Event-Related Brain Potentials in Language Processing: The N's and P's

To Appear in The Bilingual Brain Unwrapped

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Abstract

The cognitive, neural, and linguistic mechanisms underlying the comprehension and production of language are complex. This complexity is compounded when we consider the fact that the majority of people in the world learn, master, and switch between *multiple* languages. One way that we can track the complex dynamics of language use in the brain is through the direct recording of brain electrical activity. In this chapter, we review studies of human event-related brain potentials (ERPs) and their use in elucidating the mechanisms of language processing and multilingualism. First, we introduce ERPs, discussing the neural origins of the signal, methods for ERP recording, and the many benefits of ERP measures for language research. We then discuss major ERP *components*, stable and reliable features of the ERP signal that reflect different aspects of sensory, perceptual, and higher-order cognitive functioning, with a focus on application to language processing in both monolingual and multilingual language contexts.

Introduction

Language is a fundamental human capability and a central part of everyday life. Although, subjectively, language seems to unfold relatively automatically for healthy individuals without comprehension or production impairments, in fact language processing is incredibly complex. This complexity arises from the notable combination of speed and flexibility required by language processing. People use language incredibly productively, flexibly combining their limited store of words and phrases to produce novel utterances that range the gamut from simple descriptions of everyday events to highly abstract concepts. Yet, this multifaceted signal -- often noisy, ambiguous, and/or unpredictable -- is produced and arrives to the comprehender at the rate of multiple words per second, containing information at time-scales from milliseconds to minutes. The complexity is compounded when we consider the fact that the majority of people in the world learn, master, and switch between *multiple* languages.

With the advancement of technology and computing, we can now track the dynamics of real-time neural activity during human language use in order to understand the mechanisms that afford such rapid, complex processing. Because electrical activity is the currency of neuronal signaling and information processing in the brain, direct measurements of brain electrical activity can provide a unique window into understanding the host of complex neurocognitive operations that subserve language comprehension and production. In this chapter, we discuss the use of event-related brain potentials (ERPs) as neural indices of language and their utility for exploring mechanisms of second language learning and bilingual language processing. As such, our goal is to provide a conceptual understanding of the ERP method and to characterize stable aspects of the ERP signal – i.e., ERP "components" – that are most relevant for studying perceptual, attentional, and higher-order cognitive mechanisms involved in language use.

The ERP Method and Neural Origins of the ERP Signal

ERPs are derived from the electroencephalogram (EEG). EEG, which etymologically translates to "electrical brain writing", is a record of transient and oscillatory brain electrical activity. Electrical changes in neurons propagate instantaneously to the scalp, allowing voltage differences between (at least two) non-invasive electrodes to be measured with millisecond-level temporal resolution. ERPs are brain responses that are consistently linked in time with specific sensory, cognitive, or motor events. They are derived from the ongoing EEG by time-aligning segments of the EEG signal relative to an event of interest, such as a stimulus onset or a participant's response, and averaging many of these similar EEG segments to reveal activity that is time and phase locked to the event. George Dawson (1947) first discerned that there were systematic transient potentials evoked in response to sensory events that were "buried" in background EEG activity but could be revealed through averaging. The rationale behind this approach is that activity in the EEG that is systematically related to processing a stimulus will summate and remain in an average. On the other hand, activity that is unrelated (i.e., not time and phase-locked) will average to approximately zero with enough trials (although see Baastiensen et al., 2012, for a discussion of event-related neural oscillations in language that encompasses non-phase aligned activity). The resulting ERP is often depicted as a waveform – voltage over time – at a given electrode location (or can be plotted as a topographic map showing the distribution over the head of voltages in a particular time band). The ERP is often described as being comprised of a set of well-characterized *components* – a stereotyped feature of the ERP with specific eliciting conditions. ERP components are defined empirically by a combination of their polarity, timing, scalp distribution, and sensitivity to task manipulations. With extensive validation, ERP components come to be associated with particular cognitive and neural processes (Fabiani, Gratton, & Federmeier, 2007; Kappenman & Luck, 2012).

The dominant sources of scalp-recorded EEG, and thus ERPs, are believed to be from cortical pyramidal cells arranged in the columnar organization of the neocortex (Nunez & Srinivasan, 2006). Pyramidal cells are the basic input-output cells of the cerebral cortex, are the most numerous excitatory cell type in the mammalian cortex, and play a critical role in advanced cognitive functions (Sprutson, 2008). For neuronal activity to contribute to potentials observed at the scalp, these neurons must be physically arranged so that their potentials summate, which is called an *open field* arrangement. The laminar organization of cortical pyramidal neurons in the cortex follows this open field alignment, with a consistent orientation that is perpendicular to the skull. Closed fields from non-radially oriented dipoles tend to cancel each other and are thus negligible at a distance (e.g., olfactory bulb, oculomotor nucleus). Thus, scalp-recorded potentials are largest for layered cortical tissue with consistent orientations. At the same time, there is some evidence that some closed-field sub-cortical structures may indirectly contribute to the scalp-observed EEG through the mediating role of radial neuroglia, which influence low-frequency coupling across distal neural assemblies throughout the brain (Buzaki et al., 2012).

Neural contributions to ERPs must also be active in relative synchrony to summate and be visible at the scalp. Thus, the largest contributors to ERPs are post-synaptic potentials (PSPs). In the case of chemical synapses, excitatory (depolarizing) or inhibitory (hyperpolarizing) PSPs are caused by changes in the membrane potential of the post-synaptic terminal as a result of neurotransmitters binding in the postsynaptic membrane. With few exceptions, the electrical activity detected at the scalp via EEG is believed to reflect the summed contribution of these PSPs from cortical pyramidal cells across large neural assemblies, rather than contributions from action potentials, which travel down the axon out of phase and are too short-lived to summate (Nunez & Srinivasan, 2006). Indeed, the specificity of EEG/ERPs to post-synaptic neurotransmission is one reason why they are critical tools in neuropharmacological research (e.g., Hegerl & Juckel, 1993).

The Benefits of ERPs for Language Research

ERPs are excellent tools for the study of language comprehension, production, acquisition, and learning in both monolingual and multilingual language contexts. First, as described above, the temporal properties of ERPs are excellent. This is particularly important because language comprehension and production occur rapidly. Average speaking rates range between 150 to 200 words per minute, and the speech signal arrives as a continuous auditory stream with no reliable pauses between spoken words to indicate where one word ends and the next begins. Accordingly, neural activity important for language processing can be quite fast. For example, brainstem-evoked responses to auditory input, called ABRs or auditory brainstem responses, can be reliably measured within the first 10 milliseconds of acoustic stimulation. These potentials reflect neural transmission through the auditory branch of the cranial nerve and lower and upper brainstem. ABRs are a clinically important tool that can be used to diagnose risk for subsequent auditory and language deficits. Similarly, although visual transduction is notably slower than auditory transduction, in reading—arguably one of the most complicated learned human activities—literate young adult comprehenders move from word to word rapidly, often fixating on individual words for only 200-250 milliseconds (Rayner et al., 2009).

Time and timing thus play critical roles in experimental language research. Much of the field of psycholinguistics is predicated upon understanding the order, staging, timing, and degree of interactivity versus seriality of specific cognitive and linguistic processes. Thus, temporal properties of language are important for adjudicating between competing theories, building computational models, and understanding individual differences in production and comprehension. Moreover, this focus on the temporal properties of neural dynamics in language is consistent with a growing interest across cognitive neuroscience more generally in understanding the temporal properties of neural signaling in human cognition, over and above localization-based human brain mapping (Cohen, 2011; Federmeier & Kutas, 2000; Luck & Kappenman, 2012; Jensen & Colgin, 2007). Other non-invasive neuroimaging methods such as fMRI are temporally limited by hemodynamic responses, which unfold on the scale of seconds. This reduction in temporal resolution means that such methods cannot reveal many important aspects of language processing. Moreover, because language is a uniquely human ability, it cannot be directly studied with animal models.

Another advantage of ERPs is that they can be measured during behaviorally mute epochs – after stimulus onset but before a behavioral response -- and even in the absence of overt behavior. This allows for an expanded empirical study of covert cognitive phenomena. In many behavioral language experiments, participants are asked to perform secondary tasks such as pressing response buttons, answering questions, or recalling information at a delay. Such tasks can lead to particular processing strategies that may not be naturalistic. In addition, such tasks may not be suitable for all populations, such as young children, older adults, patients, or second language learners. These groups may either not have the cognitive resources available to meet the task requirements in the context of processing language, or may not have developed enough meta-cognitive awareness or knowledge to complete the tasks (for example, the explicit knowledge of syntax required to make grammaticality judgments). In contrast, ERPs can reveal important dynamics of language processing and learning in most populations, even when behavioral results are inconclusive. Indeed, ERPs can even be recorded to linguistic stimuli in patients in minimally conscious or comatose states. Such work has revealed the attentional resources necessary for certain neurocognitive operations, and has even been used to predict subsequent recovery (Steppacher et al., 2013). More generally, ERPs have a long and extensive history in successfully addressing topics – especially involving early and more behaviorally opaque aspects of processing -- that have been controversial and/or elusive to study in the behavioral literature. For example, ERPs have played a seminal role in delineating aspects of spatial selective attention (Mangun, 1995), visual search (Luck & Hillyard, 1990), attentional bottlenecks (Vogel, Luck, & Shapiro, 1998), and sustained and divided visual attention (Müller, Malinowski, Gruber, & Hillyard, 2003; see Luck, 2012, for a review). These findings, in turn, provide the groundwork for studying the role of attention in other cognitive domains, including language, such as the allocation of visual attention to words in parafoveal vision during reading (e.g., Payne, Stites, & Federmeier, 2016; Stites, Payne, & Federmeier, 2017).

EEG also does not impose additional invasive procedures or auditory noise. As a neuroimaging technique, EEG is minimally invasive; contrast EEG with PET, which requires a dye tracer. EEG can also be conducted in complete silence, whereas in fMRI, for example, echo planar imaging produces a substantial amount of auditory scanner noise. This is particularly important when considering the study of speech audition and comprehension, as auditory noise can induce a substantial load on perceptual processing, particularly in adults with central auditory deficits (Wingfield & Peelle, 2015). Finally, EEG can increasingly be recorded in a wide range of contexts (e.g., schools, retirement homes, from "mobile units") and during a wide variety of tasks (including speaking and exercising; Debener et al., 2009; Aspinall et al., 2014).

Finally, another major advantage of ERPs is that the responses are multi-dimensional, allowing researchers to make qualitative inferences concerning the nature of language processes in the brain. Although component amplitude is perhaps the most often studied dimension of ERP activity, ERP components can vary in their latency, polarity, and the temporal dynamics of their scalp distributions as well. For example, components such as the P300/P3b vary in their latency as a function of stimulus categorization difficulty, and tracking these changes in latency can give an upper bound on the earliest point in time by which the brain categorizes certain stimuli. Moreover, the scalp distribution of ERPs can vary based on both stimulus characteristics and cognitive states. The C1 wave, one of the earliest reliable visual ERP components, varies in polarity based on whether the stimulus appears in the upper or lower visual field, consistent with its source in striate visual cortex (Clark, Fan, & Hillyard, 1995). Higher-order indices of cognitive processing also show similar distributional shifts based on a number of factors. For example, the N400, an index of semantic memory access (discussed in detail below) shows distributional shifts that are dependent upon the nature of the eliciting stimulus (see Kutas & Federmeier, 2000, 2011 for discussion). The multidimensional nature of ERPs thus offers researchers a much richer set of measurements than, for example, the data obtained from behavioral studies of language processing alone. Moreover, ERPs can be combined with typical behavioral paradigms, such as self-paced reading (Payne & Federmeier, 2016), or eye tracking (i.e., “fixation-related potentials”; Dimigen et al., 2011), producing even richer data about ongoing language processing.

This multidimensionality is particularly powerful in the context of well-characterized ERP components. The fact that ERP components bear relationships to particular psychological constructs, such as expectation, subjective probability, and preparation, allows researchers to draw stronger inferences about the type of processes evoked by a specific experimental comparison. There is rich research history describing relationships between EEG/ERPs and behavior and/or mental states dating back at least 75 years, with human language research dating back to the late 1970s. As such, knowing what particular components are affected by a particular linguistic manipulation (or in some special population) can provide a rich understanding of the underlying processes being brought on-line. Thus, ERP measurements provide researchers with a “psychological toolbox” to draw from in order to understand the neurocognitive basis of language. The nature of these well-characterized ERP components is the subject for the remainder of the chapter.

There are, nevertheless, important limitations and caveats to ERP methods that should be carefully considered when planning to employ this approach to language research. First, ERPs in isolation have poor or undefined spatial resolution for localizing the neural generators of a particular effect. Although EEG/ERP source-localization is an active field of study, localizing the neuroanatomical source of an ERP component is still imprecise. This is because voltages are transmitted at a distance via volume conduction, and their cortical sources cannot be directly estimated from the distribution of activity on the scalp (i.e., *the inverse problem*; see e.g., Sarvas, 1987). Not only does activity from single sources spread throughout the head, but signals from multiple sources mix linearly in the volume, causing scalp-recorded ERP responses to reflect sources from potentially many underlying dipoles (Makeig et al., 1996). The skull also acts as a high-frequency spatial filter, so that the EEG appears broader on the scalp than on the surface of the cortex. Certain ERP components with superficial generators (e.g., the C1 wave, which is generated in the upper and lower banks of the calcarine sulcus in striate cortex, area V1) can be source localized with better precision, but ERP components with many and/or deep neural generators (e.g., the N400) are difficult to localize with any confidence. However, several compensatory approaches can be utilized to further understand the cortical generators of ERP components, including co-registration of EEG/ERP methods with other neuroimaging techniques (e.g., MEG, fMRI), data from neuropsychological populations, and invasive cortical electrophysiology in patient populations (e.g., Canolty et al., 2006).

A few other caveats are also worth mentioning. Very slow activity (> ~3s) is more difficult to assess with common ERP methods, as ERP waveforms generally increase in variability (and thus, decrease in reliability) monotonically as a function of time from baseline. Moreover, the signal-to-noise ratio of ERPs is such that in most cases a large number of trials is needed in each critical condition to elicit reliable effects. Therefore, effects that rapidly habituate or can only be measured with a single trial are difficult to capture via ERP methods. That said, single-trial methods are currently in development that improve the power of detecting trial-to-trial variability in ERP components (e.g., Payne et al., 2015; Payne & Federmeier, 2016). Finally, ERPs (but not necessarily other approaches to examining EEG signals) require that the signal of interest be consistently time-locked to a definable event, which makes this approach more difficult to apply to aspects of processing whose timing is likely to be variable or difficult to ascertain (e.g., inference-drawing in language).

Major ERP Components in Language Processing and Bilingualism

The following sections will present a "tour" through the temporal structure of the event-related brain potential, providing (1) an overview of ERP components useful for language research, (2) a description of what these ERP responses reflect in terms of linguistic and neural processes, and (3) a discussion of the role of these components in understanding bilingualism and language learning. Figure 1a presents a prototypical event-related brain potential response to visually presented words. Highlighted are some of the major components that will be discussed in the following sections. The tour begins with early visual/auditory sensory components (< 200 ms), progresses to higher-order "language-related" potentials (300-1000ms), and extends to late sustained potentials (> 1 s); a final section also considers ERP paradigms that have been adapted from other literatures (i.e., motor preparation, cognitive control) to answer important questions in language processing.

<u>Sensory Components</u>

Sensory stimuli with abrupt onsets elicit a modality-specific pattern of early *sensory evoked potentials*. As previously mentioned, in the auditory domain, sensory potentials can be reliably detected as early as within the first 10-50ms after stimulus onset**.** Later sensory components (referred to as "long latency" components with respect to ABRs), such as the auditory N1/N100 and P2 (as well as the visual C1, P1, N1, and P2; see Figure 1a) occur within the first 200-300ms after stimulus onset and reflect several distinct aspects of sensory, perceptual, and attentional processing. Here, we discuss two auditory components that have been important for understanding auditory segmentation and phonological perception in language comprehension: the auditory N1 and the mismatch negativity (MMN).

The Auditory N1 and Speech Segmentation

The auditory N1 (or N100) is part of the auditory evoked response and is observed to all detectable and abrupt auditory changes. It is a negative going potential that peaks in adults between 80 and 120 milliseconds after the onset of a stimulus and is distributed largely over fronto-central regions. It has been linked to cortical generators in the superior temporal gyrus (primary and association auditory cortex), with possible additional contributions from the frontal and motor cortices (Näätänen & Picton, 1987; Godey, Schwartz et al., 2001; Simpson & Prendergast, 2013). In the context of language, the N1 has been used to understand speech segmentation and phonological learning in speech perception.

Speech segmentation is the process by which the brain determines where one meaningful unit (e.g., word or morpheme) ends and the next begins in continuous speech, and it is critical for auditory language processing. Because speech segmentation is fast and largely automatic, it has been difficult to study with behavioral and hemodynamic-based neuroimaging methods. Interest in using the N1 to study speech segmentation was increased by observations that the amplitude of the auditory N1 is larger for initial syllables of English words compared to medial syllables (e.g., Sanders & Neville, 2003a), suggesting that the N1 may index the apprehension of lexical boundaries in continuous speech. However, there are also physical differences between speech sounds that mark boundaries and those that do not. To test if the auditory N1 reflects speech segmentation *per se* and not just acoustic features, Sanders Newport, and Neville (2002) trained participants to learn a novel "mini language" made up of nonsense 3-syllable words such as *babupu* and *bupada*, and tested the effects of learning these novel word boundaries on the auditory N1 in speech perception. Participants were trained over a 20 minute session and were assessed behaviorally in addition to having their ERPs to the nonsense words in continuous speech streams monitored both before and after training.

Participants' accuracy in identifying the novel speech segments increased following training, indicating reliable learning of the lexical boundaries. Importantly, the rate of learning was highly correlated with change in N1 amplitude from before to after training, such that participants who learned to distinguish the nonsense words showed larger N1 word-onset effects while those who failed to learn the lexical boundaries showed no N1 effects. These results strongly suggest that the auditory N1 can serve as a marker for speech segmentation and perceptual learning of speech. These experimental results from short-term learning of an artificial language are consistent with correlational work examining long-term effects of second language learning. Indeed, speech segmentation seems to be especially important for affording fluent understanding of L2 speech by language learners. Sanders and Neville (2003a, 2003b) found that late Japanese learners of English, unlike native English speakers, did not show larger N1s for word-initial than word-medial syllables, or stressed than unstressed syllables, in continuous speech. Thus, it appears that late learners whose native language does not use the same kind of speech segmentation cues as the L2 may have difficulty in learning the appropriate skills to fluidly process continuous L2 speech.

The Mismatch Negativity and Categorical Perception

The mismatch negativity, or MMN, is a negative-going component reflecting the detection of deviance in auditory sensory memory. It is observed in response to changes in auditory stimuli that violate a recently-established standard pattern. A canonical experimental paradigm for eliciting an auditory MMN is as follows: A stream of sounds is presented. One type of sound, the ‘standard’, is presented frequently within this stream. Another type of sound, the ‘deviant’ is presented infrequently. The deviant can differ from the standard in pitch, intensity, duration, or other acoustic or phonetic properties. The MMN is elicited if the auditory system perceives and registers the difference between the deviant and the standard. It can be (and typically is) measured when participants are engaged in a different activity such as watching a movie or reading a book (and can even be observed when participants are asleep or in a coma; Morlet & Fischer, 2014). These results strongly suggest that the MMN reflects auditory discrimination at a pre-attentional level.

The MMN typically has a fronto-central distribution and reaches its peak about 100-250ms following deviant onset, overlapping with the sensory N1 and P2 components. Because of this overlap, it is often measured as a *difference wave* (or a point-by-point subtraction) between waveforms elicited by standard and deviant stimuli. The scalp-recorded auditory MMN has been argued to be comprised of at least two subcomponents, with contributions from two functionally distinct underlying neural processes—a bilateral supratemporal generator (in/near primary auditory cortex), which reflects pre-attentional change detection, and a right-hemisphere dominant anterior process generating the frontal MMN, which has been related to the initiation of a prepotent attentional switch caused by auditory deviance (Näätänen et al., 2007).

The MMN has been used in a number of domains to elucidate the mechanisms underlying central auditory perception and auditory sensory memory in the brain. It has also been used quite successfully as a tool to probe aspects of phonological processing and categorical perception in language processing. For example, the MMN has been used to investigate the perception of phonological categories in speech (Näätänen et al., 2007). One phonological dimension along which many speech sounds are distinguished is voice onset time (VOT: the delay between the release of a stop consonant and the onset of the vibration of the vocal folds for the following vowel). For example, in English, /ba/ and /pa/ differ in VOT. VOT can be titrated continuously, but speakers of English will indicate hearing a categorical difference between stimuli with a VOT of 30 and 50 ms, which spans the category, but not between a VOT of 10 and 30 ms or between a VOT of 50 and 70 ms, which are both within-category differences.

By setting up standards of a particular type and then using sounds from either the same or a different phonological category as deviants, one can use the MMN to assess the extent to which a within- versus across- category difference is perceived pre-attentively. In one early demonstration of this, Phillips et al., (2000) found that the magnetic equivalent of the MMN (measured using magnetoencephaolgraphy; MEG) in the auditory cortex was only elicited by acoustic deviance *between* phonological categories but not *within* those categories, indicating a neural sensitivity to categorical perception. Cross-linguistic studies reveal how this sensitivity is shaped by language experience. For example, Estonian categorically distinguishes a number of vowels along the [ö], [õ], and [o] dimension, and Estonian speakers show a corresponding sensitivity in the MMN to these acoustic differences. However, Finnish lacks some of these distinctions, and Finnish speakers show reduced MMN effects to contrasts that are not categorical in their language (Näätänen et al., 1997). Studies using infants have revealed the development of this experience-based shaping of auditory processing, as MMN patterns show increasing insensitivity to non-native speech sound contrasts between 6 and 12 months (Cheour et al., 1998; Garcia-Sierra et al., 2011; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005).

Because the MMN reveals the influence of experience and development on auditory processing, it has been a powerful tool for studying the impact of language exposure and language learning on preattentive aspects of phonological processing. In particular, studies have used the MMN to try to answer the outstanding question of whether there is a critical period of language learning beyond which native-like fluency becomes unattainable (Long, 1990). In foreign language learning environments, results regarding the critical period hypothesis are mixed. Several studies have shown that immersion can improve MMN responses to sound contrasts in a non-native language (Cheour, Shestakova, Alku, Ceponiene, & Näätänen, 2002; Peltola, Kuntola, Tamminen, Hämäläinen, & Aaltonen, 2005). MMN amplitudes similar to native Finnish speakers were found for highly proficient Hungarian-Finnish bilinguals who had lived in Finland for years but learned Finnish after childhood (Winkler et al., 1999). On the other hand, several other studies have found that immersion and classroom teaching are not sufficient to make learners more sensitive to non-native sound contrasts (Nenonen, Shestakova, Huotilainen, & Näätänen, 2003; Peltola et al., 2003; Peltola, Tuomainen, Koskinen, & Aaltonen, 2007; Rinker, Alku, Brosch, & Kiefer, 2010). Collectively, these findings suggest that even though age of acquisition is an important factor, other variables also play a part in determining the extent to which preattentive auditory processing remains plastic beyond infancy. Moreover, MMN studies have revealed that such plasticity is consequential for language proficiency. For example, Jakoby, Goldstein, and Faust (2011) compared Hebrew learners who did and did not succeed in learning English. They found that unsuccessful learners showed longer MMN latencies for English speech sound contrasts than successful learners, indicating that the unsuccessful group could not discriminate the English sound change as rapidly as the successful group.

“Language” Components

In the following section, we review the two most common components that follow the sensory potentials in time and that have been prominently linked to language processing: the N400 and the P600. Although most commonly studied as “language related” potentials, we will review evidence showing that these components are reflective of domain-general aspects of neurocognitive processing, but at the same time are valuable tools for probing real-time language comprehension in the brain.

The N400 and Semantic Comprehension. In a seminal paper using ERPs to study language processing, Kutas and Hillyard (1980) asked participants to read sentences such as:

a) CONGRUENT: It was his first day at **work**.
b) SEMANTICALLY ANOMALOUS: He spread the warm bread with **socks**.

They found a difference in the response to semantically anomalous (b) versus congruent (a) sentence final words, in the form of a negative deflection, larger for the anomalous words and peaking around 400 ms after the onset of the target word. At the time, this pattern was surprising, as unexpected events (low probability "oddball" stimuli) in other domains had typically been associated with a positivity known as the P300 or P3b. Kutas & Hillyard (1980) also observed this kind of positivity, but associated with physically unexpected words (e.g., words composed of upper case letters when lower case letters are expected), as in (c):

c) PHYSICALLY UNEXPECTED: She put on her high heeled **SHOES.**

Thus, there was an interesting dissociation in the nature of the brain response to physical versus semantic expectancy. The response associated with semantic expectancy became known as the N400 (for an extensive review, see Kutas & Federmeier, 2011). It is a negative going voltage deflection peaking around 400ms with a widespread scalp distribution that varies to some extent with stimulus type (centro-posterior for visual words, central for auditory words, and fronto-central for pictures; see Figure 1b). Figure 1a shows a prototypical N400 response to a semantic-pragmatic violation (condition SV), such as what would be observed to (b). Studies localizing the source of the N400 have implicated a widespread cortical network of semantics including the superior and middle temporal gyrus, the temporal-parietal junction, and the medial temporal lobe, and with less consistency, the dorsolateral prefrontal cortex (see Van Petten & Luka, 2006; Lau et al., 2008 for reviews).

Although the circumstances of its initial discovery linked the N400 with semantic anomalies, it is in fact not a response to semantic improbability. Just as sensory potentials are elicited to all detectable perceptual changes in a given modality, the N400 is part of the normal elicited response to any word or to any other type of stimulus that carries meaning or even has the potential to carry meaning. N400 activity is observed whenever a word or a meaningful stimulus is processed. Indeed, the N400 is observed not only to spoken, written, and signed words, but also to line drawings and pictures, gestures, environmental sounds, and faces (reviewed in Kutas & Federmeier, 2011). It is also elicited to stimuli that share features with such meaningful stimuli, such as pronounceable pseudowords (e.g., DARL) and unfamiliar – but possible – objects. The latency of the N400 remains stable across stimulus type, from the highly familiar (e.g., a high frequency word) to the novel (e.g., a novel pseudoword). The N400 thus has been hypothesized to reflect a temporally constrained process of semantic memory access and retrieval, undertaken for all complex perceptual stimuli even before those stimuli have (or have not) been recognized as meaningful (Kutas & Federmeier, 2000, 2011; Federmeier, 2007; Federmeier & Laszlo, 2009).

For words out of context, the amplitude of the N400 is largely determined by orthographic neighborhood size (Holcomb et al., 2002; Laszlo & Federmeier, 2008), as well as word frequency (Rugg, 1990; Van Petten & Kutas, 1991) and concreteness (Barber, 2013). More frequent and abstract words show reduced (facilitated) N400 activity. Words with more orthographic neighbors (that is, the number of words that are orthographically similar to a target word) show larger (more negative) N400 amplitudes. This seems to suggest that information associated with orthographically similar items is initially activated as an incoming stimulus makes contact with long-term memory, such that words with many orthographic neighbors engender more activation in the semantic memory system (Holcomb et al., 2002; Federmeier & Laszlo, 2009).

Even in word lists, the N400 is sensitive to various aspects of context. For example, words that are repeated within a relatively short time frame show a reduction in the N400 response – an effect that is reduced as the interval between the first and second presentation increases (Rugg, 1985). Similarly, the N400 shows semantic associative priming effects, such that it is reduced when preceded by a semantic prime that has activated the targets features (e.g., *cat* - *dog*). Like repetition, lexical associative priming effects are affected by distance between a target and a prime (Federmeier et al., 2003). It should be noted that N400 effects in response to repetition and semantic priming are not limited to words, but have also been observed to a number of non-linguistic stimuli (Ganis et al., 1996; Grigor et al., 1999). As discussed below, repetition and priming effects have been used to test models of how form and meaning information for multiple languages are represented and accessed during comprehension.

Importantly, the impact of some word-level attributes on the N400 appears to be overridden by higher-order semantic context. Orthographic neighborhood effects remain an important determinant of N400 amplitude, persisting even to the ends of highly constraining contexts (Laszlo & Federmeier, 2009; Payne et al., 2015), whereas both word frequency effects (e.g., Van Petten & Kutas, 1991) and semantic priming (e.g., Ledoux, Camblin, Swaab, & Gordon, 2006) are reduced in the presence of sentence-level constraints. Higher-level context thus acts incrementally and immediately to shape semantic access. Indeed, one of the most reliable determinants of the N400 amplitude to a word is the prior context in which that word appeared. N400 amplitudes are a near linear inverse function of the expectancy of that word, as operationalized by, for example, cloze probability (Taylor, 1953; the proportion of people who give a particular word as the most likely completion of a sentence fragment). Thus, words with high cloze probabilities (e.g., *The little girl refused to go to sleep until he told her a* *story.*) elicit smaller N400s than words with very low cloze probabilities (e.g., *They went to see the famous* *clock.*). In turn, effects at the sentence level are importantly shaped by discourse-level constraints (St. George, Mannes, & Hoffman, 1994; van Berkum, Hagoort, and Brown, 1999; Nieuwland and van Berkum, 2006). Thus, N400 amplitudes also index the incremental build-up of message-level context information. For example, the N400 to open class words is inversely related to word position within a sentence, such that amplitudes to words are systematically reduced over the course of congruent sentences (Payne, Lee, & Federmeier, 2015; Van Petten & Kutas, 1990, 1991). Such effects, nevertheless, only arise in congruent sentences but not in syntactic prose (e.g., "*The infuriated water grabbed the justified dream*.") or randomly shuffled words, suggesting that this effect is driven by the accumulation of message-level semantic context rather than a generalized habituation of the N400.

Such findings show that as meaningful context accumulates, it eases semantic access of subsequent words, reducing the work needed to retrieve those words. An interesting question in the context of multilingualism, therefore, is how this accumulating context in one language impacts the processing of words in the comprehender's other language(s). In other words, what happens when bilingual speakers encounter *code-switches*? To the extent that meaning retrieval is harder for a code-switch, one would predict larger N400 amplitudes to switches compared to non-switches. Indeed, in single-word comprehension, switch trials have been consistently found to elicit larger N400 amplitudes than non-switch trials (Alvarez, Holcomb, & Grainger, 2003; Chauncey, Grainger, & Holcomb, 2008, 2011; Duñabeitia, Dimitropoulou, Uribe-Etxebarria, Laka, & Carreiras, 2010; Palmer, van Hooff, & Havelka, 2010). Findings on how the direction of switch impacts processing (e.g., from the dominant to the non-dominant language or vice versa) have been less consistent. Several studies have observed a switching effect or a larger switching effect only when switching into a second or nondominant language (Hoshino, Midgley, Holcomb, & Grainger, 2010; Midgley, Holcomb, & Grainger, 2009; Phillips, Klein, Mercier, & de Boysson, 2006; Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009), but others found larger N400 effects when switching into the first or dominant language (Alvarez et al., 2003; Chauncey et al., 2008; Palmer et al., 2010). Importantly, not all studies show an asymmetry in switching cost. Using highly proficient Basque-Spanish, Spanish-English, and Russian-English bilinguals, respectively, Duñabeitia et al. (2010), Kotz (2001), and Geyer, Holcomb, Midgley, and Grainger (2011) all found symmetrical switching effects on the N400. Indeed, other studies have found that the semantic connections between dominant and non-dominant languages of a bilingual speaker may be modulated by several factors, including language proficiency and task demands (e.g., lexical decision vs. semantic categorization) (Kotz & Elston-Güttler, 2004; Kroll & Stewart, 1994).

Although much work has looked at single word switching, multiple-word switching is not uncommon in language use (e.g., Berk-Seligson, 1986; Poplack, 1980). Proverbio, Leoni, and Zani (2004) and van Der Meij, Cuetos, Carreiras, and Barber (2011) observed an N400 effect of code switching in sentences (for *non-cognates* -- words that are not shared between two languages) that is similar to that characterized for word lists, with switched words eliciting more negative-going ERPs than non-switched words. In Proverbio et al. (2004), for example, Italian-English interpreters processed mixed-language texts containing language switching in both directions. Single-language and mixed-language sentences were blocked, and the position of switch was consistent across trials. Hence, switching was completely predictable. They found a code-switching cost for Italian-to-English switching (L1-to-L2) but not English-to-Italian switching (L2-to-L1). More importantly, the results demonstrated that the N400 code-switching effect is not due to overall surprisal, as it was present even for completely predictable code switches.

The sensitivity of the N400 to not just individual words but to a language user's accumulated word knowledge has made it a useful tool for examining word learning in children and adults (Borovsky, Kutas, & Ellman, 2010; Mestres-Misse, Rodriguez-Fornells, & Munte, 2007). In the context of second language acquisition, studies have shown that the N400 is a sensitive tool for uncovering early stages of word learning, revealing learning in advance of behavioral indices (McLaughlin, Osterhout, & Kim, 2004), and that it shows a clear developmental progression to native-like effects when assessed longitudinally (Ojima et al., 2011). For mature bilinguals, the N400 response to semantic violations is generally stable across languages, although it may differ in peak latency for native and L2 learners or for dominant and non-dominant languages, suggesting a possible delay in semantic access in the less dominant language (E. M. Moreno & Kutas, 2005; Ojima, Nakata, & Kakigi, 2005; Weber-Fox & Neville, 1996). Some work suggests that the N400 may also be useful for investigating grammatical development in second language acquisition, discussed in more detail below (McLaughlin et al., 2010; Morgan-Short, Sanz, Steinhauer, & Ullman, 2010; Morgan-Short, Steinhauer, Sanz, & Ullman, 2012; Tanner, McLaughlin, Herschensohn, & Osterhout, 2013).

The fact that N400 amplitudes decrease as a function of the expectancy of a word has also made the N400 useful in studying L2 prediction. A series of studies published in the early 2000s showed that in highly constraining sentences, native speakers show larger N400s to articles preceding an expected noun if the article is inconsistent with that noun in phonology (DeLong, Urbach, & Kutas, 2005) or grammatical gender (Wicha, Bates, Moreno, & Kutas, 2003; Wicha, Moreno, & Kutas, 2003). For example, DeLong et al. (2005) found that native English speakers show larger N400s to the indefinite determiner in sentences like (b) below compared to in (a), where *kite* has a high cloze probability:

(a) CONSISTENT: *The day was breezy so the boy went outside to fly* ***a kite****.*
(b) INCONSISTENT: *The day was breezy so the boy went outside to fly* ***an airplane.***

These findings have been taken as evidence that native speakers anticipate information about a noun's phonology and its grammatical gender when a particular noun has a high cloze probability.

An open question in L2 research is to what extent bilinguals and second language learners use contextual cues to anticipate upcoming words in sentences, and what modulates their abilities to do so. Martin et al. (2013) and Ito, Martin and Nieuwland (2016) found that late Spanish-English bilinguals do not show N400 effects at phonologically inconsistent versus consistent articles in moderately constraining sentences (but see DeLong, Urbach, & Kutas, 2017). Bilinguals did, however, exhibit larger N400s to unexpected nouns compared to expected nouns, like native speakers, demonstrating sensitivity to contextual constraint. Using more constraining sentence contexts, Foucart, Martin, Moreno and Costa (2014) found that late French-Spanish and early Spanish-Catalan bilinguals show N400 effects at pre-nominal determiners that are inconsistent in grammatical gender with highly expected nouns. This effect was also found in spoken comprehension for late French-Spanish bilinguals (Foucart, Ruiz-Tada, & Costa, 2016).

Overall, these studies suggest that the ability of L2 speakers to make predictions during language comprehension may depend upon the degree of expectancy (in a graded rather than all-or-none fashion), on what is being predicted (e.g., phonology, semantic features, grammatical gender), and on the similarity of L1 and L2.

The P600 and Syntactic Comprehension. Following the discovery and characterization of the N400 as a neural index of semantic processing, researchers were interested in discovering whether there was also a distinct electrophysiological index of syntactic processing. Such a finding would be consistent with both linguistic and psychological models positing a strict distinction between form/grammar and meaning, as well as neuropsychological evidence suggesting separable neural systems for syntax and semantics. Early ERP experiments were designed to examine the neural response to violations of syntax, while controlling for (as much as possible) the semantic content. For example, Hagoort et al. (1993) presented sentences such as:

(a) The spoiled child **throws** the toys on the floor.
(b) The spoiled child **throw** the toys on the floor. *

Although (a) and (b) are essentially semantically identical, sentence b) is ungrammatical due to the incorrect number marking on the verb "throw". Hagoort et al. (1993) observed that such ungrammatical sentences, compared to grammatical ones, elicited a positive-going effect, following the N400, which came to be called the P600. Subsequently, P600-like responses to syntactic anomaly – and syntactic processing difficulty more generally -- have been observed and replicated across many experiments.

Figure 1a shows a prototypical P600 response to a morphosyntactic violation (MV). The P600 typically onsets around 500ms and lasts for several hundred milliseconds. Unlike the N400, which shows remarkable latency stability, the onset latency of the P600 is variable, in a manner that is correlated with reaction times (Sassenhagen et al., 2014). The P600 does not always show a clear peak, but may manifest instead as a more sustained shift in voltage, with a broad centro-parietal scalp distribution (see Figure 1b). It seems to be somewhat modality-independent, as written and spoken grammatical anomalies have been found to elicit a P600 with a similar timing and distribution. The P600 has been elicited by a range of grammatical violations, including violations of phrase structure (e.g., *"John criticized Max's of proof the theorem*.), verb tense (*The cats won't eating the food Mary leaves them.*), verb agreement (*The senators hopes to succeed*.) and gender agreement (e.g., *The woman congratulated himself on the promotion*). Such effects can even be observed to grammatical anomalies in sentences without any meaningful message-level semantics (e.g., *The boiled watering-can smokes/*smoke the telephone*; Hagoort & Brown, 1994). The P600 is not just elicited by anomalies, but also by increases in syntactic complexity and ambiguity within completely grammatical sentences. For example, late positive potentials have been observed in syntactically well-formed sentences with a non-preferred structure (i.e., garden path sentences), or in sentences requiring long-distance syntactic attachments (e.g., Kaan & Swaab, 2003). There have been several theoretical accounts of the cognitive and neural processes underlying the P600 effect. A number of these are specifically linked to aspects of syntactic analysis, such as reprocessing and syntactic reanalysis (Osterhout et al., 1994; Friederici et al., 2002), syntactic integration (Brouwer et al., 2012; Kaan et al., 2000; Fiebach et al., 2002), and “unification” of higher-order syntactic frames (Hagoort et al., 2005).

This picture of the functional specificity of the P600 to syntax has been challenged by a number of findings. First, several experiments have found evidence that P600-like effects can be triggered by non-syntactic violations. Semantic verb–argument violations, in the absence of any violations or ambiguities of syntax, evoke a so-called “semantic P600 effect” (Kuperberg, 2007). For example, Kuperberg and colleagues (2003) showed that whereas pragmatic violations such as (b) elicit an N400 effect relative to congruent sentences like (a), thematic role violations, such as those in (c) elicit a P600-like effect instead.

(a) CONGRUENT: Every morning at breakfast the boys would eat…

(b) PRAGMATIC VIOLATION: Every morning at breakfast the boys would plant…

(c) THEMATIC ROLE VIOLATION: Every morning at breakfast the eggs would eat …

Indeed, a number of studies have reported bi-phasic ERP responses to pure semantic anomalies, such that a large N400 effect is followed by a posterior positivity that strongly resembles the P600 in its temporal and spatial properties (see Van Petten & Luka, 2012 for a review). Not only can non-syntactic manipulations induce P600-like activity, but also ungrammaticality and increases in syntactic difficulty do not always elicit the P600. Increases in syntactic complexity that result in increases in working memory load are associated with LAN effects (described below), which are not always accompanied by a P600. Native speakers also vary in their ERP responses to morphosyntactic violations. Rather than always exhibiting canonical P600s to ungrammaticalities, some individuals actually show N400s and no P600s (Osterhout, 1997; Tanner & Van Hell, 2014).

Some researchers have suggested that the P600 is not only not specific to syntax, but also not specific to language – that, instead, it is part of a more domain-general neurocognitive response. For instance, Coulson and colleagues (1998) argued that the P600 may be part of the P300 family of responses, citing the functional similarity between P3b and P6 effects. For example, like the P3b, P600 effects can be modulated by task relevancy and attention (e.g., Batterink & Neville, 2013; Hahne & Friederici, 2002), and the P600 also shows strong RT alignment (Sassenhagen et al., 2014), a defining feature of P3b activity that is not present for other language-related components such as the N400 (Payne & Federmeier, 2016). This claim has not gone unchallenged, however, as researchers have shown that neuropsychological populations with basal ganglia damage show a dissociation between P600 responses (which are notably absent) and P3b oddball effects (which are present) (Frisch et al., 2003). Thus, there is continued interest in determining the neural and functional nature of the P600 response, as an important precursor to developing neurobiological models of language (cf. Small, 2008; Niewenhuis et al., 2005).

However, despite disagreement on the functional nature and underlying mechanisms of the P600, it serves as a useful measure of aspects of syntactic processing. For example, given that the P600 may index a controlled process that guides the reanalysis of an ungrammatical sentence (Hahne & Friederici, 1999), it has been widely used to investigate whether native speakers and second language learners engage similar syntactic processing strategies. A number of factors affect how easily certain structures can be learned and who is more successful at learning to process these in a native-like manner. One important factor is the similarity of the L1 and L2. Learners tend to show P600 effects like native speakers when encountering a structure that is ungrammatical in the L2. But if a linguistic structure is unique to the L2 (e.g., grammatical gender for L1-English learners), or both languages have the same grammatical feature but the systems work in different ways (e.g., the Germanic and Romance gender systems), learners may show reduced or no P600 responses to the violations (Dowens, Vergara, Barber, & Carreiras, 2010; Foucart & Frenck-Mestre, 2011, 2012; Osterhout, McLaughlin, Pitkänen, Frenck-Mestre, & Molinaro, 2006; Sabourin & Stowe, 2008). On the other hand, results of several studies indicate that L1-L2 similarity may not constrain the extent to which L2 learners can show native-like processing of certain grammatical structures. For example, Alemán Bañón, Fiorentino, and Gabriele (2014) observed native-like P600 patterns in English learners of Spanish for number and gender agreement violations. Dowens, Guo, Guo, Barber, and Carreiras (2011) also found that Chinese learners of Spanish had P600 effects for number and gender agreement violations, both of which do not exist in Chinese.

Factors related to the learners themselves, including age of acquisition and L2 proficiency, also modulate the P600 response to syntactic anomaly. Younger L2 learners are more likely to acquire native-like P600 responses to grammatical violations in their L2. For example, Weber-Fox and Neville (1996) observed native-like P600 patterns for Chinese learners who started learning English before 11 years of age, while learners whose acquisition began after age 11 showed delayed or absent P600 effects. Meulman, Stowe, Sprenger, Bresser, and Schmid (2014) and Meulman, Wieling, Sprenger, Stowe, and Schmid (2015) also found reduced P600s for late Romance language learners of Dutch and no P600s for late Slavic learners of German. However, it should be noted that an earlier age of acquisition may also lead to higher proficiency and prolonged exposure to the L2, and it is never easy to tease apart these intertwined factors. Rossi, Gugler, Friederici, and Hahne (2006) found that proficiency may play a larger role than age of acquisition in modulating the P600 effect to L2 syntactic violations. High proficiency late learners of German and Italian showed similar P600s responses to native speakers, whereas low proficiency learners showed delayed P600 effects.

The presence and size of P600 effects to ungrammaticalities has also been correlated with L2 proficiency. Low proficiency L2 learners may show N400 effects to morphosyntactic violations with small or absent P600 effects, whereas higher proficiency learners tend to predominantly show P600 effects (McLaughlin et al., 2010; Morgan-Short, Sanz, Steinhauer, & Ullman, 2010; Morgan-Short, Steinhauer, Sanz, & Ullman, 2012; Tanner, McLaughlin, Herschensohn, & Osterhout, 2013). In addition, as proficiency increases, the size of P600 effects has also been found to increase (White, Genesee, & Steinhauer, 2012). These apparent proficiency effects may, however, at least partly reflect specific grammatical knowledge rather than global language proficiency, per se. White et al. (2012) found larger P600 effects for trials that were correctly responded to in a grammaticality judgment compared to when trials were analyzed irrespective of accuracy.

Similarly, Lemhöfer, Schriefers, and Indefrey (2014) reported a P600 effect to gender agreement violations in German learners of Dutch when trials were sorted by the subjective gender assignments of each participant, but crucially they found no P600 effects when trials were not sorted in this manner.

Overall, the P600 could be a useful tool to investigate the extent to which a learner has achieved native-like neurological responses to L2 syntactic anomaly, and to assess the various factors that modulate higher-level syntactic processes in language comprehension. Given, however, that monolingual native speakers do not invariably exhibit P600s to morphosyntactic violations, caution should be used when interpreting the absence of P600s in L2 learners, as this does not straightforwardly imply a lack of native-like processing. Indeed this latter fact raises questions about what native-like processing should look like as measured using ERPs. Minimally, it suggests that qualitative similarities or differences in averaged L1 and L2 ERP responses may underdetermine any conclusions about the extent to which L1 and L2 populations use the same mechanisms when processing linguistic constructs. Though this makes the task of comparing L1 and L2 processing more difficult, it also opens up a rich new avenue of research aimed at uncovering what factors modulate the variability in both L1 and L2 neural responses during language comprehension (e.g., Tanner et al., 2016; Tanner, Bulkes, Shantz, Armstrong, & Reyes, 2016; Tanner, Inoue, & Osterhout, 2014).

Late Anterior Potentials and Language Comprehension

In addition to the P600, other late (post-N400) potentials have been implicated in language comprehension. These potentials have not received much attention in the bilingualism and second-language learning literature to date, but their sensitivity to higher-order comprehension processes -- such as semantic re-analysis, frame-shifting, and referential processing -- positions them to serve as useful measures for understanding bilingual language comprehension processes.

Frontal Positivity. A late, anteriorly-distributed positivity following the N400 is consistently observed when comprehenders encounter semantically congruent but unexpected words in strongly lexically constraining contexts (Federmeier et al., 2007, 2010; Thornhill & Van Petten, 2012; Payne & Federmeier, under review, Van Petten & Luka, 2012 for a review). For example, Federmeier, Wlotko, Ocha-Dewald, and Kutas (2007) jointly examined lexical expectancy and sentential constraint effects on the ERP response to sentence-final words, in sentences such as (*a*)-(*d*):

(*a*) **Strongly Constraining, Expected:** Sam could not believe her story was *true.*

(*b*) **Strongly Constraining, Unexpected:** Sam could not believe her story was *published.*

(*c*) **Weakly Constraining, Expected:** I was impressed by how much she *knew.*

(*d*) **Weakly Constraining, Unexpected:** I was impressed by how much she *published.*

Critically, the lexically identical unexpected items (*b*) and (*d*) were matched for cloze probability (~ 0%) across the two levels of contextual constraint, so that any additional processing in (*b*) that is not present in (*d*) is likely driven by the cost of encountering an unlikely but plausible word in a context that is strongly predictive of a different word. Federmeier et al. (2007) found that N400 responses were graded in magnitude in a manner consistent with each condition's average cloze probability (a < c < b=d). Importantly, conditions *b* and *d* did not differ in N400 activity. However, only strongly constraining but unexpected items (*b*) were shown to elicit a late anterior positivity following the N400 (see Figure 2a). Federmeier and colleagues (2007) argued that this component likely reflects the increased resource demands needed to override or suppress the anticipated semantic representation, and perhaps to revise the message-level representation following prediction violations. A number of other studies have reported a similar late anterior positivity (DeLong et al., 2007, 2012; Thornhill & Van Petten, 2012; Luka & Van Petten 2012; Federmeier, Kutas, & Schul, 2010; Payne & Federmeier, 2016), and have shown that this anterior potential is dissociable from the P600 (DeLong et al., 2014; Van Petten & Luka, 2012, Kuperberg, 2013). These findings have been taken as evidence that readers encounter costs when strongly-held predictions are violated. Such prediction costs have been inconsistently observed in the behavioral literature. As such, the anterior positivity is considered an important electrophysiological index of predictive processing in language comprehension.

Frontal Negativity. Although language comprehension is highly incremental in nature (Van Petten et al., 1993; Payne et al., 2015), comprehension routinely involves taking into account relevant information that becomes available after a message-level representation has already been established. In these cases, the initial meaning representation may need to be revised or reshaped. This is common in figurative comprehension, such as the comprehension of metaphors or jokes, which often entail a shifting of the contextual frame. Take, for example, sentences such as:

By the time Mary had her fourteenth child, she had run out of names to call her *husband*.

Coulson and colleagues (Coulson & Kutas, 2001; Coulson & Lovett, 2004; Coulson & Williams, 2005) have examined ERPs during the comprehension of such figurative language and have observed a slow anterior negative potential that they argue is associated with such higher-order frame-shifting processes. Similar frame-shifting mechanisms may be routinely utilized in literal comprehension as well. Indeed, moderately constraining but plausible sentences also seem to exhibit a late frontal negativity (e.g. Kutas, 1993; Federmeier & Kutas, 2005; Davenport & Coulson, 2011; see Figure 2b). Wlotko and Federmeier (2012) systematically investigated the role of this anterior negativity in literal comprehension. Sentences with moderate but not strong contextual constraint appear to elicit a strong anterior negativity to the critical sentence-final word. Importantly, they showed that the negativity was largest among items with a small number of strong alternate endings, suggesting that items that contain a robust alternative interpretation elicit the processes involved in the reconsideration of that interpretation.

Late negativities have also been observed during discourse comprehension when referential processing is engaged (see Van Berkum et al., 2007 for a review). Van Berkum and colleagues have examined the effects of discourse-level referential factors by manipulating the number of referents for a singular definite noun phrase (e.g., *the girl*), such that there are either multiple possible discourse referents or a single unambiguous referent (Van Berkum et al., 1999). They observed a late sustained negative shift when the critical noun phrase refers to multiple possible referents, an effect they have termed the *Nref.*

The LAN and Working Memory

In addition to effects of code switching on the N400, some studies have found effects on other language-related components that may index working memory usage. For example, two studies have reported a code-switching effect that was larger over left frontal sites. Effects with this timing and distribution have been seen in language studies more generally and are commonly referred to as “left anterior negativity” or LAN effects. The LAN has been associated with difficulty in processing morphosyntactic agreement (Gunter, Friederici, & Schriefers, 2000) and, in some cases, for phrase structure violations (e.g., Hagoort et al., 2003). Some have linked this effect to longer-lasting frontal negativities associated with working memory loads (e.g., Kluender & Kutas, 1993), such as in filler-gap clauses, object-relative constructions, or other long-distance dependencies (Felser et al., 2003; King & Kutas, 1995). Although the exact functional role of these slow waves in language processing is debatable, such effects resemble those found during working memory maintenance (Vogel, & Machizawa, 2004), and are correlated with individual differences in working memory span (Munte et al., 1998). Moreno, Federmeier, and Kutas (2002) and Ng, Gonzalez, and Wicha (2014) investigated the comprehension of Spanish words embedded in English sentences. In Ng et al., the English texts were stories containing multiple switches. Both studies found a LAN-like switching effect. The authors argued that that language switching in context requires working memory resources, perhaps recruited for morphosyntactic and semantic integration of the switch between adjacent elements in the text. In addition, Moreno et al. (2002) observed a posterior late positivity to code switches, which may be related to the P600 component.

Components Sensitive to Cognitive Control and Error Processing

The functional significance of the “language” components reviewed above highlights an important question in the field about the extent to which language arises from specialized processes or, instead, co-opts more domain general cognitive and neural processing mechanisms. However, regardless of one’s exact position on this debate, it is clear that domain general factors are at work in some aspects of language processing, and, as such, domain general responses related to cognitive control, error processing, and even motor preparation are useful tools for language studies. Here, we will discuss the anterior N2, the error-related negativity, and the lateralized readiness potential as used in the go/no-go task.

The Anterior N2. The anterior N2 is a well-studied electrophysiological component that has been strongly linked to domain-general and immediate cognitive control of action (e.g., cancelling a prepared response, resolving conflicting response tendencies, Gerinhg & Willoby, 2002, Nieuwenhuis et al., 2003). In an exhaustive review of N2 effects, Folstein and Van Petten (2008) describe how the amplitude of the anterior N2 has been found to vary as a function of conflict resolution and the need for cognitive control across a large number of paradigms (the Stroop task, go/no-go, the Eriksen flanker task). Importantly, the anterior N2 is found most frequently in tasks that specifically place high demands on strategic cognitive control and conflict resolution in response selection (e.g., selection under high response competition demands or response inhibition, Gehring et al., 1992; Bruin & Weijers, 2002). Studies attempting to localize the anterior N2 have found its sources to be consistent with generators in medial-frontal cortex, most reliably in the anterior cingulate cortex (ACC), a cortical substrate that is often implicated in attentional control functions such as error monitoring and response inhibition (Bekker et al., 2005; Nieuwenhuis et al., 2003). The anterior N2 has also been observed during conflict resolution processes in sentence processing. For example, the anterior N2 has also been shown to trigger inflated reading times in response to strong semantic prediction violations (Payne & Federmeier, 2016; see Figure 2c).

Inhibitory control is especially relevant to bilingualism. Given that the prevalent assumption is that two languages of a bilingual are always active even if one language is irrelevant to the task, bilingual individuals may juggle two languages at any time (Kroll, Bobb, & Wodniecka, 2006). The ability to rapidly suppress one language and switch to another manifests most obviously in code-switching. Of particular interest, then, is how inhibition is exercised in code-switching, especially in relation to the first-learned (L1) and second-learned (L2) language. Much of the ERP literature on code-switch production relates back to a seminal behavioral study by Meuter and Allport (1999) in which trials that required bilinguals to switch from one language to the other led to slower naming latencies than non-switch trials. Critically, this switching cost was asymmetrical: switching from L1 to L2 was faster than from L2 to L1. This finding was argued to support the Task Set Inertia hypothesis (Allport, Styles, & Hsieh, 1984), whereby naming in different languages is similar to shifting task sets (Philipp & Koch, 2011) such that disengagement from the preceding language set results in a switch cost representing the amount of effort required to disengage.

Several language production studies using ERPs have also found asymmetrical switch costs, but the direction of the effects vary. In a picture naming task wherein the response language was predictable, Misra, Guo, Bobb, and Kroll (2012) observed asymmetrical switch costs from one language block to the next. In particular, they found a modulation of N2 amplitude (250-550 ms after a code-switch onset). They compared responses in L1 when it was named first and after a switch out of L2, as well as responses in L2 when it was named first versus after a switch. They found a bigger difference for the L1, suggesting an increase in inhibition of L1 after naming in L2. However, other studies found the opposite pattern of ERP effects, where L1-to-L2 switches produced a larger N2 than L2-to-L1 switches. Jackson, Swainson, Cunnington, and Jackson (2001) had native bilingual English speakers name numerals in English and in their second language (which varied across subjects). They compared naming in each language when it was preceded by naming in the same language or naming in the other language (e.g., L1-L2 versus L2-L2, and L2-L1 versus L1-L1). They observed an N2-like left fronto-central negativity starting at ~300ms after the onset of the numerals only when switching into L2, but not when switching into L1 (see also Verhoef, Roelofs, & Chwilla, 2009; Chauncey, Holcomb, & Grainger, 2009). Overall, production of code-switches in isolation tends to elicit a larger N2 when compared to non-switches. However, it remains an open question as to the nature of the cognitive control processes that are recruited to produce code-switches. For instance, Christoffels, Firk, and Schiller (2007) argued that the N2 switching effect might reflect response conflict monitoring rather than response inhibition per se.

Error-Related Negativity

Over twenty years ago, a number of researchers discovered a component associated with the commission of errors in choice RT experiments (Falkenstein et al., 1989, 1990, 1991; Gehring et al., 1990, 1993). This component was called the error negativity (Ne) or the error-related negativity (ERN). The Ne/ERN is most robustly observed in a *response-locked* waveform (time-locked relative to a participant's response rather than to stimulus onset), compared between correct response trials and incorrect response trials. It appears as a negative component onsetting at or shortly before the participant's motor response, peaking around 100ms later. The ERN typically has a frontal-central scalp distribution, and has been observed in a large number of tasks wherein errors are made, including cases in which participants are not aware of their errors (Wessel, 2012). Some have argued that the ERN and anterior N2 might be related, given similarities in scalp distribution and time course (Simson et al., 1976; Squires et al., 1976; for reviews, see Folstein & Van Petten, 2008; Pritchard et al., 1991). Moreover, as for the anterior N2, there is increasing evidence that the ERN is generated in the anterior cingulate cortex and is functionally implicated in cognitive control functions such as modulating subsequent response behavior (Debener et al., 2005).

A number of studies have used the ERN to examine error-control functions in bilingualism. For example, Sebastian-Galles, Rodriguez-Fornells, de Diego-Balaguer, and Diaz (2006) investigated whether high proficiency L1 Spanish dominant and L1 Catalan dominant bilinguals were able to distinguish a vowel contrast that existed in Catalan but not in Spanish. When listening to Catalan nonwords, the Catalan dominant bilinguals showed ERN effects for errors (compared to correct judgments), whereas the Spanish dominant bilinguals did not. Thus, despite acquiring an overall high level of proficiency in their early-acquired second language, the Spanish dominant speakers showed continued uncertainly in their phonological judgments, suggesting the possibility of limitations in plasticity for acquiring phonological contrasts in a second language. Ganushchak and Schiller (2009) also investigated L2 phonological representations, in proficient German-Dutch bilinguals. Participants monitored phonemes in implicit picture naming in Dutch under more or less time pressure. The bilinguals showed a larger ERN when under increased time pressure in contrast to the Dutch native speakers, who showed a smaller ERN in the high-pressure condition. The results indicated that when under stress, bilinguals may have difficulty suppressing L1 interference and, thus, activate multiple candidates for naming, causing higher conflict and therefore a larger ERN.

The ERN has also been employed in investigations of L2 grammar learning. In Davidson and Indefrey (2009, 2011), Dutch learners of German classified German short prepositional phrases with and without gender and declension violations. In their 2009 study, there were three phases: pre-test, learning and training with feedback, and a post-test without feedback. In their 2011 study, there were two phases: pre-test without feedback and training with delayed feedback. There was also explicit instruction in the earlier but not later study. The aims of the later study were therefore to separate response-related and feedback-related ERPs and examine the change of these ERP activities over the time course of learning.

In their 2009 study, a larger ERN response during the training and post-test phases, relative to pre-test, was observed. More importantly, there was a significant correlation between the ERN amplitude at training and the overall improvement in performance from pretest to posttest. The ERN was therefore interpreted as related to acquisition of knowledge. However, in the 2011 study, significant negative-going ERPs for error over correct trials were observed almost exclusively at feedback but not at response. This lends evidence to the debate that the response they observed was largely *feedback*-related, although the feedback negativity has been argued by many to be a variant of the ERN (and the N2 as well) (Miltner, Braun, & Coles, 1997; Van Veen & Carter, 2002). Moreover, the feedback ERN decreased in amplitude while the feedback-related positivity—a P600-like component that followed the ERN—became larger in the course of training (although the amplitudes of the two components were not correlated), as the participants' performance improved. Most important, only participants with a larger feedback positivity showed improvement over time. Overall, it can be concluded that feedback-related ERPs—ERN or later positivity—could map the learning process and hold predictive power for successful grammar learning.

<u>The Lateralized Readiness Potential (and N2) in studies of language production</u>

The Go/No-Go Paradigm has been used to study inhibitory control and response preparation in experimental psychology and cognitive neuroscience dating back to the turn of last century (Donders, 1868; Wundt, 1880). In this procedure, subjects are required to respond to one choice, but must withhold responses to other stimuli. Such paradigms have been used in cognitive electrophysiology to examine neural indices of response preparation and to study how information is temporally staged. A component of particular utility in the context of the go/no-go paradigm is the Lateralized Readiness Potential (LRP). The LRP is derived from the Readiness Potential (RP), a response associated with motor planning and preparation that begins around one and a half seconds prior to the onset of a voluntary motor movement. When that preparation involves a lateralized response (e.g., pressing a button with the right or the left hand), the RP contains a lateralized component, largest contralateral to the side of the body that the participant is preparing to move. Critically, this preparation can be observed even when, ultimately, no motor response is made (Miller & Hackley, 1992), making the LRP a useful index of even transient aspects of response selection. In particular, the fact that the LRP reflects the current state of preparation, from incremental information transmitted from stimulus evaluation processes to the motor system, means that it can be used to study the order of information extraction from a stimulus.

For example, the LRP has been used to examine the temporal ordering of availability of grammatical and phonological information during preparation for naming. In a seminal study, van Turennout et al. (1998) mapped go and no-go responses to either grammatical attributes (i.e., grammatical gender) or phonological attributes (i.e., word initial speech sound) in a modified picture naming task to examine whether grammatical or phonological properties are retrieved first. They found evidence for partial response preparation for grammatical features even when the phonological features of the word meant no response was necessary. Importantly, the converse was not true, in that partial response preparation was not observed for phonological features when grammatical features determined that no response was necessary. These data demonstrated that speakers can retrieve the grammatical gender of a noun upwards of 40 milliseconds before its phonological properties (van Turennout et al., 1998; but see Shantz & Tanner, 2017, who show that this ordering of information retrieval may be induced by experiment design and task configuration rather than being a global property of lexical feature retrieval).

The Go/No-Go Paradigm has also been used to investigate the relative time course of L2 feature retrieval during production. Guo and Peng (2007) had Chinese-English bilinguals make go/no-go decisions on the basis of semantic information (i.e., animacy) or word-form information (i.e., the initial letter of the word) in a picture naming task. They examined the N2 as an index of retrieval timing. The results showed that go and no-go N2s diverged earlier when semantics determined the go/no-go decision than when word-form information determined this decision. They further compared these results to data from native Chinese speakers performing a similar task in their L1. This comparison found no differences in the timing with which semantic and word-form information was retrieved in L1 and L2 picture naming. Using an implicit picture naming task, Shantz and Tanner (2016) examined the time course with which native speakers and L1-English learners of German retrieved information about a word's grammatical gender and its phonology. They also found that the relative timing of retrieval for grammatical gender and phonological information did not differ across L1 and L2 speakers. The results of these studies suggest that L2 learners may not be delayed relative to native speakers in their retrieval of lexical features during language production, at least for highly familiar words.

In the bilingual literature, a key question is whether lexical information is indiscriminately accessed for both languages even when one language is not relevant to the task. Using a simultaneous language and lexical decision task (i.e., respond to Spanish words and ignore Catalan words and non-words), Rodriguez-Fornells, Rotte, Heinze, Nösselt, and Münte (2002) found that high-proficiency Spanish/Catalan bilinguals did not show motor preparation potentials for non-target Catalan words, suggesting that language membership information can be used to block information access in the task-irrelevant language. Later studies also examined the timing with which language membership is retrieved, here using measures of the N2/P3 rather than of the LRP. In no-go trials, an N2 was also observed prior to the no-go LRP, whereas go trials elicited a target P3b response instead. These peaked potentials can be easier to measure (especially for timing-related information) than the slowly developing LRP, and thus have been a growing focus for studies aimed at pinpointing the relative staging of information access.

In an implicit picture naming task in which the go/no-go decision was determined by whether the first phoneme was a consonant or vowel, Rodriguez-Fornells, De Diego Balaguer, and Münte (2006) found that Spanish-German bilinguals had a larger negativity for the no-go trials when there was consistency across languages in first phoneme consonant/vowel status, suggesting that bilinguals cannot shield themselves from interference of the irrelevant language in speech production. In Hoversten, Brothers, Swaab, and Traxler (2015) and Yiu, Pitts, and Canseco-Gonzalez (2015), the conventional go/no-go paradigm was used to examine the order and time course of availability of language membership versus meaning access when balanced English/Spanish bilinguals read isolated words from either language. Both studies found that language-membership information was retrieved earlier than meaning. However, in Ng and Wicha (2013), the order of information access varied with the target language: when Spanish was the target, meaning was retrieved before language-membership information, but when English was the target language, language-membership information was accessed prior to meaning. On the whole, the go/no-go paradigm can be used to probe order of information retrieval in either language comprehension or production. In the bilingual context, it is especially useful for examining competing information access across languages.

General Conclusion

In the past half century, ERPs, together with other behavioral and neuropsychological techniques, have opened up new avenues for understanding human cognitive processes as they occur in real-time. In particular, ERPs provide a set of functionally specific measures that can help researchers target the underlying mechanisms that subserve language, memory, learning, and other cognitive abilities. The specificity of these measures allows researchers to determine where there are -- and are not -- links across language and domain-general cognitive domains, as well as across monolingual and bilingual speakers, under a wide variety of task conditions.

List of key words

Event-Related Potential (ERP), Electrophysiology, N1, N2, MMN, ERN, P300, N400, P600, LRP, NRef, Syntax, Semantics, Comprehension

Internet sites related to the specific topic:

http://www.scholarpedia.org/article/N400
http://www.scholarpedia.org/article/Electroencephalogram
https://www.sprweb.org/
http://erpinfo.org/
http://cognitionandbrainlab.org

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Figures.

Figure 1. Typical "Language" Event-Related Brain Potentials. Panel A shows typical ERPs to visually presented words, highlighting visual sensory potentials (P1, N1, P2), as well as prototypical N400 and P600 responses to violations of semantics/pragmatics and morphosyntax, respectively (see text for detail). Panel B shows scalp distributions of the prototypical N400 and P600 effects. Data from Leckey & Federmeier (in preparation).

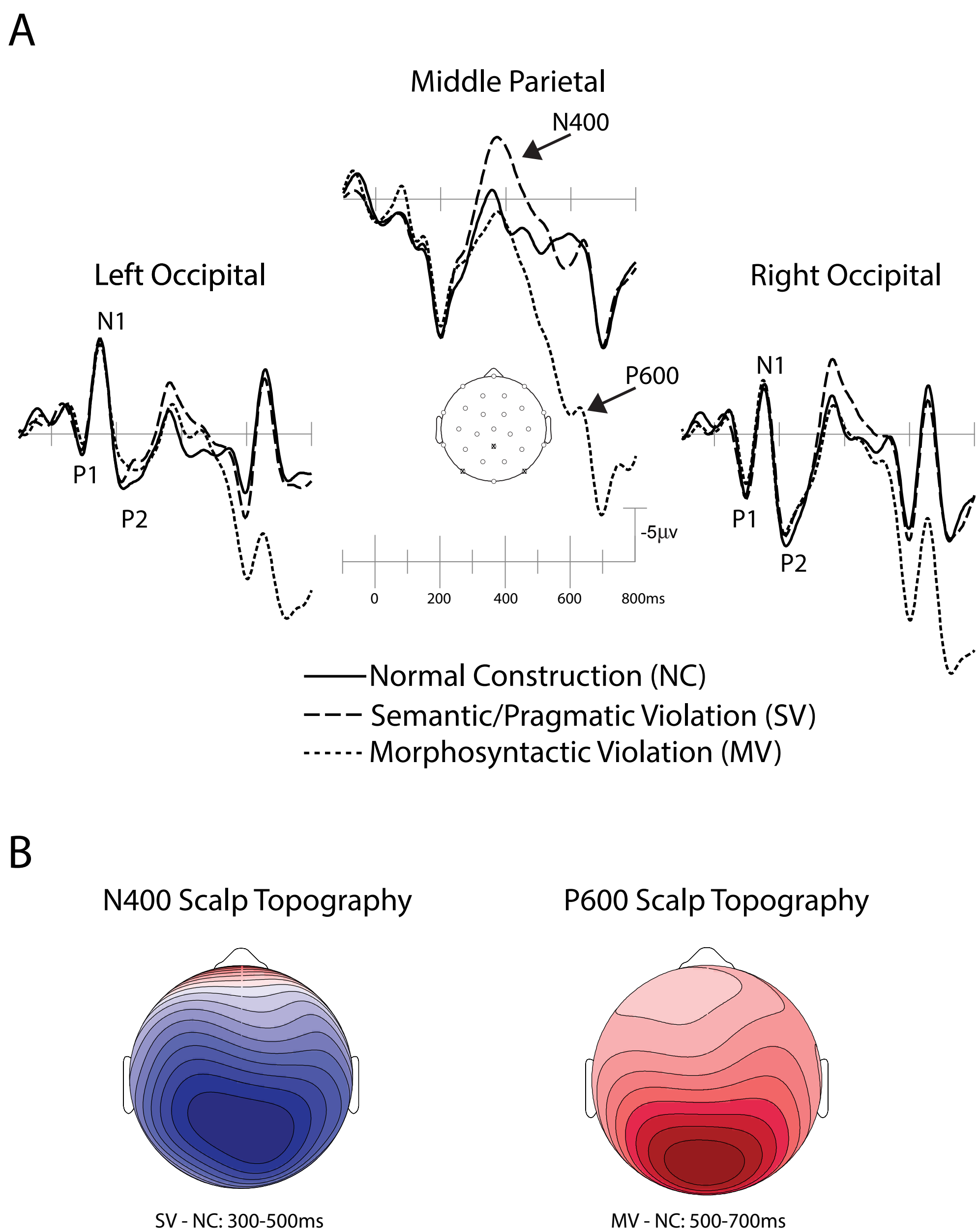

Figure 2. Anterior Language-Related Potentials. A. Frontal positivity to unexpected words in strongly constraining contexts. B. Frontal negativity to moderately constraining expected words C. Anterior N2 to prediction violations eliciting extremely slow reading times.