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Event-Related Potentials and Language Processing: A Brief Overview

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Abstract

Since the publication of the first papers on event-related brain potentials (ERP) and language in the 1980s, the field of electrophysiology of language has evolved a great deal. This article is a brief overview of ERPs and language-processing research. It discusses how ERPs are derived, provides the pros and cons of using ERPs for language-processing research, and gives a summary of the major ERP components relevant to research on speech perception (mismatch negativity), word and sentence comprehension (N400, left anterior negativity, P600), and word production (lateralized readiness potential, N200). Additionally, it addresses current controversies concerning the interpretation of these components. Applications of the ERP technique are illustrated with research on first and second language acquisition, bilingualism, and aphasia.

Introduction

Language processing occurs at an extremely fast rate. Words are recognized in well under a half of a second, and the difference between perceiving /d/ vs. /t/ comes down to a difference in voicing onset of a few milliseconds. To fully understand that stages are involved in language processing and their timing, psycholinguists need a method that has very good temporal resolution. Recording event-related brain potentials (ERPs) is such a technique.

This article discusses the pros and cons of using ERPs in language-processing research, introduces some of the key language-related ERPs components and current controversies, and illustrates how ERPs have been used to address issues in first and second language acquisition and aphasia. The overview below is not intended to be an exhaustive review. For more comprehensive overviews of ERP components related to language processing, see Kutas et al. (2006) and Hagoort et al. (1999); for more details on the technical and methodological aspects of the ERP technique, see Luck (2005).

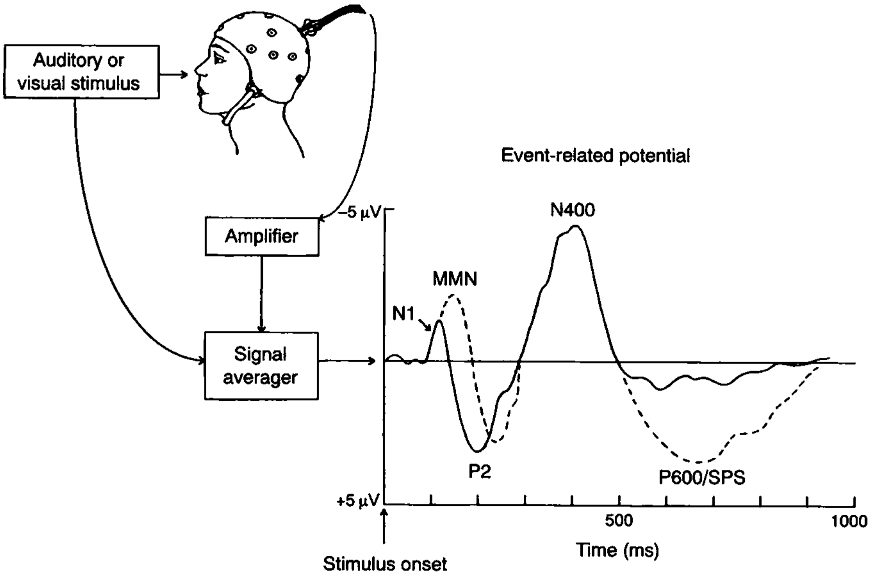

Fig. 1. Illustration of how ERPs are obtained. Electrical activity is recorded from the scalp while the participant is, for example, reading or listening to words. The signal thus obtained is amplified and averaged, time-locked to the stimulus of interest, yielding the ERP. Usually, two or more conditions are compared (represented by the solid and dotted line). The MMN (mismatch negativity) component is largest at frontal electrodes, the N400 typically is the largest at central sites, and the P600 is the largest at parietal locations. See the main text for a discussion of these components. This figure was originally published as Figure 1 in Osterhout et al. (1997). Copyright Elsevier 1997. Reprinted with permission from the publisher and the first author.

What Are ERPs?

OBTAINING ERPS

Electrical brain activity can be recorded by placing electrodes on a person's scalp. ERPs are obtained by presenting the participant with stimuli and/or a certain task, and recording the electrical potentials (brain waves) from the start of the stimulus or other event of interest. These potentials are then averaged over a large number of trials of the same type, yielding the ERP. Averaging will enhance the brain potentials that are related to the onset of the event, and will reduce brain potentials that are not tied to the onset of the event and are assumed to be random. A typical ERP is displayed in Figure 1. Time in milliseconds is depicted on the *x*-axis, with '0' corresponding to the onset time of the relevant stimuli or events; the *y*-axis represents voltage differences in microvolts. In this figure, negative polarity is plotted up. Figure 1 displays the ERP for only one electrode, although typically, ERPs are recorded from 16 to 128 electrodes simultaneously. The ERP is a sequence of positive- and negative-going deflections. Several waveforms, such as the N1, P2, and N400, have been distinguished on the basis of their polarity, timing (latency) of the onset or the peak, their duration, and/or distribution across the scalp, that is, at which positions on the scalp a waveform is smallest or largest. The name of a waveform is often based on such characteristics. For instance, the P2 is the second positive peak occurring in the ERP; an N400 is a negative-going waveform with a peak latency of about 400 ms. Experiments often contain two or more conditions, and investigate how ERP waveforms change as a function of the experimental manipulation. Waveforms, such as the N1, P2, and N400, are commonly called 'components'. Ideally, a component is a reflection of the neural mechanisms involved in certain functional (i.e. cognitive or perceptual) processes. One needs to bear in mind, though, that the relation between the shape of an ERP on the one hand and the underlying functional and neural processes on the other hand is somewhat vague: the latency, peak amplitude, and even scalp distribution may vary even though the underlying functional and neural processes can be claimed to be the same. Moreover, a particular ERP waveform may reflect various functional and neural processes. Measuring peak amplitudes or latencies may therefore not be the optimal way to identify components. To overcome this drawback, alternative mathematical techniques, such as independent component analysis and principal component analysis, have been developed to decompose ERPs into subcomponents (Donchin and Heffley 1978; Makeig et al. 1997). These methods will not be further discussed here. For an overview of these and other analysis techniques, see Luck (2005).

Event-related brain potentials reflect large-scale electrical activity in the brain. More specifically, they reflect wide-spread activity that ultimately affects the synchronous build-up of post-synaptic potentials in large groups of neurons. Such potentials can only be measured at the scalp if the neurons are situated relatively close to the skull, and are parallel to each other (open configuration). Pyramidal cells in the neocortex meet these criteria. Hence, these cells are likely to contribute most to the activity measured at the scalp. The polarity of a waveform (positive or negative) is not very informative concerning the underlying neural mechanisms. The polarity may depend on whether the connections to the neurons are inhibitory or excitatory, but this is also affected by the location and orientation of the neurons, and the location of the electrodes. Recent research suggests that ERPs may not only reflect systematic changes in amplitude in response to each event, but also may be affected by a resetting in time (phase) of the ongoing oscillatory signals in the brain (Makeig et al. 2004; David et al. 2005). For more details on the neural underpinnings of ERPs, see Luck (2005) and Kutas et al. (2006).

ADVANTAGES OF ERPS FOR THE STUDY OF LANGUAGE

Compared to more traditional behavioral methods, such as self-paced reading, ERPs provide several advantages for the study of language processing. First, ERPs allow researchers to collect a continuous stream of data with a temporal accuracy of a few milliseconds: the sampling rate is typically between 250 and 512 Hz (samples per second) in language-related experiments. This matches the fast rate of language comprehension, and hence, is an attractive feature for researchers wanting to track continuous online processing. One should bear in mind, however, that ERPs only give an estimate of the upper boundary of the timing. Processes may have occurred or started before the ERP component is visible, or may not even elicit an ERP component. Timing information can therefore not be interpreted as absolute timing. In addition, in order to measure a small temporal difference between conditions, large numbers of stimuli are needed (see also below).

A second advantage of ERPs is that the responses obtained are multidimensional. This allows the researcher to make qualitative inferences concerning the nature of the processes. This is in contrast to data obtained from, for example, self-paced reading studies. Self-paced reading data can indicate whether the reader experiences difficulty in one condition vs. the other at a particular point during sentence processing. However, it is hard to tell from an increase in response times whether the difficulty is caused by a semantic or a syntactic processing problem. As we will see below, various ERP components have been related to specific types of processes. This enables the researcher to draw inferences concerning the types of processes involved and their relation to one another.

A third, strong advantage of ERPs is that no potentially interfering secondary task is needed in order to obtain data. In typical behavioral studies, participants are asked to press a button to indicate, e.g. the grammaticality of the sentence, or whether a word is a real word of English. Such tasks may lead to particular processing strategies. In addition, such tasks may not be suitable for young children, patients, or beginning second language learners, who may not have the meta-linguistic knowledge required, or for whom such tasks may impose too much burden on attention and working memory.

Fourth, the recording of ERPs is one of the few techniques that allow researchers to investigate online processing of spoken words and sentences. Being able to present materials in spoken rather than written form is also an advantage when dealing with children and patient populations.

LIMITATIONS OF ERPS FOR THE STUDY OF LANGUAGE

The use of ERPs also has some limitations, which may make this technique less attractive to researchers investigating language processing. First, often many trials are needed to obtain ERPs with a good stimulus-to-noise ratio. The number of trials needed depends on the size of the effect and the number of participants, among other things. Typically, however, an experiment investigating sentence processing with 20 participants would require at least 40 stimulus tokens per condition, especially when the effect one is looking for is rather small. Presenting 40 or more items per condition in an experiment may lead to subject fatigue and processing strategies that are not intended by the investigator. In addition, constructing such a large number of stimuli is often time consuming. In well-designed word or sentence processing experiments, a particular item is not repeated within a given participant. Instead, sets of items are created, with each set containing the different versions (conditions) of the item. The items are then counterbalanced over participant lists, such that no participant receives more than one version of a particular item, but all versions of each item are presented in the experiment as a whole. For an ERP experiment with four different conditions, a researcher would therefore need to construct at least 4 times 40, resulting in 160 item sets. Given the tight restrictions on matching critical items for length, frequency of occurrence, and other potentially confounding differences between the conditions of interest, it can take over a year before a good set of materials is constructed.

A large number of items per condition is also needed because many trials will be lost due to artifacts. ERPs are sensitive to muscle tension and eye movements, which may confound the actual brain response. When dealing with healthy adult participants, trials with such artifacts are often rejected from analysis. Participants are instructed to remain still and not to blink during designated times to minimize the number of artifacts. Such instructions, however, may affect the participant's attention to the stimuli and lead to fatigue. When dealing with patients or children, one can often not request they control their blinking and movements. In this case, a mathematical method can be used to calculate and correct the effect of the distortion in the ERPs (for drawbacks, see Luck 2005).

Another potential problem concerns visual presentation in sentence-processing experiments. To avoid eye movements and to control the time-locking of the ERPs to critical stimuli, sentences are presented word-by-word or phrase-by-phrase. The presentation rate is often rather slow (typically, a 500-ms onset-to-onset interval, although some laboratories use faster rates). This slow, piecemeal presentation may impose some load on working memory not found during normal reading, and may confound the processing task intended by the experimenter, especially when testing children or patients. Nevertheless, results from experiments using a slow visual presentation rate are generally comparable to studies using natural speech.

Finally, although ERPs have a good temporal resolution, the pattern of activation recorded at the scalp is not very informative as to where in the brain the activity occurs. This is due to the inverse problem. If one knows the exact localization, orientation, and strength of a neural source, one can calculate what the scalp distribution looks like. The reverse, however, does not hold, because one could come up with an infinite number of different generator configurations to account for the observed pattern at the scalp. In addition, electrical potentials as measured by ERPs are easily distorted by brain fluids and irregularities in the tissue and skull. Researchers interested in source localization therefore prefer magneto-encephalography (MEG). This technique measures the magnetic fields surrounding the electrical currents, which are less prone to distortions. Data from either MEG or ERPs, provided that a dense array of electrodes is used, can be fed into source localization programs to estimate the location of the neural generators. Nevertheless, the ERP and MEG source localizations obtained remain estimates (for more on source estimation techniques and problems, see Luck 2005). Ideally, one can further constrain these solutions with location information obtained from lesions studies and from other brain imaging techniques such as functional magnetic resonance imaging and positron emission tomography that have a better spatial resolution.

In spite of these limitations, ERPs have shown to be extremely valuable for the cognitive neuroscience of language. In the following sections, some ERP components will be discussed that are relevant to research on speech perception, word and sentence comprehension, and word production.

ERPs and Speech Perception

MISMATCH NEGATIVITY

The mismatch negativity, or MMN, is a component reflecting auditory deviance. In order to elicit the MMN, a stream of sounds is presented. One type of sound, the 'standard', is presented frequently within this stream. Another type of sound, the 'deviant' or 'oddball' is presented infrequently. The deviant differs from the standard in pitch, duration, voice onset time (VOT), or other acoustic or phonetic properties. If the difference between deviant and standard is registered, an MMN is elicited. This is a negative deflection around 100–200 ms after onset of the deviance point, with a frontal scalp distribution (Figure 1). Sources of the MMN have been localized near the primary auditory cortex (Heschl's gyrus), with an additional source in the frontal lobe (Phillips et al. 2000; Opitz et al. 2002). The MMN can be elicited even when participants are engaged in a different activity such as watching a movie or reading a book, or when they are asleep or even in a coma. This suggests that the MMN is an index of auditory discrimination at a pre-attentional level (see Näätänen 2001; but cf. Woldorff et al. 1991).

Although the MMN is elicited by all kinds of auditory stimuli, linguistic as well as non-linguistic, it has proven valuable for speech perception research. In a seminal study, Näätänen et al. (1997) presented native speakers of Estonian with different Estonian vowels. The vowel [e] was presented as the frequent standard, with the Estonian vowels [ö], [õ], and [o] as infrequent deviants. Native speakers of Estonian showed an MMN to all three deviants. The same stimuli were played to native speakers of Finnish. Finnish shares the [ö] and [o] with Estonian, but lacks the [õ]. The Finnish speakers showed similar MMNs to the [ö] and [o] deviants as the Estonian speakers. However, their MMN to the Estonian [õ] was smaller, even smaller than expected on the basis of the physical (F_2) difference from the standard. The Finnish speakers did show sensitivity to the degree of physical (frequency) deviance in the case of non-linguistic tone pips. Combined, these data suggest that the pre-attentive auditory perception of speech sounds is affected by language experience.

The MMN has also been used to investigate the formation and perception of phonological categories. For instance, the distinction between a /d/ and a /t/ is the onset of the voicing (voice onset time, VOT): if the VOT is relatively long, that is, at least 50 ms, the sound will be perceived as voiceless /t/; If the VOT is short (30 ms or shorter), the sound will be perceived as voiced /d/. Speakers of English will indicate hearing a difference between stimuli with a VOT of 30 and 50 ms, which spans the category, but not, or not as reliably, between a VOT of 10 and 30 ms, or between a VOT of 50 and 70 ms, which are both within-category differences. By using sounds from either the same or a different category as deviants, one can see to what extent a within- versus across-category difference is perceived pre-attentively. Research shows that the MMN to within-category deviants is smaller than to between-category deviants when VOT is manipulated (Phillips et al. 2000; but see Sharma et al. 1993). Results for other features that determine phonological categories, such as the place of articulation, are more controversial, see Phillips (2001) for a review.

Given their sensitivity to acoustic and phonological contrasts, the MMN and other ERP components not discussed here, such as the N1 and P2 (e.g. Tremblay et al. 2001), are useful tools to track the acquisition of speech-relevant distinctions over the course of language acquisition.

APPLICATION: FIRST LANGUAGE ACQUISITION

Research on speech perception in young children generally uses methods based on head turning, preferential looking or sucking rate. These are rather indirect measures, and the interpretation of such data is sometimes controversial (Cheour et al. 1998). ERPs are an attractive addition to behavioral methods, because no overt response is needed to obtain data. This enables researchers to investigate speech perception in very young children, even neonates (DeHaene-Lambertz and Pena 2001; Cheour et al. 2002). Furthermore, ERPs may be more sensitive than behavioral techniques with respect to timing and individual differences (Rivera-Gaxiola et al. 2005).

An interesting question in language acquisition research is how children's perception of phonological categories changes over the course of their development. Previous behavioral findings showed that infants are initially sensitive to all kinds of phonemic distinctions, even those that are not relevant for the language spoken by their caregivers. By the time they are about 1 year old, children have become less sensitive to foreign distinctions and are more tuned to the categories used in the language spoken around them (Werker and Tees 1984). These findings have been replicated with ERPs. As mentioned above, adult speakers show a smaller MMN to vowel categories that are not part of their native language inventory, such as the Estonian [õ] for Finnish speakers (Näätänen et al. 1997). Seven-month-old Finnish children, however, do show a large MMN to the Estonian [õ]. When they are 11 months old, the MMN to this foreign [õ] declines, and is smaller than the MMN shown in children of the same age for whom Estonian is the native language (Cheour et al. 1998). This shows that infants become less sensitive to phonemic distinctions that are not used in the languages they hear around them, and illustrates how ERPs can be successfully applied to language acquisition research.

ERP Components in Word and Sentence Comprehension

SEMANTIC PROCESSING: N400

In a seminal paper on ERPs and language processing, Kutas and Hillyard (1980) report a negative going component for words that are semantically anomalous given the preceding context (*He spread the warm bread with socks*), which they dubbed the 'N400' component. Since then, hundreds of experiments have replicated these results and investigated the cognitive and neural mechanisms underlying this component.

The N400 is a negative going component, peaking between 300 and 500 ms after onset of the critical stimulus (word or picture) (Figure 1). It typically has a right-central maximum, although the scalp distribution differs depending on the presentation mode (visual, auditory) and nature of the stimuli (pictures, words). The term 'N400' is often used to refer to the component itself (all content words elicit an N400); the term 'N400 effect' is used to refer to the difference in N400 amplitude in two conditions (e.g. semantically anomalous words vs. plausible words; or words preceded by an unrelated versus a related word). Several neural sources have been proposed for the N400, among which are locations in the anterior temporal lobe (Nobre and McCarthy 1995). For more details on the N400 and its likely neural generators, see Van Petten and Luka (2006).

The prevailing view of the N400 is that it reflects difficulty with semantically integrating the stimulus into the preceding context. This context can be a single word, sentence, discourse (Van Berkum et al. 1999), or a non-linguistic context, such as a picture sequence (West and Holcomb 2002) or a movie (Sitnikova et al. 2003). One argument in favor of the view that the N400 reflects semantic integration is that the N400 amplitude to content words (nouns, verbs, and adjectives) decreases with each increasing linear word position in the sentence, that is, with a more strongly established semantic context (Van Petten and Kutas 1990; Van Petten 1993). Second, the N400 amplitude is affected by the expectancy of the word given the preceding context: if a word is highly expected given a preceding context, as in *The bill was due at the end of the month*, the N400 amplitude is smaller than when a word is unexpected, but still plausible, as in *The bill was due at the end of the hour* (Kutas and Hillyard, 1984).

The N400 has also been found to be sensitive to lexical properties, although this is somewhat controversial. Content words that are highly frequent in the language elicit a smaller N400 than lower frequency words (Van Petten and Kutas 1990, 1991; Van Petten 1993). Furthermore, the N400 is smaller for words with more lexical neighbors (i.e. words that are one letter different, Holcomb et al. 2002). Moreover, the N400 is sensitive to subliminal (masked) lexical priming (Deacon et al. 2000; Rolke et al. 2001), which is generally considered an automatic, intra-lexical process (but see Brown and Hagoort 1993).

Finally, the N400 is sensitive to long-term semantic relations (Federmeier and Kutas 1999). For instance, given the context *They wanted to make the hotel look more like a tropical resort. So along the driveway they planted rows of* . . . , the word *palms* is highly expected. An ending such as *tulips*, which is unexpected, elicits a large N400. However, an unexpected ending that is categorically related to the expected ending, such as *pines*, elicits a smaller N400 amplitude than categorically unrelated endings such as *tulips*, even though both endings are equally implausible and unexpected. This suggests that the semantic relations between the expected and the actual word affect the N400, and not only the immediately preceding context itself.

SYNTACTIC PROCESSING

Many ERP studies investigating syntactic processing have used sentences that contain words that are either ungrammatical, or syntactically correct but non-preferred continuations of the preceding sentence fragment (garden paths). An example of a syntactic violation is a subject-verb agreement violation, as in *The spoiled child throw the toys onto the floor* (Hagoort et al. 1993). An example of a garden path is *John painted the table and the chair was already finished* (Kaan and Swaab 2003a). Initially, *the table and the chair* is interpreted as the direct object of *painted*. At *was*, however, this analysis can no longer be pursued. Instead, *the chair* must be reanalyzed as the subject of *was*.

Two kinds of components have been associated with syntactic violations or difficulty: the left anterior negativity and the P600. These components will be discussed below. In addition, a slow negative wave has been observed across multiple words in complex sentences, which has been associated with working memory load during sentence processing (King and Kutas 1995; Münte et al. 1998; Fiebach et al. 2002). See Kutas et al. (2006) for discussion of this latter ERP waveform.

LEFT ANTERIOR NEGATIVITY

A left anterior negativity (LAN) is observed for grammatical violations (Kutas and Hillyard 1983; Friederici et al. 1993; Coulson et al. 1998), and, more rarely, for garden paths (Kaan and Swaab 2003a). As the name suggests, the LAN is a negativity that is most prominent at left-anterior scalp positions. However, its laterality and anterior location are not consistent across studies (Hagoort et al. 2003a), and the labeling is often used rather sloppily. Two types of LAN have been distinguished based on their timing: an early LAN (ELAN), typically occurring 100–200 ms after onset of the critical stimulus, and an LAN, typically peaking between 300 and 500 ms. Potential neural generators of the ELAN have been found in the inferior frontal gyrus and the anterior temporal lobe (Friederici et al. 2000). The ELAN has been associated with automatic processing of phrase structure information. It is typically found for word category or phrase structure violations (e.g. when a passive participle rather than a noun follows a determiner) (Neville et al. 1991; Friederici et al. 1993; Hahne and Friederici 1999). The later, 300–500 ms LAN has been associated with difficulty with morpho-syntactic agreement processes (Friederici 2002). However, this interpretation of the LAN is controversial, as the later LAN has also been found for phrase structure violations (Hagoort et al. 2003a), and an early component for agreement violations (Deutsch and Bentin 2001). One factor that may influence the timing is the position of the affix that bears the agreement or word category information: the earlier the parser encounters the information, the sooner it senses the difficulty and the earlier an LAN is elicited. Another controversy concerns the language specificity of the LAN: whereas some researchers claim that it reflects processes specific to syntax, others claim that it is a more general index of working memory load (Kluender and Kutas 1993a,b; Coulson et al. 1998; Rösler et al. 1998).

P600

The second component elicited for syntactically incorrect or non-preferred continuations of a sentence is a P600 component (Osterhout and Holcomb 1992; Hagoort et al. 1993). This component has been elicited quite consistently across studies and languages, and may or may not be preceded by an (E)LAN. A P600 is a positive deflection with a posterior maximum, peaking between, roughly, 500 and 900 ms (Figure 1).[1] The P600 has been shown to be sensitive to the degree to which a syntactic continuation is expected: words that that are ungrammatical continuations elicit a larger P600 than ones that are grammatical, but non-preferred (Osterhout et al. 1994).

In addition, the P600 can be elicited by continuations that are both grammatical and preferred, but simply harder to process than a control condition. For instance, Kaan et al. (2000) investigated *wh*-questions, such as *Emily wondered who the performer in the concert had* <u>*imitated*</u> *for the audience's amusement.* At the embedded verb, that is, the position at which the *who* is syntactically and thematically integrated into the structure, a larger P600 component was seen relative to a control condition containing *whether* instead of *who* (see also Featherston et al. 2000; Fiebach et al. 2002; Phillips et al. 2005). Behavioral studies have shown that the human parser immediately integrates a *wh*-phrase at the verb, especially when this verb is transitive like the ones used in the study of Kaan et al. (Stowe 1986; Boland et al. 1995). Because the *wh*-phrase is not adjacent to the verb, some difficulty is involved in establishing the syntactic and thematic relation between the fronted *wh*-phrase and the lexical verb (Gibson 1998, 2000). The occurrence of a P600 in this case therefore suggests that the P600 is not restricted to syntactic errors or syntactically unexpected continuations.

The P600 is not limited to syntactic difficulty, however. For instance, recent studies report a P600 in situations in which a new discourse referent needs to be established in the discourse model (Burkhardt 2005, 2006; Kaan et al. 2006). Outside the language domain, a P600 component has been found for violations of musical structure (Besson and Macar 1987; Patel et al. 1998), sequencing (Núñez-Peña and Honrubia-Serrano 2004), and mathematical rules (Lelekov et al. 2000). This suggests that the P600 occurs when a stimulus is difficult to integrate into the structure of the preceding context, regardless of whether 'structure' is syntactic or even linguistic in nature.

Several accounts have been proposed concerning the specific cognitive processes underlying the P600. Assuming a serial model of sentence processing, Friederici (2002) distinguishes several parsing stages: (i) phrase structure building; (ii) agreement checking and other processes that operate upon a phrase structure; and (iii) thematic integration and revision processes. The P600 is a reflection of these later (non-automatic) revision processes. The ELAN and LAN, on the other hand, are associated with earlier first and second phases of syntactic processing, respectively. Hagoort (2003), on the other hand, assumes a parallel unification model of sentence processing. In this model, all sorts of information are available and used at the same time. The P600 then reflects the time it takes to unify the information and to select an analysis among competitive analyses of the input; the LAN reflects the inability to unify because of, for instance, agreement errors.

Other interpretations do not assume a unique syntactic or linguistic function of the P600. Some researchers (Coulson et al. 1998) regard the P600 as an instance of the P3b component found for unexpected stimuli (Donchin and Coles 1988). Kolk and colleagues (Van Herten et al. 2006; Kolk and Chwilla 2007) interpret the P600 as a reflection of a general error monitoring process. This monitoring process is triggered whenever a discrepancy is detected between syntax and semantics, or between expected and actual input, among other things. This interpretation was initially put forward to account for a P600 found to apparent semantic violations, such as at the verb *eat* in *At breakfast the eggs would typically eat* . . . (Kuperberg et al. 2003). Even though the noun phrase *the eggs* is semantically anomalous as the subject of *eat*, a P600 but no N400 has been observed in this and similar conditions (Hoeks et al. 2004; Kim and Osterhout 2005; Van Herten et al. 2005). According to Kolk et al., the conflict between the preferred and actual thematic role of *eggs* triggers error monitoring and reprocessing (hence a P600), and blocks the semantic integration (hence the absence of an N400). For a summary of other accounts of this phenomenon, see Kuperberg (2007). Although both the error monitoring account and the P3b account are attractive in that they can explain the occurrence of a P600 outside the syntactic domain, they have problems accounting for the occurrence of the P600 to expected, grammatical continuations, as in *wh*-questions.

Even though the cognitive mechanisms associated with the N400, LAN, and P600 components are still debated, the distinction between these components has been valuable in investigating language processing in aphasic patients and second language learners, among other populations.

APPLICATION: APHASIA

Brain damage can sometimes lead to language problems (aphasia). It is a matter of debate whether these patients' language deficits are the result of loss of linguistic knowledge or of slowed processing (for an overview, see Kolk 1998). ERPs are a useful tool to investigate these issues: the stimuli can be presented auditorily, and no additional response is needed from the patients, hence avoiding additional processing load. If aphasics' problems are due to slowed processing, these patients will show the same ERP components as healthy control subjects, but more delayed in time.

Swaab and colleagues investigated semantic integration in aphasics that were good or poor comprehenders. Compared to control subjects, the N400 to semantic anomalous sentence endings was delayed in poor comprehending aphasics, but not in good comprehenders (Swaab et al. 1997). This supports the view that the poor comprehending aphasics suffered mainly from a slowed processing rather than a loss of, or an inability to retrieve, the meaning of the words.

Several studies investigating syntactic processing in Broca's aphasia (Wassenaar et al. 2004; Wassenaar and Hagoort 2005) report a reduced P600 to agreement violations, with the amplitude being smaller, or even absent, when syntactic comprehension impairment is more severe (but see Friederici et al. 1998; Hagoort et al. 2003b). A recent study using a sentence-matching paradigm (Wassenaar and Hagoort 2007) also reports an absence of a P600 in Broca's aphasics compared to controls. On the other hand, off-line behavioral performance is above chance in these patients. These results support the view that at least in less severe aphasics, syntactic knowledge is intact, but (fast) online processing is difficult.

APPLICATION: SECOND LANGUAGE ACQUISITION

An important question in second language research is to what extent second language learners employ the same neural and cognitive mechanisms as native speakers. ERPs have been used as arguments in this discussion (for an overview, see Stowe and Sabourin 2005). For instance, Hahne and colleagues tested Russian and Japanese learners of German on syntactic and semantic violations in German sentences (Hahne 2001; Hahne and Friederici 2001). Both groups showed an N400 to semantic violations. Neither group showed an ELAN; the P600 was reduced for the Russian learners of German, and was absent in the less fluent Japanese learners of German (see also Weber-Fox and Neville 1996). The absence of an (E)LAN in language learners has been taken as evidence that non-native speakers do not employ the same automatic mechanisms as native speakers (Hahne 2001). However, recent studies suggest that proficiency plays a large role, and that an (E)LAN can be elicited in non-native speakers provided they are very fluent (Ojima et al. 2005; Rossi et al. 2006; Steinhauer et al. 2006). Taken together, current ERP data suggest that second language learners use the same processing mechanisms as do native speakers. These mechanisms may be delayed in time, or used to a different extent, depending on the learner's proficiency and the aspect of language (syntax or semantics) investigated.

Another line of research in second language processing has focused on early stages of language learning. A few studies have reported a discrepancy between conscious behavioral responses and ERPs in language learners. For instance, McLaughlin et al. (2004) conducted a longitudinal study in which English students of French were tested after 14, 63, and 138 h on average of classroom instruction. Participants saw pairs of letter strings and had to indicate whether the second string was a licit word in French or not. After 14 h of instruction, behavioral performance was still at chance. However, the ERPs elicited significantly different responses to pseudo words versus real words, with pseudo words showing a larger N400 compared to real words. This suggests that at a more automatic stage of processing, the students had learned at least some aspects of French word forms, even though this was obscured in their behavioral responses. A similar discrepancy was obtained regarding syntactic violations in sentences in French (Osterhout et al. 2006), and Spanish (Tokowicz and MacWhinney 2005). In both studies, the acceptability judgments were near chance, but the ERPs in the language learners showed a P600 to the violations. These studies illustrate the strength of ERPs in obtaining data when behavioral methods may not be sensitive enough.

ERP Components in Word Production

LATERALIZED READINESS POTENTIAL

Studying overt language production with ERPs is difficult because mouth movements cause severe artifacts in the ERP signal. For this reason, researchers have used an indirect way to study production, namely by associating a particular (semantic, syntactic, phonological) aspect of the to-be-produced word to a particular manual response. Using the left and right scalp electrodes just above the motor strip, one can record the activity related to hand movement preparation. The potential will be more negative at the electrode in the hemisphere opposite (contralateral) to the response hand, than in the hemisphere at the same side as the response hand (ipsilateral). These recordings are time-locked to the onset of either the stimulus or to the actual response. The potentials at the ipsilateral electrode are then subtracted from the potentials at the contralateral electrode, and averaged over left and right response hand trials, to cancel out activity not related to response hand selection. The resulting ERP is called the lateralized readiness potential, or LRP, which indexes response hand preparation (for more details on how to derive LRPs, see Jansma et al. 2004). Word production paradigms using the LRP typically employ a two-choice go/no-go task. In such a task, the participant sees a series of pictures and is asked to respond with the right hand if, e.g. a living object is depicted, and with the left if an inanimate object is presented, but to respond only if, for example, the name of the object starts with an /s/ (go), and to withhold the response if the name starts with a /b/ (no-go). Using such paradigms, investigators have tested in which order distinct sorts of information are being accessed during word production (Levelt 1999), and the relative timing of these production stages. For instance, using a paradigm as the above and varying the kind of information the go/no-go decision was based on, semantic information was shown to precede phonological information by 120 ms in production (Van Turennout et al. 1997), and gender information to precede phonological information by 40 ms (Van Turennout et al. 1998). This research illustrates the strength and application of the high temporal resolution provided by ERPs.

INHIBITION: N200

Another component used to study language production is the N200 (Schmitt et al. 2000). This component is a negative-going, fronto-central component. The N200 is elicited in go/no-go tasks as described above. It indexes the inhibition of the response in the no-go condition. By varying the nature of the information on which the go/no-go decision is based, and by measuring the timing of the N200, more insight is provided regarding the availability and timing of different sorts of information. Studies using this component have largely replicated results found with LRPs with respect to the relative ordering of semantic, phonological, and syntactic information during word production. The N200 has the advantage over the LRP that it occurs more reliably. For a more detailed overview of ERP studies on language production, see Jansma et al. (2004).

APPLICATION: THE BILINGUAL LEXICON

The N200 has been used to investigate language production in bilinguals. According to some models of the bilingual lexicon (De Bot 2004), bilinguals will activate words in both languages during production. The question is whether language selection will take place before the stage of phonological coding. This was tested in an ERP experiment in which highly fluent, early Spanish-German bilinguals were asked to respond when the German name of a picture started with a vowel, but to withhold their response when it started with a consonant, or vice versa (Rodriguez-Fornells et al. 2005). Some of the items created a conflict, that is, the name would start with, for example, a vowel in German, but with a consonant in Spanish. Compared to monolinguals, bilinguals showed an enhanced N200 for both go and no-go items in the conflict condition, suggesting that they suffered from interference from their other language (Spanish) at the stage of phonological encoding, and that language selection has not been completed at this stage. A similar experiment was carried out in which the go/no-go decision was based on gender information (Rodriguez-Fornells et al. 2006). Items were included that created a conflict, that is, were feminine in one language, but masculine in the other language. Again, compared to monolinguals, the bilinguals showed a larger N200 for both go and no-go items, suggesting that the gender information was accessed in both languages.

Conclusion: The Strengths of ERPs for Language Processing Research

Since the publication of the first seminal paper on ERPs and language (Kutas and Hillyard 1980), the field of electrophysiology of language has evolved a great deal. Various linguistic phenomena have been investigated and a number of ERP components have been discovered that have proven useful in investigating language comprehension and production.

The strengths of the ERP technique lie in its high temporal resolution, and in the fact that no behavioral task is needed to obtain data, which makes this technique very suitable to use in patients, children, and second language learners, who may not have the knowledge, cognitive resources and/or physical abilities to perform behavioral tasks. ERPs also allow researchers to tap into more automatic processes, as opposed to behavioral responses that are based on more conscious decisions from the participant. The most exciting results from ERPs are in these realms.

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Short Biography

Edith Kaan received her PhD in Linguistics at the University of Groningen, Groningen, the Netherlands. She is currently an assistant professor in Linguistics at the University of Florida, specializing in Psycholinguistics and Neurolinguistics. Her main research interests are the cognitive and neural underpinnings of sentence and discourse comprehension, although she has also been conducting work on the perception of lexical tones, and on second language acquisition. She has over 15 years of experience using Event-Related Potentials to study language processing, and has published in *Brain Research*, *Journal of Cognitive Neuroscience*, *Language and Cognitive Processes*, *Trends in Cognitive Science*, and other journals. She is currently supported by a grant from the National Institute on Deafness and Other Communication Disorders.

Notes

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[1] The P600 is not a monolithic component, but has been shown to consist of subcomponents, each with their own characteristic timing and scalp distribution. These subcomponents have been related to functional differences (Hagoort et al. 1999; Friederici et al. 2002; Kaan and Swaab 2003b).

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