrelated word (e.g. Bentin, McCarthy, & Wood, 1985; Holcomb, 1988; Holcomb & Anderson, 1993; Holcomb & Neville, 1990; Kutas & Hillyard, 1989). This difference in amplitude is referred to as the N400 priming effect.

The Lexical Processing Nature of the N400 Priming Effect

Previous studies indicate that the N400 priming effect mainly, if not exclusively, reflects post-lexical integration processes (Brown & Hagoort, 1993; Chwilla, Brown, & Hagoort, 1995; Chwilla, Hagoort, & Brown, 1994; Osterhout & Holcomb, 1994; Rugg, Furda, & Lorist, 1988) and, in certain task situations, expectancy-induced priming (Holcomb, 1988; Brown, Hagoort, & Chwilla, 1988), but it does not reflect lexical access.

Support for this view comes from experiments in which clear dissociations between RT and the N400 have been observed. Brown and Hagoort (1993) did not find an N400 priming effect when the prime was masked, whereas under the same condition a RT priming effect was obtained. This finding suggests that spreading activation influences RT, but not the N400. Holcomb (1993) assessed the effects of stimulus degradation on the size of the RT and the N400 priming effect. Behavioural studies had shown that degradation reduces the speed of word processing and that this effect interacts with semantic priming (Meyer, Schvaneveldt, & Ruddy, 1975). The locus of this effect has been typically claimed to be an early encoding stage, preceding or coinciding with lexical access (cf.

Holcomb, 1993). Holcomb found an interaction of degradation with semantic priming for RTs, but degradation did not modulate the size of the N400 priming effect. This finding was taken to indicate that the N400 is not related to the early processes of lexical access.

Further evidence that the N400 priming effect mainly reflects post-lexical processes comes from three studies on the effects of selective attention. McCarthy and Nobre (1993) visually presented lists including semantically related words. Subjects were instructed to detect members of a specified semantic category in one spatial location while ignoring words in another. They observed the N400 component for words in both locations indicating that they had been processed for meaning. However, N400 was influenced by priming only for words in the attended location. Similarly, Bentin, Kutas, and Hillyard (1995) assessed the effects of selective attention on the N400 priming effect in a dichotic listening task. Subjects were instructed to memorize the words presented to one ear while ignoring the words presented to the opposite ear. Both streams contained semantically related and unrelated pairs. An N400 priming effect was found in the attended channel, but not in the unattended channel. Kellenbach and Michie (1996) used a task that required selection of stimuli on the basis of colour, together with a lexical decision to items in the attended colour. An N400 priming effect was elicited only when the prime had been processed in the focus of attention and had, therefore, "delivered" its meaning for an integrational process with the subsequent target word. They interpreted their findings to suggest that "the ease with which an item is integrated into prior attended context modulates the N400 component" (p. 169).

More direct support in favour of a semantic matching/ integration account of the N400 priming effect comes from the observation that N400 effects are found not only for associatively related word pairs, but also for pairs that are exclusively semantically related (Hagoort, Brown, & Swaab, 1996). Moreover, the size of the auditory N400 effects was the same for both types of relationships, suggesting that both effects arise at the same level of representation,[3] most probably the lexical semantic level (for additional behavioural evidence, see De Groot, 1990). These observations strengthen the view that N400 priming effects are caused by the semantic relatedness between primes and targets and do not result from connections between the word form representations (e.g. Fischler, 1977; Shelton & Martin, 1992).

Some researchers have suggested that the N400 effect is also sensitive to processes of lexical access. This view was based on the presence of N400 priming effects in: (a) shallow processing tasks (cf. Besson, Fischler, Boaz, & Raney, 1992; Kutas & Hillyard, 1989), and (b) lists with a low proportion of related word pairs (Holcomb, 1988). Our reply to the first point is that the observed N400 priming effects might indicate that although a particular task does not require semantic processing, semantic processing might still

[3] Based on RT work of Moss, Ostrin, Taylor, and Marslen-Wilson (1995), one might have expected a larger N400 effect for associatively related than for purely semantically related word pairs. In their auditory lexical decision experiments RT priming effects were observed for a broad range of semantic relationships, and in all cases a boost in priming effect was found when the word pairs in addition were also associatively related. As in the Hagoort et al. (1996) study subjects listened attentively to the word pairs, no RT data are available to compare with the Moss et al. results. The fact that no boost in N400 effect was found for highly associated versus purely semantically related word pairs is consistent with our view that the N400 and RT do not reflect a completely overlapping set of processes.

have been involved (for an extensive discussion, see Chwilla et al. 1995). More objective criteria are needed to determine whether or not the performance of a so-called "shallow task" involves lexical processing. Chwilla et al. (1995) demonstrated that a shallow task was indeed performed non-lexically at the RT level, but they did not observe an N400 priming effect, although the ERP data did reveal that lexical processing had taken place. The second point can also be easily accounted for by the semantic matching mechanism, because there is no reason to assume that this mechanism only operates when the proportion of related word pairs is high.

Taken together, the results provide strong support for the view that the N400 priming effect is not affected by spreading activation and thus reflects only a subset of the priming mechanisms measured with RT. We assume that the N400 priming effect reflects only two of the three priming mechanisms—namely, semantic matching/integration and expectancy-induced priming—whereas RT is also affected by spreading activation.

Backward Priming

The central question addressed in the present experiments was, which mechanism underlies backward priming? Let us first consider which of the three priming mechanisms can explain effects of backward priming and, if so, in what manner.

Expectancy-induced Priming. In expectancy-induced priming it is assumed that the subject uses the information in the prime to generate an expectancy set of potential target words. This mechanism can only account for backward priming under the assumption that the subject generates associates likely to match the upcoming target. In the case of a unidirectional backward relationship, however, the chance that the subject generates the backward associate is by definition minimal. Therefore, a priori it is very unlikely that backward priming is caused by this mechanism.

Spreading Activation. At first sight it is unclear how spreading activation can account for backward priming. The problem arises from the fact that the most commonly used spreading activation model (Collins & Loftus, 1975) assumes that the processing of the prime affects the processing of the target *before* the target has been presented. It is thereby assumed that the activation only spreads forward from the prime to the target.[4] If, however, it is assumed that a feedback loop between the target and prime representations exists, then spreading activation can account for backward priming. Based on the notion that the processing of the target node "reactivates" the prime representation, Koriat (1981) proposed that backward priming effects were due to spreading activation. More specifically, he suggested that when a prime is followed unexpectedly by a related target,

[4] Note that the feature of unidirectionality does not apply to all models of spreading activation. In particular, the ACT* model of Anderson (1983) accounts for priming in a fundamentally different way. According to this model, several words can be sources of activation simultaneously. Priming effects are obtained because the prime node is still active when the target is presented.

the representation of the prime tends to be reactivated by the target, and this activation facilitates the processing of the target word.

Semantic Matching/integration. Seidenberg, Waters, Sanders, and Langer (1984) proposed that backward priming is due to a post-lexical mechanism, and that forward priming is due to spreading activation. They argued that priming for backward-associated word pairs could only arise from a post-lexical relatedness-checking strategy, because only then could the backward relationship from the target to the prime become obvious to the subject. Note that backward priming is compatible with the semantic matching/integration mechanism because the relatedness checking is probably independent of the order in which the words are presented. Seidenberg et al. (1984) tested their hypothesis by investigating the effects of forward and backward associates in the lexical decision and the naming task. They replicated backward priming effects in lexical decision but found no such effect in naming. From this they concluded that backward priming effects were restricted to lexical decision, probably because this task is especially prone to post-lexical strategies (cf. Balota & Lorch, 1986; De Groot, 1984; Den Heyer, Briand, & Dannenbring, 1983; Tweedy, Lapinski, & Schvaneveldt, 1977; West & Stanovich, 1982). Based on this study, the effects of backward priming have been typically attributed to a post-lexical relatedness-checking strategy (Balota & Lorch, 1986; Neely & Keefe, 1989; Neely, 1991; Shelton & Martin, 1992), and the possibility of a spreading activation account of backward priming has largely been ignored.

Recent results of Peterson and Simpson (1989), however, are not entirely consistent with a post-lexical account of backward priming. They demonstrated that with the use of short inter-stimulus intervals (ISI) of 0 or 200 msec and a cross-modal presentation (an auditory prime was followed by a visual target), backward priming can also be observed in a naming task. However, in contrast to their results in the lexical decision task, in the naming task the backward priming effect was strongly reduced in the 200- compared to the 0-msec ISI condition. Peterson and Simpson proposed that the locus of the effect differs in the two tasks—namely, that backward priming in naming arises from facilitation of lexical retrieval processes (e.g. spreading activation in our terminology), whereas backward priming in lexical decision arises from post-lexical processes, at least at the 200-msec ISI. According to Peterson and Simpson (p. 1027, Note 2), it is not clear which mechanism underlies backward priming in the lexical decision task at the 0-msec ISI. This effect could de due either to spreading activation or to a post-lexical relatedness-checking strategy.

From the above it is clear that the possibility that backward priming arises from spreading activation cannot be excluded. In fact, the overall pattern of results of the Peterson and Simpson study appears to be consistent with such a view.

PRESENT EXPERIMENTS

The aim of the present experiments was to determine further which mechanism evokes backward priming effects in the lexical decision task by assessing the effects of backward priming on both RT and the N400 when an auditory prime is paired with a visual target.

For RT we expect a backward priming effect. However, because RT is affected by both pre-lexical and post-lexical processes, it is difficult to determine the locus of the effect. We combined the RT and the N400 measure to separate the effects of spreading activation from the effects of the two other priming mechanisms. Assuming that the N400 priming effect reflects post-lexical sources of priming but does not reflect spreading activation, any sensitivity of the N400 effect to backward priming has important consequences with regard to the locus of the effect. If backward priming effects are obtained for the N400 and RT alike, both with a short and a long interval, this would support a semantic matching/ integration account of backward priming. In contrast, if backward priming effects are observed for RT but not for the N400, this would support a spreading activation account of backward priming.

In addition, we attempted to separate the effects of expectancy-induced priming from the effects of semantic matching/ integration by varying the ISI (0 vs. 500 msec). The time course provides additional information with regard to the locus of the effect (De Groot, 1984; Den Heyer, 1985; Den Heyer et al., 1983; Tweedy et al., 1977). As the generation of an expectancy set is time-consuming, expectancy-induced priming could only account for backward priming effects at the long ISI.[5] In contrast, there is evidence that semantic matching/ integration already takes place at very short intervals (De Groot, 1985), so that this mechanism can account for backward priming effects at both intervals. Thus, in the unlikely case that backward priming effects arise from the mechanism of expectancy-induced priming, both RT and N400 backward priming effects should only be obtained at the ISI of 500 msec, but not at the ISI of 0 msec.

In previous studies on backward priming either asymmetric associatively related word pairs (Koriat, 1981; Peterson & Simpson, 1989) or compounds (Seidenberg et al. 1984; Shelton & Martin, 1992) have been used. The same effects have been obtained in these studies, suggesting that both types of stimuli are processed in a similar way. In these studies both types of materials were used to get a sufficient number of items.

[5] A possible problem with regard to the temporal constraints for generating expectancies is posed by the auditory presentation of the primes. As spoken words can be recognized before all sensory information has been delivered (e.g. Marslen-Wilson, 1987), subjects might have had more time to generate an expectancy set. The critical question, therefore, is what was the effective SOA in the 0-msec ISI condition? To estimate the amount of extra time, we have to take into account the recognition point of the prime: 58% of the primes were monosyllables, in which case the recognition point in Dutch is either on the final or the penultimate phoneme. For these words the effective SOA will have been about 20 to 40 msec. With the exception of three trisyllabic primes, all other primes were bisyllabic. In these cases the recognition point will as a rule fall beyond the syllabic boundary. So here, too, for most primes the effective SOA will certainly fall far short of the mean duration of the prime, which was 556 msec. In conclusion, then, our effective SOA for most cases will not have exceeded 200 msec. Recently, Stolz and Neely (1995) showed that an expectancy set for related target words is not obtained at SOAs shorter than 200 msec. Therefore, we can rule out that expectancy-induced priming entered into the backward priming effect in the 0-msec ISI condition.

EXPERIMENT 1

Method

Subjects

Twenty-eight right-handed subjects, 20 female and 8 male (mean age = 23.7, *SD* = 3.67) recruited from the Max Planck Institute subject pool participated in the experiment. Hand dominance was assessed with an abridged Dutch version of the Edinburgh Inventory (Oldfield, 1971). Eight subjects reported the presence of left-handedness in their immediate family. All subjects were native speakers of Dutch and had normal or corrected-to-normal vision. Subjects were paid DFL 10 per hour.

Apparatus and Stimuli

Subjects were seated in a comfortable reclining chair in a dimly illuminated, sound-attenuating, and electrically shielded chamber. Two push-buttons were fixed on a small table in front of the subject. The stimuli consisted of 528 cross-modally presented pairs of spoken words and visual letter strings (prime and target combinations). The prime was presented binaurally through headphones. The target was presented visually at moderate contrast at the centre of a PC monitor (in a window approximately $3.0° \times 0.8°$ of visual angle). As targets, letter strings of three to eight letters were presented. Half of the target stimuli were real Dutch words, and the other half were nonwords. The nonwords were constructed in accordance with the phonotactic and orthographic constraints of Dutch and were derived from real words unrelated to the primes by substituting one or two letters. The primes of the word–word and the word–nonword pairs were matched with respect to word class and the number of syllables.

The critical prime target combinations consisted of 66 bidirectionally related word pairs (e.g. "spider"–"web"), 66 bidirectionally unrelated word pairs (e.g. "bird"–"soap"), 66 unidirectionally forward-related word pairs (e.g. "mouse"–"cheese"), and 66 unidirectionally backward-related word pairs (e.g. "baby"–"stork").[6] Thus, 198 out of 264 word–word pairs were related, yielding a relatedness proportion of .75. The nonword ratio (i.e. the proportion of trials with a nonword target and a word prime out of all trials in which targets are unrelated to their word primes) was .80, as in 264 out of the 330 unrelated trials a nonword target was preceded by an unrelated prime word.

A pair was considered to be bidirectionally related when prime and target were the first or second associate of each other (43 and 23 word pairs, respectively), according to Dutch word-association norms (De Groot, 1980; De Groot & De Bil, 1987). Associative strength was determined by the percentage of report of the target as an associate of the prime among 100 university students. The mean percentage of association for the bidirectionally related pairs was 43 (*SD*=19) in the forward direction and 41 (*SD*=21) in the backward direction. A pair was considered to be bidirectionally unrelated if the target occurred neither as an associate of the prime in these norms, nor as the prime as an associate of the target, nor had any other obvious relation to the prime, and vice versa. A pair was considered to be unidirectionally forward-related when an associative relation existed from the prime to the target but not from the target to the prime. Correspondingly, a pair was considered to be unidirectionally backward-related when an associative relation existed from the target to the prime but not from the prime to the target. We refer to the four types of pairs as *bidirectional*, *unrelated*, *forward*, and *backward* pairs.

To construct a large-enough set of both types of unidirectional stimuli, we used both words that are asymmetrically semantically/ associatively related (e.g. "baby"–"stork"), and words that are

[6] The materials are available from the first author by e-mail.

constituents of compounds (e.g. “lip”–“stick”). Although there is not complete agreement on the way in which compounds are lexically represented, there is clear evidence supporting the claim that for compounds that are not truly semantically opaque, spreading activation between the compound constituents takes place (cf. Zwitserlood, 1994). Zwitserlood (1994) found that at an SOA of 300 msec, semantic priming effects occur between the compound and both of its constituents not only in transparent but also in partially opaque Dutch compounds. Because the compounds in the present experiments were in the large majority of cases either transparent or partially opaque, we predicted that the same priming mechanisms would account for the priming effects observed for both types of materials.

Published association norms were used, where possible, to verify the unidirectionality of these relations (De Groot & De Bil, 1987; Lauteslager, Schaap, & Schievels, 1986). From these norms 52 unidirectionally associatively related pairs of words were selected. This set was complemented by 80 compounds, yielding a total set of 132 unidirectionally related pairs. This set was divided into a forward and a backward set; each set consisting of 26 associatively related pairs and 40 compounds. Because for the compound pairs no association norms were available, we collected association norms from 30 university students to test whether presentation of the prime words of the backward-related prime–target pairs would yield the target as an associate of the prime. These norms showed that for the backward-related items either none of the subjects (76 out of 80 cases) or in just a few cases just one of the subjects (4 out of 80 cases) produced the target as an associate of the prime. The results of the association test thus confirmed that in case of the backward pairs there was no forward association from the prime to the target.

A pilot RT study was performed to match the word targets of the different relatedness categories on RT. In this pilot study all word and nonword targets were presented in isolation. A separate group of subjects (n = 24) performed a lexical decision task. They had to indicate whether or not the target word was a real word. On the basis of these RTs, 66 critical target words were selected for each of the four relatedness categories. The mean RT to the critical items was 504 msec (SD = 44 msec) for the forward, 513 msec (SD = 39 msec) for the backward, 511 msec (SD = 37 msec) for the bidirectional, and 511 msec (SD = 39 msec) for the unrelated word pairs. Note that the mean RT for the forward-related items was slightly shorter than that for the backward-related items. The forward and backward pairs were comprised of the same word–word combinations. However, the order of the unidirectionally related word pairs was reversed between subjects (e.g. half of the subjects saw the pair “stork”–“baby” [forward pair] and the other half of the subjects saw the pair “baby”–“stork” [backward pair]), so that none of the items was repeated.

All prime words were spoken by a female native speaker of Dutch, who was naive with respect to the purpose of the study. All practice, filler, and test materials were recorded during the same session. The stimuli were digitized with a sampling frequency of 20 kHz, with a band-pass filter range of 50 Hz to 10 kHz. The onset and the offset of the word stimuli was determined with the aid of a waveform editor. All spliced materials sounded natural. The material created in this way was output to DAT tape by means of a 12 bit D/A converter and a DAT taperecorder. On the second channel of the tape, inaudible to the subjects, timing pulses were set concurrently with the onset of the spoken words. These pulses were used to trigger the presentation of the visual target, as well as for the recording of the RTs. The duration of the auditory prime varied between 288 msec and 810 msec, with a mean of 556 msec. The mean durations (and standard deviations) of the four types of prime items were 547 (84) msec for the bidirectional pairs, 551 (86) msec for the unrelated pairs, 551 (86) msec for the forward pairs, and 546 (86) msec for the backward pairs, and 586 (110) msec for the non-critical word prime–nonword target pairs.

To facilitate the averaging of ERP signals, we kept the target–target interval constant by varying the inter-trial interval as a function of prime duration between 3.2 sec (for the longest word) and

3.7 sec (for the shortest word). The target word followed the prime by an inter-stimulus interval of 500 or 0 msec. The target was presented for 200 msec in upper-case letters.

Electrophysiological Recording

EEG was recorded with tin electrodes mounted in an elastic electrode cap (Electrocap International) from three midline sites (Fz, Cz, Pz) and two pairs of lateral electrodes. Symmetrical anterior temporal electrodes were placed halfway between F7 and T3 and F8 and T4 sites, respectively. Symmetrical posterior temporal electrodes were placed lateral (by 30% of the interaural distance) and 12.5% posterior to the vertex. The left mastoid served as reference. Electrode impedance was less than 3 kOhms. As eye movements distort the EEG recording, the electro-oculogram (EOG) was recorded. Vertical EOG was recorded bipolarly by placing an electrode above and below the right eye. The horizontal EOG was recorded bipolarly via a right-to-left canthal montage. EEG and EOG signals were amplified by Nihon Kohden amplifiers (type AB-601G; time constant = 8 sec, low-pass filter = −3dB cutoff at 30 Hz). All physiological signals were digitized on-line with a sampling frequency of 200 Hz using a 12 bit A/D converter. Stimulus presentation and recording of RT data were under control of a Miro GD laboratory computer.

Procedure

Subjects were told that a spoken word would be followed by a visually presented letter string that could be a word or a nonword. They were instructed to attend to both the spoken words and the visual letter strings. Subjects performed a lexical decision task: They had to decide whether or not the letter string was a real Dutch word. If the target was a word, they had to press the right-hand button with the right index finger and if not, the left-hand button with the left index finger. Subjects were asked to respond as fast as possible, but to remain accurate. The interval (ISI) between the offset of the prime and the target was varied between subjects: It was either 500 msec or 0 msec.

The 528 prime–target pairs were divided into 3 blocks of 176 pairs and presented in a fixed order. Each block lasted about 13.8 min in the ISI = 500 condition and about 12.3 min in the ISI = 0 condition. There was a pause of 5 min between blocks. A short practice session with 30 prime–target pairs preceded the experimental session. Subjects were trained to speed up RT (< 1 sec) and to control their eye movements. They were trained not to make eye movements until approximately 1 sec after the button press and to fixate on the centre of the screen in anticipation of the prime–target sequence.

Data Analysis

EEG and EOG records were examined for artifacts and for excessive EOG amplitude during the epoch from 150 msec preceding the prime to 1 sec after the onset of the target. Only trials in which the EOG amplitude did not exceed 100 μV and in which no other artifacts were present were included in the average. ERPs were averaged time-locked to the target, relative to a 100-msec pre-target baseline. Note, that in the ISI = 0 condition, the baseline corresponds to the 100-msec epoch preceding prime offset. The N400 priming effect was measured by computing the mean amplitude in the 330–430-msec epoch following the target. The choice of the window for analysing the N400 priming effect was based upon visual analysis and corresponds to the time interval in which maximal differences between conditions were obtained.

Analyses were restricted to word targets. Analyses of the ERP (N400) data involved ANOVAs with ISI (500, 0) as between-subjects factor, and relatedness type (bidirectional, unrelated, forward, backward) and Electrode (Fz, Cz, Pz, left anterior temporal [AL], right anterior temporal site [AR], left posterior temporal [PL], and right posterior temporal site [PR]) as within-subject factors. Where interactions with the factor Electrode are reported, ANOVAs were performed after a (z-score normalization procedure to equalize the mean amplitudes across experimental conditions, thus allowing effects of distribution to be examined independently of overall differences in amplitude. This normalization procedure is equivalent to the normalization procedure suggested by McCarthy and Wood (1985).

For RT and error data by-subject (F1) and by-item (F2), ANOVAs were carried out with ISI and relatedness type as factors. For ERPs only by-subject analyses were carried out, as is customary for analysing ERP data. The reason for not conducting by-item analyses for the ERPs was a practical one—namely, that our programme for analysing ERP data was not designed to extract the single-trial ERP records per item but was designed to do this per subject. To control for an increase in Type I error in within-subjects tests, the degrees of freedom of F-tests were adjusted using the procedure as described by Greenhouse and Geisser (1959). The adjusted degrees of freedom and p-values are presented in the text. The significance of contrasts was assessed by post hoc Newman–Keuls tests, with a significance level of 0.05 unless explicitly stated otherwise.

Results

Table 1 summarizes the behavioural results—that is, the mean RT and error rates as a function of relatedness type and ISI. Priming effects for RT were computed by subtracting the related lexical decision times (bidirectional, forward, and backward response latencies, respectively) from the unrelated lexical decision times.

RT Results. The by-subject and by-item analyses yielded a main effect of relatedness type, $F1(1, 26) = 84.88$, $p < .0001$, $F2(1, 65) = 37.19$, $p < .0001$. As Table 1 shows, RTs for both ISI conditions were shorter for all three types of related prime–target pairs (bidirectional, forward, and backward pairs) compared to the unrelated pairs. Moreover, RTs were shorter for bidirectionally related than for unidirectionally related pairs. Post hoc Newman–Keuls tests verified this apparent pattern. Significant differences in RTs were obtained for bidirectional, forward ($p < .01$), and backward ($p < .05$) pairs compared

TABLE 1
Mean Reaction Times, Standard Deviations and Mean Error Rates for Both of the ISI Conditions for the Different Types of Prime–Target Pairs as a Function of the Direction of the Relationship in Experiment 1

	ISI = 500 msec				*ISI = 0 msec*			
Meaning Relation	*msec*	*SD*	*Priming-effect*	*Errors*	*msec*	*SD*	*Priming-effect*	*Errors*
Unrelated [baseline]	540	42		5.50	542	47		4.79
Bidirectional	491	39	49	0.86	472	31	70	1.14
Forward	510	39	30	1.71	494	37	48	1.64
Backward	518	30	22	2.00	507	29	35	1.71

SD - standard deviation
Note: Reaction times and standard deviations are given in milliseconds.

to unrelated pairs. Table 1 suggests that RTs were faster for forward- than for backward-related word pairs. However, as there was a similar difference in mean RT between the two conditions when the target words were presented in isolation in the pilot experiment (see Apparatus and Stimuli section), we do not assign any functional significance to this finding.

There was a trend towards an interaction of ISI with relatedness type in the by-subject analysis, $F1(1, 26) = 2.92$, $p < .10$, that was significant in the by-item analysis $F2(1, 65) = 6.27$; $p < .03$. This interaction indicated that priming effects were larger in the ISI = 0 condition than in the ISI = 500 condition. As ISI was a between-subject factor in the experiment, differences in the overall size of the priming effects should be interpreted with some caution. Most importantly, however, the overall priming pattern was very similar at both ISIs: relative to the priming effect for the bidirectional items and after correcting for the differences in baseline RT from the pilot experiment, the size of the priming effect for the forward items was 59% at ISI = 0 and 47% at ISI = 500; for the backward items the size of the priming effect was 53% and 49%, respectively. At ISI = 0 the priming effect for the backward items was 90% of the priming effects for the forward items and at ISI = 500 the priming effects for the backward items was 104% of the priming effects for the forward items.

Error Data. Analysis of the error data yielded a main effect of relatedness type in both by-subject analysis $F1(1, 26) = 31.49$; $p < .0001$ and by-item analysis $F2(1, 65) = 17.81$, $p < .01$. Subjects made more errors to unrelated word pairs (5.1) than to bidirectional (1.0), forward (1.7), or backward (1.9) word pairs. A post hoc test revealed that the difference in error rate between the unrelated and the other three relatedness types was significant at the 1% level. No main effect of ISI or interaction with relatedness type was obtained in the by-subject or by-item analyses. The results of the error data are in agreement with the picture emerging from the RT data.

Compounds vs. Semantically/Associatively Related Words

To check whether the compounds behaved in a similar way to the semantically/ associatively related items, we analysed both forward and backward priming effects separately for the two types of items. Relative to the unrelated targets, priming effects were observed in the forward-related compounds (a priming effect of 25 msec: $F1(1, 26) = 32.96$; $p < .001$; $F2(1, 104) = 10.39$; $p < .003$), the forward-related semantic/ associative targets (a priming effect of 61 msec: $F1(1, 26) = 96.20$; $p < .0001$; $F2(1, 90) = 45.69$; $p < .0001$), as well as in the backward-related compounds (a priming effect of 29 msec: $F1(1, 26) = 48.30$; $p < .001$; $F2(1, 104) = 15.24$; $p < .001$) and the backward-related semantic/ associative targets (a priming effect of 27 msec: $F1(1, 26) = 40.09$; $p < .001$; $F2(1, 90) = 9.73$; $p < .01$). As the targets for these two types of items were not sufficiently matched in terms of length and frequency, differences in the size of the priming effects are difficult to interpret. However, the presence of priming effects for both types of items in forward and backward relatedness conditions supports the claim that these two types of relations are not processed in a fundamentally different way (cf Zwitserlood, 1994). In the analysis of the ERP data, we therefore collapsed both types of items to obtain an adequate signal-to-noise ratio.

Event-Related Potentials. Grand averages for the target words and for each electrode position as a function of ISI (500 and 0 msec) and relatedness type are presented in Figure 1, and the mean amplitudes of the waveforms in the N400 epoch (330–430 msec posttarget) subjected to analysis are given in Table 2. Note that in this and all other figures negativity is plotted upwards. The mean percentage of trials in the subject averages rejected for artifacts or incorrect responses was 12% (SD = 10.4) for the bidirectional condition, 11% (SD = 10.7) for the forward condition, 12% (SD = 7.5) for the backward condition, and 13% (SD = 11.2) for the unrelated condition.

Figure 1 shows that the target word presentation is followed by a small negativity peaking at about 100 msec (N1), maximal in amplitude at fronto-central sites. The N1 was followed by a positive deflection peaking at about 160 msec (P2), with largest amplitudes at the midline sites. After the P2, the ERPs look somewhat different for the two ISI conditions. In the ISI = 0 condition the P2 is followed by a negativity reaching maximal

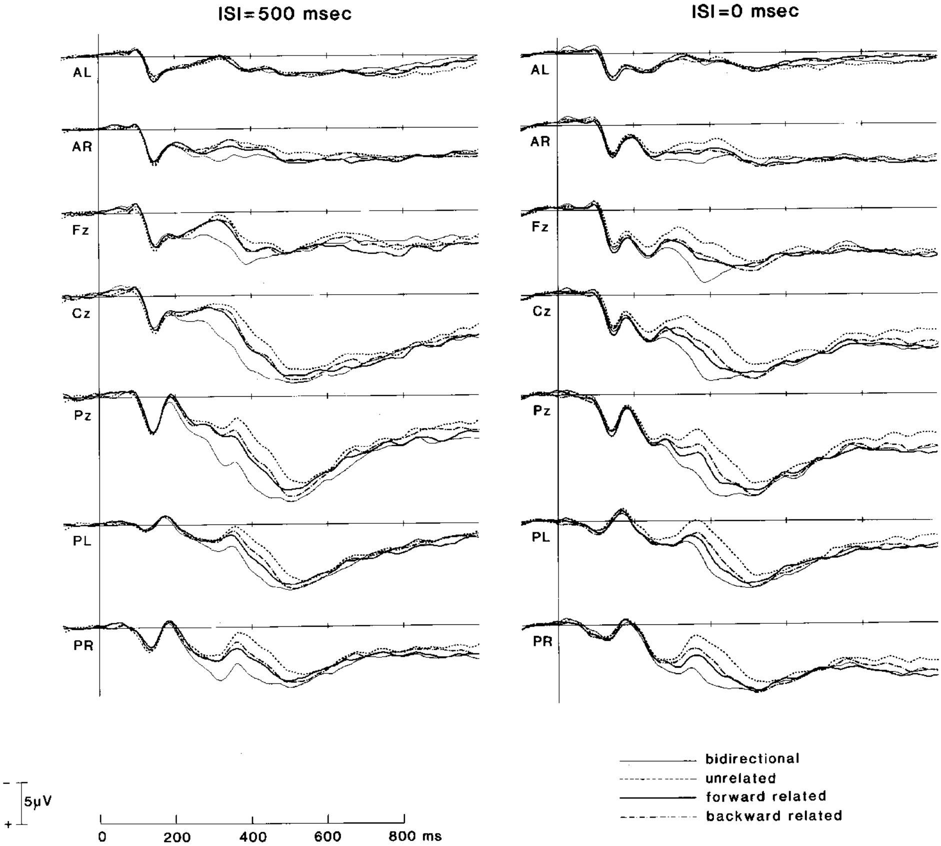

FIG. 1. Experiment 1: Grand ERP averages over 14 subjects for the left and right anterior electrodes (AL, AR), the three midline electrodes (Fz, Cz, Pz), and the left and right posterior electrodes (PL, PR), as a function of ISI (500 and 0 msec). The four different relatedness types of the prime–target pairs (unrelated, bidirectional, forward, backward) are superimposed.

amplitudes at about 190 msec (N2). In the ISI = 0 condition the N2 is visible at all electrodes, whereas in the ISI = 500 condition the N2 is primarily visible at the posterior electrodes. This difference in ERPs might arise from the temporal overlap of the processing of the auditory prime and the visual target that only occurs in the ISI = 0 condition, where the target immediately follows the offset of the prime.

The most distinguishing feature of the waveforms for both ISIs is a broad negative-going wave peaking at about 370 msec post-target. The amplitude of this negative shift was powerfully affected by the semantic relatedness between prime and target, yielding largest amplitudes to unrelated prime–target pairs. Due to the sensitivity of this negativity to semantic relatedness and its centro-parietal distribution, we refer to this component as the N400. The N400 is followed by a parietally distributed positivity (P300) that peaked at about 550 msec. To facilitate a comparison of the N400 and the RT data, the significances of the contrasts for both measures are summarized in Table 3.

The N400. Figure 1 clearly shows that an N400 to the target word was elicited in both ISI conditions. The N400 was strongly affected by the relatedness type, $F(1\ 26) = 36.76$, $p < .0001$, and this effect of relatedness on the N400 did not interact with the ISI factor, $F(1, 26) < 1$.

TABLE 2
Mean N400 Amplitude Within the 330–430-msec Epoch Post-target for Both ISI Conditions for the Different Relatedness Conditions in Experiment 1

ISI		*AL*	*AR*	*Fz*	*Cz*	*Pz*	*PL*	*PR*
500 msec	unrelated	2.14	2.49	3.86	4.45	5.70	1.75	2.18
	bidirectional	1.66	4.98	7.94	11.39	13.99	6.40	8.12
	forward	2.04	3.60	5.35	7.32	9.44	4.25	4.99
	backward	1.56	2.90	4.98	6.69	8.44	3.20	4.21
0 msec	unrelated	1.32	3.58	5.70	6.02	8.29	1.33	3.75
	bidirectional	1.61	6.71	11.67	13.61	15.70	6.69	9.81
	forward	1.23	5.00	8.41	10.24	12.35	4.56	7.16
	backward	1.72	4.90	8.04	8.94	10.77	3.59	5.96

TABLE 3
F-values for the Subject Analyses for Reaction Time and for the N400 in Experiment 1

		df[a]	*RT*	*N400*
Effect	ISI	1, 26	0.19	0.57
	Relatedness type	1, 26	84.88***	36.76***
	ISI × Relatedness Type	1, 26	2.92	0.22
Posthoc comparisons	Bidirectional vs unrelated	1, 26	$p < .01$	$p < .01$
	Forward related vs unrelated	1, 26	$p < .01$	$p < .05$
	Backward related vs unrelated	1, 26	$p < .05$	$p < .05$

[a] Degrees of freedom were adjusted according to Greenhouse and Geisser (1959).
*** $p < .001$

The amplitude of the N400 was largest (more negative-going) in response to unrelated targets and smallest to bidirectional targets; the amplitude of the N400 to the forward- and backward-related prime–target pairs fell in-between. Figure 2 shows that the topographical distribution of the N400 is the same for backward pairs as for forward and bidirectional pairs. This result indicates that there are no qualitative differences in priming effects between the relatedness conditions.

A main effect of electrode, $F(1, 26) = 19.16$, $p < .001$, indicated that the N400 was maximal at centro-parietal sites. A post hoc test showed that the N400 was larger at Cz and Pz than at bilateral anterior and posterior left sites ($p < .05$). A Relatedness Type × Electrode interaction, $F(1, 26) = 10.70$, $p < .01$, indicated a clear relatedness effect for bidirectional as well as unidirectionally related word pairs at all electrodes except the anterior left electrode (see Figure 2). At the anterior left site there was no effect of the relatedness type. Post hoc tests confirmed these observations: significant differences in N400 amplitude between bidirectional and unrelated word pairs were present at all electrodes (AR, Fz, Cz, Pz, PL, PR: $p < .01$) except at AL. Moreover, significant differences between both types of unidirectionally related pairs (forward and backward) and the unrelated baseline condition were found at electrodes Fz, Cz, Pz, PL, and PR ($p < .05$), but not at the anterior left and anterior right electrode.

To examine further the priming patterns for both intervals, separate ANOVAs were performed for each ISI condition. Main effects of relatedness type were obtained for both

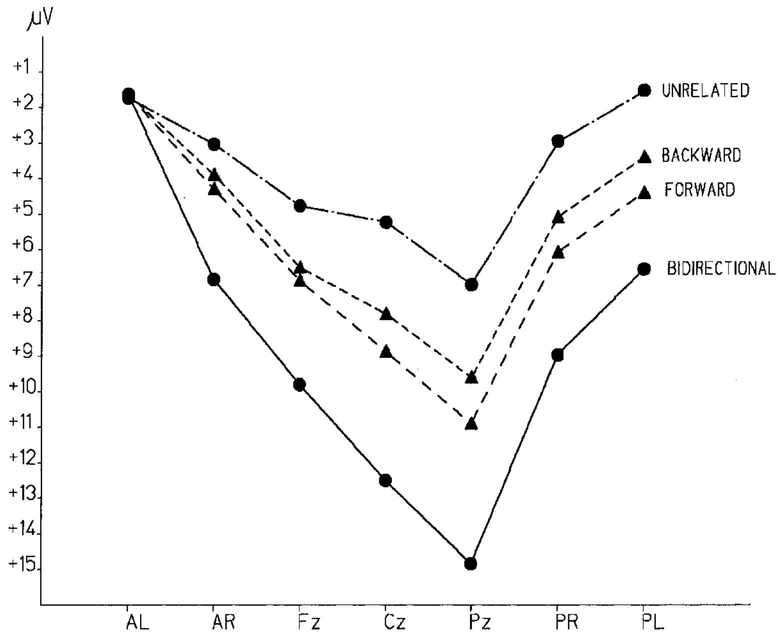

FIG. 2. Experiment 1: Mean N400 amplitude within the 330–430-msec epoch post-target, as a function of the relatedness type of the prime–target pairs (unrelated, bidirectional, forward, backward), separately for the left and right anterior electrodes (AL, AR), the three midline electrodes (Fz, Cz, Pz), and the left and right posterior electrodes (PL, PR), and averaged over ISIs.

intervals—$F(1, 13) = 23.10$, $p < .0001$ for the ISI = 500, and $F(1, 13) = 15.88$, $p < .0001$ for the ISI = 0 condition, respectively. Post hoc tests for both intervals demonstrated that N400 amplitude was larger (i.e. more negative-going) for unrelated than for bidirectional, forward, and backward word pairs ($p < .05$). In addition, N400 amplitude was larger for forward- and backward-related pairs than for the bidirectional pairs $p < .05$). For both ISIs, no difference in N400 amplitude was found between forward- and backward-related word pairs. Additional ANOVAs in which the N400 was measured within a broader latency window (300–500 msec post-target) confirmed all N400 effects reported in this paper.

Discussion

Our RT results replicate the finding that backward associations yield RT priming effects in a lexical decision task (Koriat, 1981; Peterson & Simpson, 1989; Seidenberg et al., 1984; Shelton & Martin, 1992). Moreover, the present results extend the temporal range under which RT backward priming effects are obtained when an auditory prime is paired with a visual target. To date backward priming effects under cross-modal conditions have only been reported for inter-stimulus intervals up to 200 msec (Peterson & Simpson, 1989). The present results show that in the lexical decision task backward priming effects under cross-modal presentation conditions are not restricted to short intervals but are also obtained with an ISI of 500 msec.

The crucial question addressed by the present experiment was whether backward priming effects would occur for the N400. The results on this point are clear. Backward priming effects were obtained for the N400 and for RT. The N400 amplitude was clearly smaller for backward-related than for unrelated word pairs. The fact that the N400 amplitude is modulated by purely backward target-to-prime relationships supports the view that backward priming in the lexical decision task is mainly mediated by semantic matching/ integration (Seidenberg et al., 1984) and not by the mechanism of spreading activation, as suggested by Koriat (1981).

For this claim to stand, it is necessary to rule out the possibility that the N400 priming pattern, in particular the backward priming effect, could be ascribed to other factors. It is well known that a large positive ERP component—named "the P300"—is elicited in any task that requires the subject to make a binary decision. The P300 is most pronounced when an overt immediate response to task-relevant stimuli is required (for reviews, see Donchin, 1981; Donchin & Coles, 1988; Johnson 1988). Because in the present experiment subjects were required to make an overt speeded lexical decision to the target word in addition to the N400, a P300 component was evoked. One potential problem, therefore, concerns component overlap. Because both the N400 and the P300 occur within roughly the same latency range, changes in N400 might have been confounded with differences in P300 latency and/ or amplitude. In particular it has been shown that the latency of the P300 reflects the duration of stimulus evaluation, and often co-varies with RT measures (e.g. Donchin, Ritter, & McCallum, 1978; Magliero, Bashore, Coles, & Donchin, 1984). The critical question is whether the variations in N400 amplitude might have resulted from a shortening in latency and/ or an increase in amplitude of the following P300 component. A close examination of Figure 1 suggests that the latency of the P300 in the present study does correspond with RT. Therefore, it might be argued that the N400 effects are confounded as a result of modulations in P300 latency. Because our line of reasoning demands that the ERP effects can be unambiguously identified as changes in N400 amplitude, a second experiment was carried out to clarify this point.

EXPERIMENT 2

A second experiment was conducted to rule out an explanation of the N400 relatedness effects in terms of an overlapping P300. One way to do this is to demonstrate that the same N400 priming pattern is maintained under conditions in which the influence of P300 is minimized. This was accomplished by changing the response requirements: an implicit lexical decision task was used in which subjects did not overtly respond to the critical word targets but made an overt response to nonwords only. The absence of an overt response to the word targets was expected to attenuate the P300 component and, crucially, to minimize P300 latency differences between conditions, thereby reducing component overlap and simplifying the interpretation of the N400 priming effects.

Method

Subjects

Experiment 2 was conducted at the Nijmegen Institute for Cognition and Information. Fourteen right-handed subjects, 12 female and 2 male (mean age = 24.1, SD = 4.2), participated in this study. Four subjects reported the presence of left-handedness in their immediate family. All subjects had Dutch as their first language and had normal or corrected-to-normal vision. Subjects were paid DFL 10 per hour.

Apparatus and Electrophysiological Recording

The auditory prime was presented via a DAT taperecorder. The control over the timing of events was the same as in Experiment 1, with the exception that the presentation of the visual target and the recording of RTs was under control of a Macintosh computer. The EEG and EOG signals were amplified (time constant = 10 sec, bandpass = 0.02–30 Hz) and digitized on-line at 200 Hz.

Procedure

Experiment 2 was a replication of the ISI = 500 condition of Experiment 1, except that an overt speeded response was required to nonwords only. Subjects were instructed to press a response button with their right hand when the target letter string was a nonword and to refrain from responding when the target was a real word. As the data from Experiment 1 show that there is no difference in the potential overlap of N400 and P300 as a function of ISI, there was no reason in principle to choose one or other ISI. We opted for the long one.

Data Analysis

The analyses performed on the ERPs and the false nonword responses to word targets were identical to those of Experiment 1, but of course there were now no correct responses to words to analyse.

Results

Error Data. Analysis of the nonword responses to the critical word targets disclosed a main effect of relatedness type both in the by-subject analysis, $F1(1, 13) = 8.67$, $p < .001$, and in the by-item analysis, $F2(1, 65) = 14.84$, $p < .001$. Subjects made more errors to unrelated word pairs (3.6) than to bidirectional (0.5), forward (1.5), or backward (2.1) word pairs. Post hoc tests indicated that the difference in error rate between the unrelated and the other three relatedness types was reliable (bidirectional $p < .01$, forward and backward $p < .05$), but that differences among the three were not.

Event-Related Potentials

The grand average waveforms for each electrode site superimposed for the four relatedness conditions are presented in Figure 3, and the mean amplitudes of the waveforms in the N400 epoch (330–430 msec post-target) subjected to analysis are given in Table 4. The mean percentage of trials in the subject averages rejected for artifacts or incorrect responses was 5% ($SD = 4.9$) for the bidirectional condition, 9% ($SD = 7.5$) for the forward condition, 12% ($SD = 7.5$) for the backward condition, and 16% ($SD = 11.2$) for the unrelated condition.

The overall morphology of the waveforms looks similar to Experiment 1, the most salient characteristic being the modulation in N400 amplitude as a function of relatedness type. As in Experiment 1, the N400 was largest at centro-parietal sites, peaked at about 370 msec, with maximal differences between conditions within the 330 to 430 msec period following the target. Although a late positivity that peaked at about 520 msec is evident at centro-parietal sites, it is attenuated compared to the equivalent conditions in Experiment 1. Most notable is the reduction in the differences in P300 latency between the relatedness conditions.

Figure 3 shows that the amplitude of the N400 was clearly affected by relatedness type, $F(1, 13) = 13.57$, $p < .001$. A reduction in N400 amplitude relative to the unrelated baseline condition was found for bidirectional as well as for forward and backward word pairs, with the greatest difference for the bidirectional pairs. As in Experiment 1, no differences in the topography of the N400 priming effects were found between the backward pairs and the bidirectional and forward pairs (see Figures 4 and 5).

A main effect of electrode, $F(1, 13) = 5.21$, $p < .05$, indicated that the N400 amplitude was largest at centro-parietal midline sites. A post hoc test showed that N400 amplitude was reliably larger at Pz than at any other electrode. The ANOVA on the normalized data yielded a Relatedness $\times$ Electrode interaction, $F(1, 13) = 6.20$, $p < .05$, indicating that N400 priming effects were present at the midline and the posterior electrodes but not at the anterior sites (see Figure 4). Post hoc tests confirmed that the difference in N400 amplitude between the unrelated condition and each of the related conditions (bidirectional, forward, and backward) was significant at Fz, Cz, Pz, PL, and PR (p .05), but not at the anterior electrodes (AL, AR).

To test whether the differences in N400 might result from a shortening in latency or an increase in amplitude of the following P300 component, additional analyses were performed on P300 peak latency and amplitude in the 400–600-msec latency region.

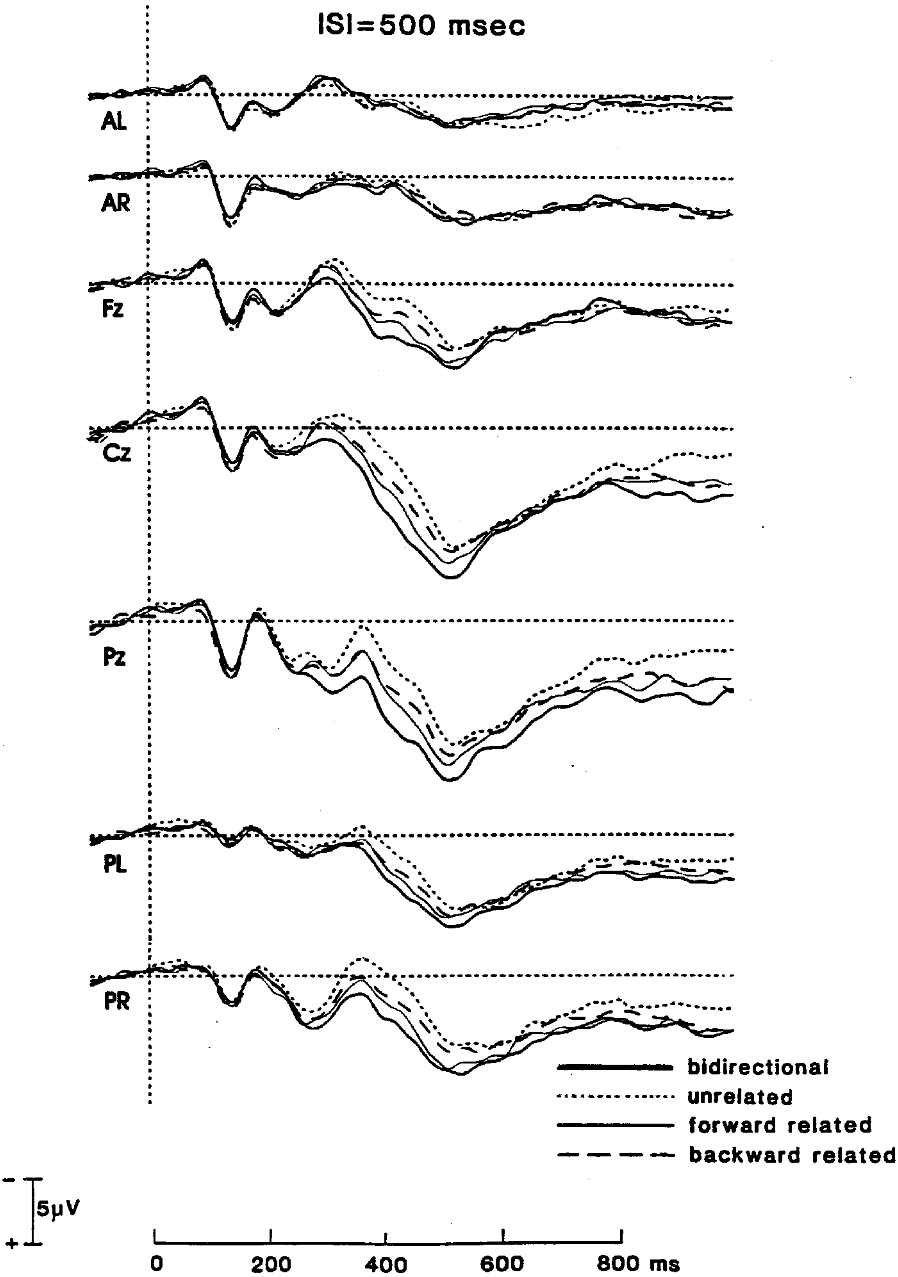

FIG. 3 Experiment 2: Grand ERP averages over 14 subjects for the left and right anterior electrodes (AL, AR), the three midline electrodes (Fz, Cz, Pz), and the left and right posterior electrodes (PL, PR) for the ISI = 500 condition. The four different relatedness types of the prime–target pairs (unrelated, bidirectional, forward, backward) are superimposed.

TABLE 4
Mean N400 Amplitude Within the 330–430-msec Epoch Post-target for the ISI = 500 Condition for the Different Relatedness Conditions in Experiment 2

	ISI = 500 msec						
	AL	*AR*	*Fz*	*Cz*	*Pz*	*PL*	*PR*
unrelated	0.43	0.13	0.12	0.37	2.47	0.10	−0.87
bidirectional	0.09	1.13	3.36	5.23	7.63	2.35	2.99
forward	−0.16	0.54	1.96	3.39	5.14	1.52	1.70
backward	0.63	0.76	1.68	2.62	4.89	1.56	1.07

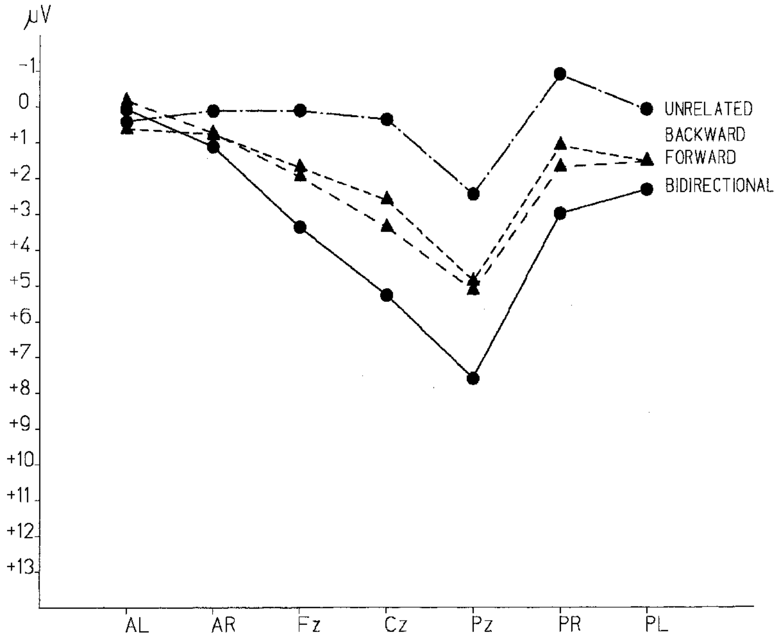

FIG. 4 Experiment 2: Mean N400 amplitude within the 330–430-msec epoch post-target for the ISI = 500 condition, as a function of the relatedness type of the prime–target pairs (unrelated, bidirectional, forward, backward), separately for the left and right anterior electrodes (AL, AR), the three midline electrodes (Fz, Cz, Pz), and the left and right posterior electrodes (PL, PR).

Analysis of P300 peak latency did not yield an effect of relatedness type, $F(1, 13) = 1.99$, $p = .13$ (unrelated = 537 msec, related = 523 msec, forward = 522 msec, backward 528 msec), nor an interaction with electrode, $F(1, 13) = 0.93$, $p = .54$. Analysis of P300 peak amplitude revealed a significant effect of relatedness, $F(1, 13) = 5.25$, $p < .05$. Post hoc tests revealed that this effect was caused by the amplitude in the related condition being significantly greater (11.0 μV) than in the unrelated (9.1 μV) and the backward related (9.5 μV) condition ($p < .05$). Notice that the difference in P300 amplitude between

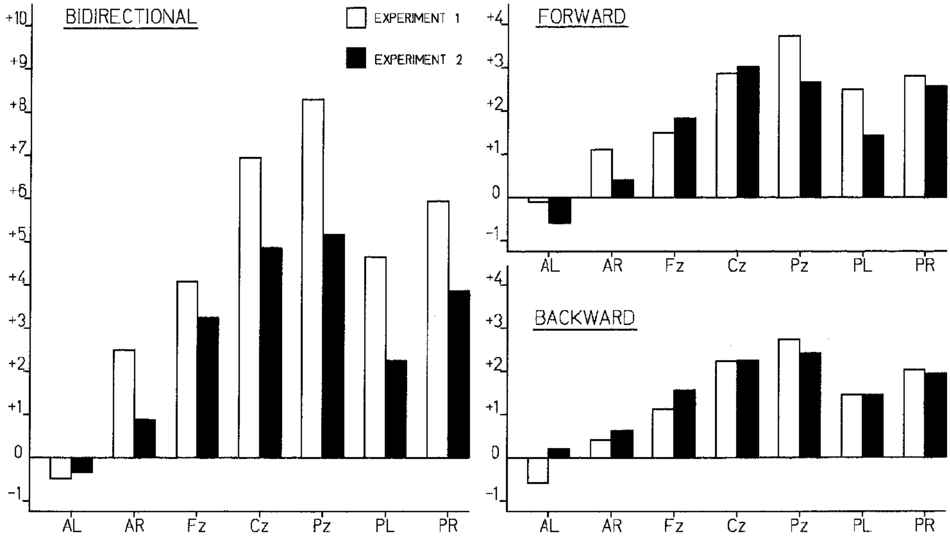

FIG. 5. Experiment 1 and 2: Difference in N400 amplitude between unrelated and bidirectionally related word pairs (left), forward related word pairs (top right), and backward related word pairs (bottom right) for Experiment 1 and 2 for the ISI = 500 condition for the three midline (Fz, Cz, Pz), left and right anterior (AL, AR), and posterior (PL, PR) electrodes.

the unrelated condition and both the backward and the forward condition was not significant. Therefore, variations in P300 amplitude might have contributed to the N400 priming effect to the bidirectionally related pairs but cannot account for the N400 priming effect to the forward- and backward-related pairs.

Discussion

The results of Experiment 2 replicate all of the N400 findings of Experiment 1—that is, significant N400 priming effects were found for bidirectional and for unidirectionally forward- and backward-related prime–target pairs. Despite the change in response requirements, the N400 priming effects in both experiments were very similiar in terms of topography and timing. Importantly, the size of the N400 backward priming effects and the N400 forward priming effects between experiments was about the same (see Figure 5). As in Experiment 1, the magnitude of the N400 effect is nearly identical for foward- and backward-related pairs. The main difference in the N400 results between experiments was that the N400 effect to bidirectional pairs was smaller and showed a later onset in Experiment 2 than in Experiment 1. Thus it appears that the omission of an overt response mostly affected the N400 effect in the bidirectionally related condition but left the N400 priming effects in the unidirectional related conditions unchanged.

The main issue addressed in this experiment was whether the N400 priming effects of Experiment 1 could have been due to differences in P300 latency and/ or amplitude. Although a P300 is clearly present in Experiment 2, the change in task resulted in a strong reduction in the differences in P300 latency between the experimental conditions. In addition, a small decrease in P300 amplitude was observed. The results of the P300 analyses show that the modulations in N400 amplitude as a function of relatedness type, and in particular the N400 forward and backward priming effects and their similarity, cannot be attributed to changes in P300 latency or amplitude.

GENERAL DISCUSSION

In two lexical decision experiments we investigated the phenomenon of backward priming. The three-process model of Neely and Keefe (1989) provides three priming mechanisms—spreading activation, semantic matching/integration, and expectancy-induced priming—that could in principle evoke backward priming effects.

We used the N400 component of the ERP to constrain the interpretation of the effects of backward priming on lexical decision time. Previous work had shown that the N400 priming effect mainly reflects post-lexical semantic integration processes and (under certain circumstances) expectancy-induced priming but, in contrast to RT, does not appear to reflect spreading activation.

The results of the experiments are very clear: robust N400 priming effects for backward-related word pairs were demonstrated at short and long intervals in the lexical decision task. Moreover, the results of Experiment 2 showed that the ERP effects reflect genuine changes in N400 amplitude and cannot be attributed to changes in P300. Taken together, the results clearly support the view that backward priming effects in lexical decision result mainly from a post-lexical integration process, such as semantic matching/integration, not from spreading activation.

Although the presence of backward priming effects for both the N400 and RT suggests that these effects mainly arise from priming mechanisms other than spreading activation, we cannot entirely exclude the possibility that a contribution from spreading activation could be reflected in the RT backward priming effect but not in the N400 backward priming effect. Given the larger priming effects at an ISI of 0 msec (an interaction significant by items), one could argue that spreading activation had its contribution at an ISI of 0 msec, but not at an ISI of 500 msec. However, this interpretation is not completely consistent with the pattern of results. If spreading activation had contributed to priming at 0 ISI but not, or less, at a 500-msec ISI, the priming effect for the forward items should have shown an increase relative to the priming effect for the backward items at the short ISI. The reason is that according to the most frequently used spreading activation model of Collins and Loftus (1975), the prime facilitates the processing of the target before the target has been presented. It is thereby assumed that the activation spreads forward from the prime to the target. As a result, the forward items should have profited from automatic activation spreading but the backward items should not. However, this is not what the results show. The size of the priming effects for forward and backward items is very similar at both ISIs. Further evidence against a possible contribution of spreading activation is that the size of the RT priming effect (after correcting for the differences in RT that were already present when the target words were presented in isolation—see Apparatus and Stimuli section) was the same for forward- and backward-related pairs. If spreading activation indeed did contribute to our backward priming RT results, the priming effect for backward-related pairs should have been smaller than that for the forward-related pairs; moreover, it should have been notably larger in the 0-ISI than in the 500-ISI condition. This is because for the backward related pairs the activation first has to spread back from the target to the prime before it can spread forward to the target to yield the priming effect. Due to this feedback loop, one should predict more activational decay for the backward-related than for the one-step spread of activation for the forward-related prime-target pairs. Thus, although we cannot rule out with certainty that spreading activation might have played a role in evoking RT backward priming effects, the whole pattern of RT results as well as the N400 data renders this possibility very unlikely.

Taken together, the demonstration of backward priming effects for the N400 and RT indicates that these effects arise, at least to a large extent, from those priming mechanisms that have been shown to affect both measures. Because RT and the N400 priming effect are both modulated by semantic matching/ integration and expectancy-induced priming, either or both of these mechanisms must contribute to backward priming. As stated earlier, the likelihood that backward priming stems from expectancy-induced priming is considered to be small, because this idea would imply that subjects generate backward associates. Despite this theoretical argument, there are hitherto no empirical grounds for excluding the possibility that backward priming is due to this mechanism. We tried to disentangle possible backward priming effects of expectancy-induced priming from those of semantic matching/ integration by manipulating the inter-stimulus interval (0- vs 500-msec ISI). As the generation of an expectancy set takes time, expectancy-induced priming cannot account for backward priming effects at the 0-msec ISI. In contrast, semantic matching/ integration is assumed to be less dependent upon temporal constraints and can therefore account for backward priming effects at short and long intervals.

In the present study, no modulation in N400 backward priming effect was observed as a function of ISI. Importantly, for both intervals significant N400 backward priming effects were obtained. As Table 3 shows, for the N400 there was no interaction between ISI and relatedness type, nor was an interaction with interval found in the by-subject RT analysis; the interaction observed in the by-item analysis resulted from the opposite pattern to that predicted if expectancy-induced priming contributed to the backward priming effects: RT priming effects were larger in the short than in the long ISI condition. Consistent with these findings, no changes in the number of errors as a function of ISI were found. Therefore, based on the N400 as well as the RT and the error results, the hypothesis that backward priming stems from expectancy-induced priming can be rejected.

In summary, the sensitivity of the N400 effect to backward priming and the absence of an interaction with ISI strongly suggests that backward priming effects in the lexical decision task mainly reflect post-lexical processes that arise from the mechanism of semantic matching/ integration, as has been proposed by Seidenberg et al. (1984). Consistent with this view, the size of the N400 and the RT priming effect in the present study was the same for pairs that are related in a forward and backward direction. The use of a semantic matching/ integration mechanism can easily account for this result, because the direction of the presentation of the prime and the target most probably does not affect the outcome of the relatedness-checking procedure. Semantic matching can also explain why priming effects were larger for bidirectional than for unidirectionally related word pairs. As only the bidirectional pairs were highly associatively related (i.e. the prime and the target were the first or the second associate of each other), the increase in priming effect very probably reflects the greater ease of the semantic matching/ integration process.

We have discussed our data in the hybrid three-process theory of Neely and Keefe (1989). However, this is not the only framework for explaining semantic priming. Alternative models have been proposed as well (Masson, 1991, 1995; Ratcliff & McKoon, 1988; Sharkey & Sharkey, 1992). The question is whether these alternative models could explain our results with equal success. Ratcliff and McKoon (1988) proposed the compound cue model. This model postulates an integrative mechanism that explains priming in binary decision tasks. It is assumed that subjects join together the prime and the target during encoding and use the familiarity value of this combination when performing the lexical decision task. The claim that subjects use familiarity to make lexical decisions is not new (e.g. Balota & Chumbley, 1984). The basic idea is that words are more familiar than nonwords, and that priming occurs because the familiarity value for associated prime target pairs is higher than for unassociated pairs. A critical assumption of the model is that the process of assessing familiarity occurs very rapidly. In this way the model, in contrast to the semantic matching/ integration mechanism, can also explain automatic priming effects. To make predictions about task performance, the compound cue mechanism of Ratcliff and McKoon (1988) has to be implemented in a model of memory. Several models of memory, such as the search of associative memory (SAM, Gillund & Shiffrin, 1984) and the theory of distributed associative memory (TODAM: Murdock, 1982), predict backward priming in lexical decision because the familiarity value for a compound cue containing two related words will be higher than the familiarity value of a compound cue for unrelated words, regardless of their order of presentation. The influence of a backward target-to-prime relationship is most explicitly taken into account when the compound cue mechanism is implemented in the SAM model of Gillund and Shiffrin (see Ratcliff & McKoon, 1988). In the latter implementation, one of the terms involves backward association, so that the strength of the association from the target to the prime is an important determiner of the magnitude of the priming effect. Therefore, the compound cue model also gives a comprehensive account of the RT and N400 priming results reported in the present experiments.

Another class of models is that of connectionists models (Masson, 1991, 1995; Sharkey & Sharkey, 1992). A basic feature of these models is the use of distributed memory representations instead of local representations (where a single node corresponds to a single word) typically assumed by the more classical spreading activation models. The Masson model assumes that associated words have similar semantic patterns of activation. Presentation of the prime causes partial activation of the semantic patterns of related words, so that the activation pattern of a related target word stabilizes more quickly, thereby producing priming. Could a connectionist model such as that proposed by Masson (1991, 1995) explain the backward priming results? An important characteristic of Masson's distributed memory model is that the overall pattern of priming effects it generates is one of facilitation without inhibition. The model was initially designed to account for lexical processes in the naming task. As stated by Masson (1995, p. 19), ‘‘An important next step in developing the model will be to provide an account of the lexical decision task and the various postaccess processes that appear to be invoked by this task." Therefore, in its present form it cannot deal with backward priming effects that are supposed to reflect mainly post-lexical processes.

To conclude, both the semantic matching/ integration mechanism and the compound cue model can account for our backward priming results. It is important to point out that the way in which the two models operate is in fact quite similar, in the sense that both (a) occur only after lexical access for the target has occurred, (b) combine the prime and the target and exploit their associative/ semantic relatedness to explain semantic priming, and (c) only operate in lexical decision and not in naming. However, an advantage of the semantic matching account of Neely and Keefe (1989) is that it specifies more precisely under which circumstances the semantic matching operation applies (see also Neely, 1991).

What are the theoretical implications of the present results? In the first place, the demonstration of N400 and RT backward priming effects shows that integrative mechanisms such as semantic matching/ integration play an important role in yielding priming effects in the lexical decision task.

The second, more important, theoretical implication of our findings is that they shed a new light on the nature of integrative mechanisms. The presence of backward priming effects with an ISI of 0 msec indicates that subjects very rapidly integrate the lexical information (i.e. the semantic and syntactic information) that is available from the target word with the lexical information that is provided by the prime word. This result is at odds with a commonly held view that integrative mechanisms, such as the semantic matching process of Neely and Keefe (1989), are only operative with long intervals. Instead, this result shows that integrative mechanisms can operate very rapidly indeed and thus may reflect a mandatory process. The view that integrative mechanisms might reflect a fast-acting process was first proposed by De Groot (1984, 1985), based on the finding that an effect of relatedness proportion in lexical decision was already observed with an SOA of only 240 msec. De Groot argued that in order to account for this finding, the operation of a fast-acting post-lexical meaning integration process had to be postulated. With regard to its time course, she stated (1985; p. 287): "Its effects can presumably already be observed with very short SOAs, since this process starts to operate after the target has been recognized and, thus, after the time interval between prime onset and target onset, however long, has already elapsed." The reason why such a post-lexical meaning process is invoked is that the message processor searches for meaningful relationships whenever encountering words, be this in an experimental setting in which single words are presented or in fluent reading outside the laboratory. Our view that the N400 priming effect reflects such a mandatory post-lexical integration process is supported by the finding that reliable N400 priming effects are obtained in reading or listening tasks in which subjects are not required to perform any task other than the natural one, which is to read or listen for comprehension (Brown et al., submitted; Hagoort et al. 1996).

To summarize, the present experiments demonstrate that post-lexical integration processes play an important role in generating priming effects. The results show that backward priming effects in lexical decision reflect, at least in large part, post-lexical integration by a semantic matching/ integration mechanism. The fact that priming effects are obtained independent of the directionality of the semantic relations suggests considerable flexibility in the operation of the integrative mechanism with respect to the order in which words are read or heard.

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