Event-Related Potentials

A Methods Handbook

edited by Todd C. Handy

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The MIT Press
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Preface

Research using event-related potentials (ERPs) has expanded dramatically in the last decade. As a result, there has been a corresponding increase in the number of investigators who—with little formal training in the method—are applying ERP measures to questions of cortical function. Fueling this trend has been the growing availability of commercial ERP recording systems and their relatively inexpensive cost when compared to big-ticket neuroimaging items such as fMRI. Yet unlike the variety of methods books now available for fMRI, and despite the boom in ERP-driven research, a comparable tome presenting the fundamentals of ERP methodology has been noticeably absent. This book aims to meet this need for practical and concise information on the methods of ERPs—a book that should be intelligible to the novice ERP investigator, but sufficiently rigorous so as to be informative to the most seasoned of electrophysiology experts.

The book is divided into three parts. The first section, Experimental Design, comprises four chapters, all centering on issues germane to the initial planning of an ERP experiment. The section begins with a chapter by Otten and Rugg that introduces the basic ideas and assumptions underlying the interpretation of ERP data as it pertains to questions of perceptual, cognitive, and motor function. Luck then provides a practical compendium of ten essential points to consider when designing an ERP experiment, issues integral to understanding the effective application of ERP methods. Following that, Handy details the canonical ways in which ERP data are quantified, with a focus on how planned analyses constrain experimental design. Dien and Santuzzi conclude the section by reviewing the theoretical and practical aspects of ANOVAs as applied to ERP datasets. Taken together, these chapters provide a solid and practical foundation for understanding the design of ERP experiments and how to interpret ERP data.

The middle section of the book, Data Analysis, comprises seven chapters, presenting a variety of approaches to ERP data analysis. The first two chapters cover issues associated with the "preprocessing" of ERP data. Edgar, Stewart, and Miller detail the essential elements of digital filtering in ERP research, including a survey of fundamental terms and concepts tied to digital signal processing. Talsma and Woldorff review the different kinds of artifacts that can arise in ERP data, and the different types of procedures for removing such artifacts from ERP waveforms. The next five chapters then address specific analytic methods in depth. Slotnick discusses the nuances underlying the localization of ERP source generators in cortex, procedures derived from the topographic mapping of voltage over the surface of the scalp. In a chapter on high-resolution ERP recordings, Srinivasan proposes that the localization of cortical EEG sources can be improved by considering the surface Laplacian—or second spatial derivative—of skull current density. Moving from source localization to ERP componetry, Dien and Frishkoff provide an introductory treatment of principal components analysis (or PCA), a means of linearly decomposing ERP waveforms into more basic elements. Spencer considers how to interrogate single-trial ERP data, including the use of discriminant analysis, analytic approaches that—unlike standard signal averaging—can account for the intertrial variability in ERP data. Herrmann, Grigutsch, and Busch conclude the section with a discussion of wavelet analysis, procedures that isolate specific frequency bands in ERP data and that are a particularly powerful approach for examining event-related oscillatory behavior in EEG. Collectively, these chapters provide an important introduction to the different ways that ERP data can be analyzed, and the kinds of questions that these different techniques can address.

The final section of the book, Special Applications, covers the use of ERPs as they pertain to specific participant populations and other methodologies. To begin, DeBoer, Scott, and Nelson review the use of ERPs in the developmental domain, including the practical aspects of how to design experiments and record data when using infants and young children as participants. In the following chapter, Swick considers the use and interpretation of ERPs in neuropsychological populations, emphasizing how data from these patients has helped to elucidate the cortical systems underlying different ERP components. Switching gears, Soltani, Edwards, Knight, and Berger then explain the practical details of intracranial ERP recordings, and further, how intracranial ERPs relate to—and differ from—ERPs recorded from the scalp surface. In the final chapter, Hopfinger, Khoe, and Song detail how hemodynamic neuroimaging has helped inform traditional questions in ERP methodology, concluding with an eye toward recent developments in neuroimaging techniques that may help to solve long-standing problems in ERP research. In sum, the section gives insight into the broader context of ERP methodology, in terms of both the participants used in ERP research and how researchers can combine ERPs with related methodologies.

This book would not have been possible without the assistance of a number of key individuals. First and foremost are the contributors themselves, busy leaders in their fields who nevertheless committed their valuable time to the project; all cheerfully provided outstanding chapters, and I thank them warmly. Second, without a publisher the book would have gone nowhere. The MIT Press—and Barbara Murphy and Katherine Almeida, in particular—have provided stellar support throughout the life-

span of the project, and I greatly appreciate their professional efforts. Third, Michael Gazzaniga generously provided shelter and funding while I was planning and editing the book, even though it often took me away from duties more directly productive to his laboratory. Again, a warm thanks. Finally, I am deeply indebted to ErinRose Handy for gracefully—and all too frequently—allowing me to step away from my role as a husband in order to pursue my selfish academic whims. My career continues to depend on her faith and encouragement.

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1 Experimental Design

1 Interpreting Event-Related Brain Potentials

Leun J. Otten and Michael D. Rugg

Our ability to feel, think, and act can in some way be attributed to the workings of the brain. For over a century, scientists have used measures of brain activity to gain insights into perceptual, cognitive, and motor functions. As a result, researchers have developed a variety of methods to measure brain activity noninvasively (e.g., Rugg, 1999). These methods roughly fall into two classes: "electromagnetic" approaches that directly measure brain activity by recording the electromagnetic fields generated by certain neuronal populations, and "hemodynamic" approaches that indirectly measure brain activity by recording changes in vascular variables that are linked to changes in neural activity. Importantly, these methods differ in a number of aspects, including the preconditions for detecting a signal, the homogeneity with which neural activity is sampled from different parts of the brain, and the relative strengths in determining *when* versus *where* neural activity takes place. They therefore provide complementary views on neural activity.

This chapter focuses on electromagnetic measures of neural activity. Within this class of methods, there are several ways to examine electrical and magnetic activity, in both the temporal and spatial domains (e.g., Näätänen, Ilmoniemi, & Alho, 1994; Tallon-Baudry & Bertrand, 1999). Here we restrict discussion to event-related brain potentials (ERPs), which are small changes in the electrical activity of the brain that are recorded from the scalp and that are brought about by some external or internal event (see Coles & Rugg, 1995; Kutas & Dale, 1997). This electrical activity changes rapidly over time and has a spatially extended field. It is therefore usually recorded with a temporal resolution in the order of a few milliseconds from multiple scalp locations. The goal of this chapter is to explain how one can make functional interpretations from ERP data. After a brief introduction to the issues that ERP analysis aims to address, we outline the type of inferences that one can and cannot make from ERP data. The final two sections then examine the assumptions that underlie functional inferences, and how functional interpretations of ERP data may develop in future. The material considered here is similar to that covered by Kutas and Dale (1997) and Rugg and Coles (1995).

What Issues Can ERP Analysis Address?

A first step toward making functional interpretations from ERP data is to consider what purpose ERPs serve. One can study ERPs in their own right, that is, to gain a better understanding of aspects of ERPs themselves. For example, there has been substantial work to characterize individual features of ERP waveforms, and to identify the intracerebral origins of ERPs. More often, however, researchers use ERPs as a tool to resolve questions in disciplines such as psychology, psychiatry, and neuroscience. For example, ERPs have helped to delineate psychiatric and neurological conditions such as schizophrenia and ADHD (e.g., Ford et al., 1999; van der Stelt et al., 2001), why people take longer to respond in situations of conflicting information (e.g., Duncan-Johnson & Kopell, 1981), how attention normally works (e.g., Mangun & Hillyard, 1995), and why memory declines as we grow older (e.g., Rugg & Morcom, in press). Attempts have even been made to use ERPs as a lie-detection tool (Farwell & Donchin, 1991)!

In this chapter, we confine our discussion of functional interpretations from ERPs to their use in the field of cognitive neuroscience, although the logic and assumptions laid out here also apply to most other applications. Cognitive neuroscience "aims to understand how cognitive functions, and their manifestations in behavior and subjective experience, arise from the activity of the brain" (Rugg, 1997, 1). We focus on what ERPs can reveal about cognitive functions in healthy individuals, using within-group comparisons. Comparisons between groups of individuals, especially when special populations such as clinical or younger/older people are involved, require additional considerations (see Picton et al., 2000; or Rugg & Morcom, in press, for introductions to this topic).

Explanations in cognitive neuroscience can be articulated at many different levels, ranging from functional to cellular and even subcellular accounts (e.g., Marr, 1982). One can use ERPs to address questions at several of these levels. For example, at a functional level, some use ERPs to address whether the brain honors the distinction between syntax and semantics (e.g., Friederici, 1995). At a lower level, researchers use ERPs to investigate the speed of interhemispheric transmission (e.g., Lines, Rugg, & Milner, 1984), or the effects of pharmacological manipulations (e.g., Hsu et al., 2003). Often, interest spans across levels, and explanations at one level may constrain explanations at another level. In the next section, we discuss how one can use ERP data to make functional inferences.

Making Inferences from ERPs

We can classify inferences from ERP data in several ways. It is possible to order inferences on the basis of their complexity and underlying assumptions (Rugg & Coles, 1995), or on the emphasis placed on the temporal versus the spatial information that ERPs provide. Here, we draw a distinction between inferences that one can make with and without adopting a functional interpretation of some feature of an ERP waveform. ERPs have been in use since the 1960s, and many studies have attempted to associate particular features of ERP waveforms with specific cognitive processes. On the basis of the findings of such studies, it is sometimes possible to use specific ERP features (or "components"—see below) as markers for the engagement of the cognitive process with which they are correlated. One can also draw meaningful interpretations of ERP data without making assumptions about the functional significance of any particular waveform feature. In the following sections, we therefore distinguish between inferences made with and without such theoretical commitments. We discuss the latter class of interpretation first.

Inferences Not Based on Prior Knowledge

ERPs can be employed to study cognitive processes even when there is little or no prior useful information to bring to bear on the functional significance of any feature of the elicited ERP waveforms. In practice, this is a common situation. There are generally three kinds of inferences made in these circumstances: about the timing, degree of engagement, and functional equivalence of the underlying cognitive processes. These inferences rely on three aspects of ERP differences observed between conditions: their time course, amplitude, and distribution across the scalp, respectively. We will illustrate these inferences with a concrete example.

Consider an experiment in which ERPs are elicited at three electrode sites in two conditions (1 and 2), and in two situations (A and B; see figure 1.1). The simplest type of inference from these data is based on the observation that the ERP waveforms elicited in the two conditions differ. (For this and all subsequent types of inference, this observation can be substantiated by an appropriate quantification of the waveforms; see chapter 3 of this volume). On the assumption that specific cognitive processes are manifested in specific and invariant patterns of neural activity (see below), a reliable ERP difference between conditions implies that the cognitive processes associated with the two conditions differ in some respect. Understanding how the cognitive processes differ depends on a conceptual analysis of the differences between conditions.

Even this simple inference can lead to useful insights. For example, a longstanding question in cognitive psychology is the level to which unattended information is processed. One can address this question by recording ERPs for unattended information, and establishing whether the content of the unattended information influences the ERP waveforms. Using this logic, researchers have found that ERP waveforms for unattended information differ when an unattended, visually presented word is presented twice in succession (Otten, Rugg, & Doyle, 1993). This suggests that unattended visual information can be processed to the level of its identity.

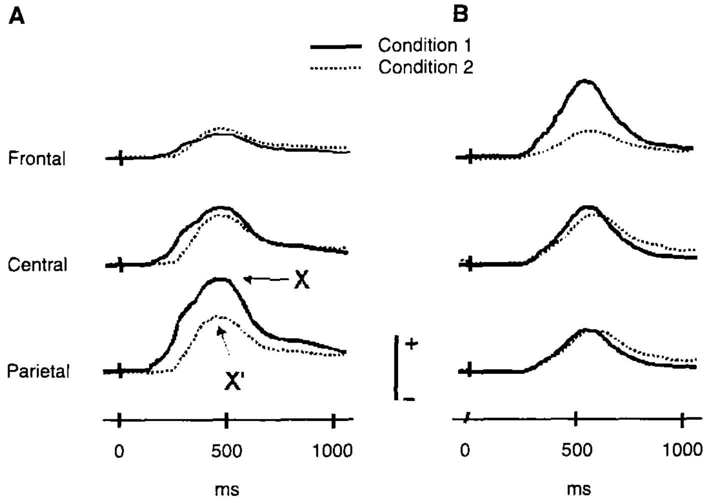

Figure 1.1
Hypothetical ERP waveforms elicited at three electrode sites in two experimental conditions in two experimental situations (*A* and *B*). The differences between the waveforms allow a number of functional interpretations. See text for details.

Expanding on the first type of inference, the second type of inference takes advantage of the high temporal resolution of ERP waveforms, which makes them especially valuable for drawing inferences about the timing of cognitive processes. In situation A of figure 1.1, the ERP waveforms in the two conditions start to differ at about 250 ms after the onset of the event of interest. This implies that the cognitive processes that differentiate the two conditions began to differ by 250 ms. Using this logic, researchers have demonstrated that the ERP waveforms elicited by attended and unattended stimuli can differ as early as 50 ms after stimulus onset (Woldorff & Hillyard, 1991). Accordingly, attentional processes must have been engaged within 50 ms, providing important information about the functional characteristics of selective attention.

The final two classes of inference discussed in this section are based on interpretation of the scalp distribution and amplitude of an ERP effect, respectively. Information about the scalp distribution of an ERP effect forms the basis of efforts to estimate the nature of the intracerebral sources that underlie the effect (e.g., Scherg, 1990). More importantly in the present context, however, this information contributes to the determination of whether functionally nonequivalent processes are engaged across conditions. Crucially, one can make such inferences even in the absence of knowledge about the intracerebral sources of the ERP effects in question.

In situation A of figure 1.1, the difference between the two conditions is largest at the parietal electrode site. By contrast, in situation B, the difference between conditions is largest at the frontal electrode site. As we discuss later, there are several reasons why scalp distributions may change. Regardless of the cause, however, different scalp distributions imply that different patterns of neural activity are associated with the two situations. So far as one is willing to accept the assumption that experimental conditions that are neurophysiologically dissociable are most likely functionally dissociable as well (see below), one can use ERPs to assess whether the cognitive processes engaged in different experimental conditions are functionally distinct.

We can apply the same logic to differences in scalp distribution that emerge over time. ERP effects can be compared not only across experimental conditions as exemplified above, but also across time points within a condition, or across time points across conditions. In any case, a difference in scalp distribution implies a difference in underlying neural pattern. In turn, different neural patterns imply that distinct functional processes were engaged across conditions, times, or both.

For example, when people are asked to decide whether or not they remember having experienced an item before, new and old items elicit different ERP waveforms. This difference is largest over left parietal scalp sites in an early time region of the waveforms, before becoming largest over right frontal scalp sites later on (see Rugg & Wilding, 2000, for review). These scalp distribution differences suggest that different patterns of neural activity are engaged over time. Accordingly, memory retrieval may rely on multiple, qualitatively different functional processes, operating at different points in time. Without evidence that the two effects are dissociable, however, the possibility that they act in concert to support a common process cannot be ruled out. As it happens, the left parietal and right frontal ERP effects are sensitive to distinct experimental manipulations (Rugg & Wilding, 2000).

If scalp distributions do not differ across conditions or time, does this have any functional implications? If experimental manipulations do not result in scalp distribution differences, but the associated ERP effects nonetheless differ in amplitude, this is usually taken to suggest a quantitative, as opposed to a qualitative, difference in the cognitive processing engaged in the two conditions. That is, the experimental manipulations are thought to have engaged the same cognitive process(es), but to differing degrees. Later on, we discuss caveats surrounding interpretations from such amplitude differences and null results.

Inferences Based on Prior Knowledge: ERP "Components"

As discussed in the previous section, we can make useful inferences about cognitive processes from ERP data without knowing what any particular waveform feature represents. However, we can gain additional information with knowledge about the functional significance of some aspect of an ERP waveform. ERPs can be thought of as time-varying scalp fields that result from the summation of electromagnetic activity generated by neuronal populations in different parts of the brain. Clearly, it would be informative to understand these fields both in terms of the neuronal populations responsible for them and the different cognitive processes with which they are associated. In essence, this is what the decomposition of ERP waveforms in terms of their underlying "components" attempts to achieve.

There is no universally accepted definition of what constitutes an ERP component. Because neural and cognitive processes overlap in both space and time, features of the waveform such as peaks or troughs can result from the summation of several contributing sources, and thus may not reflect functionally homogeneous neural or cognitive processes. Component definitions range between two extremes, sometimes referred to as the "physiological" and "functional" approaches to component identification. According to the physiological approach (e.g., Näätänen & Picton, 1987), an ERP component should be defined in terms of its anatomical source within the brain. To measure a component, it is therefore necessary to isolate the intracerebral sources underlying an ERP waveform. By contrast, according to the functional approach (e.g., Donchin, 1981), an ERP component should be defined predominantly in terms of the functional process with which it is associated. On this account, it is irrelevant whether one or several anatomical sources contribute to the component, as long as they constitute a functionally homogeneous system.

In practice, ERP components are usually defined with respect to both their functional significance and their underlying neural source(s). Along these lines, Donchin, Ritter, and McCallum (1978) give an operational definition of an ERP component. According to this view, a component is a part of the waveform with a circumscribed scalp distribution (alluding to the underlying neural configuration) and a circumscribed relationship to experimental variables (alluding to the cognitive function served by the activity of this configuration). Several procedures, based on the analysis of scalp distribution and sensitivity to experimental manipulations, have been proposed as methods to dissociate and measure overlapping components (see Picton et al., 2000).

What can we gain from the concept of an ERP component? Despite the difficulties surrounding their definition and measurement, components serve at least three purposes. First, they provide a language that allows communication across experiments, paradigms, and scientific fields. Second, they can provide a basis for integrating ERP data with other measures of brain activity. Third, components can serve as physiological markers for specific cognitive processes. In the case of some components, sufficient information has accumulated to indicate, in broad terms at least, their functional significance. Below, we illustrate how one can make functional interpretations from ERP data using the notion of a component (see also chapter 2 of this volume).

Again, consider the waveforms illustrated in figure 1.1. Assume that in situation A, the positive deflection in the waveforms (labeled X and X') is a known ERP component, associated with some specific cognitive process. (This assumption is for the purposes of exposition only. In reality, it is highly unlikely that such a large, temporally extended ERP deflection would reflect the activity of a single generator system, or a single cognitive process.) On this assumption, the first inference one can make from these data makes use of the time course of the component across conditions. The time course can be quantified with one of several temporal measures of the component, for example its onset, peak latency, rise time, or duration (see chapter 3 of this volume). In figure 1.1, the component onsets later in condition 2 than 1. This implies that the cognitive process presumed to be associated with the component is engaged at a later time in condition 2 than 1.

Next, figure 1.1 shows that the amplitude of the component in situation A differs between conditions. As with the time course of a component, we can define its amplitude in several ways. The observed amplitude difference in figure 1.1 implies that the cognitive process is engaged to a different degree across conditions. This inference relies crucially on previous work associating variance in the amplitude of the component with variance in the degree to which the associated cognitive process is engaged. To illustrate this type of inference, based on its scalp distribution and approximate time of occurrence, the positive peak seen in situation A of figure 1.1 may reflect the P300 or P3b component (Donchin, 1981; Donchin & Coles, 1988). Donchin and Coles (1988) proposed that P300 amplitude variations reflect variations in the degree to which an internal representation of the experimental context is updated. On this account, the differences between conditions shown in situation A of figure 1.1 support the inference that updating processes are greater in condition 1 than 2. Such inferences based on amplitude measures only apply when comparing the same component across conditions.

The reader may have noticed that all the inferences discussed in this and the previous sections were framed in terms of comparisons between experimental conditions. That is, they are based on an analysis of differential ERP effects. Functional interpretations of any measure of neural activity rely crucially on a carefully designed experiment. The processes of interest must be isolated with judiciously selected experimental conditions. Virtually without exception, this requires the researcher to manipulate the process across two or more experimental conditions. Accordingly, functional interpretations are usually made from differences in neural activity, computed between the conditions that are presumed to isolate the process(es) of interest.

What Cannot Be Inferred from ERPs?

ERP data can provide valuable information about cognitive functions in many situations. When using ERP data to make functional interpretations, it is important to keep these strengths in mind. Equally important, however, is to recognize the limitations of ERP data. For example, ERPs can provide no information about neural activity giving rise to "closed" electromagnetic fields (see below). In addition, many of the inferences discussed in the previous sections rely on assumptions that may be violated in any