

2 A Closer Look at ERPs and ERP Components

Overview

This chapter provides a deeper analysis of the nature of ERPs, with the goal of helping you understand how ERPs are generated in the brain and how the intracranial signals combine together to create the waveforms we record on the surface of the scalp. The peaks that you see in scalp ERP waveforms typically reflect the sum of multiple internal, underlying components, and the conclusions of an experiment often require determining how these underlying components differed across groups or conditions. However, as I mentioned in chapter 1 (and will continue to emphasize throughout this book), it is very challenging to isolate and measure the internal underlying components on the basis of the data that you actually record from the scalp. This is called the *superposition problem*, and this chapter will explain how it arises and why it is so difficult to solve. This can be a little depressing, but don't despair! Chapter 4 describes some strategies you can use to solve this problem (or work around it), along with examples of previous experiments that have successfully used these strategies to provide definitive answers to important scientific questions. Chapter 3 provides a description of the specific ERP components that are most commonly observed in typical experiments.

It is easy to confuse the peaks that we observe in our scalp waveforms with the internal underlying brain components that sum together to create these peaks. In this chapter, I frequently use the phrase *underlying component* to make it clear that I am talking about internal brain activity, not the observed peaks on the scalp.

This chapter will begin with a discussion of basic electrical concepts, followed by a detailed discussion of the neural origins of ERPs and how they mix together in scalp recordings. We will then discuss why it is so difficult to localize the internal generators of scalp ERPs. This will be followed by a description of how the ERPs we record from scalp electrodes can radically misrepresent the underlying components. We will then discuss how difference waves can be used to solve this problem and isolate the underlying components. We will end by considering different ways of defining the term *ERP component*. You might think that it would be more logical to start with the definitions, but they will be much easier to grasp once you've spent some time thinking concretely about the nature of the signals we record from scalp electrodes. The chapter

ends with a general discussion of methods that can be used to identify the underlying components that vary across groups or conditions in a given study.

This chapter is designed to provide you with a deep conceptual understanding of ERPs, and it is therefore somewhat abstract. You need this kind of understanding to evaluate previous ERP experiments and to design new ERP experiments. In fact, this chapter includes six specific “rules” for interpreting ERP data. However, if you are in the middle of collecting or analyzing data from an ERP experiment and you need to know the practical details of how to collect clean data and perform appropriate analyses, you might want to skip ahead to chapters 5–10. You can then come back to chapters 2–4 when you are ready to think more deeply about your results and to design new experiments. But don’t forget to come back later, because chapter 2 is ultimately the most important chapter in the entire book.

Basic Electrical Concepts

If you are going to measure electrical signals in your research, you need to know a little bit about electricity. In this section, I will provide an overview of the most basic terms and concepts. If you took physics in high school or college, you have already learned these terms and concepts (although many people have told me that electricity was the part of physics they never really understood). If you didn’t take physics, then don’t worry, because I didn’t either. When I was in high school, I took shop classes on electronics rather than physics, because I was more interested in being able to fix my guitar amplifier than I was in learning to predict the velocity of a ball rolling down a hill. Fortunately, the relevant concepts are pretty simple.

Current

Current is the actual flow of electricity (charged particles) through a conductor. It is a measure of the number of charge units (electrons or protons) that flow past a given point in a specific amount of time. Current is measured in amperes, where 1 ampere is equal to 1 coulomb (6.24×10^{18}) of charge units moving past a single point in 1 second.

By convention, physicists and engineers refer to current flowing in the direction of positively charged particles. For example, 1 coulomb of positively charged particles flowing from the left hemisphere to the right hemisphere is viewed as being electrically equivalent to 1 coulomb of negatively charged particles flowing from the right hemisphere to the left hemisphere. Thus, we would talk about the current flowing from the left hemisphere to the right hemisphere in both cases, regardless of whether it is positive charges moving from left to right or negative charges moving from right to left.

When discussing the flow of electricity, it is useful to use the flow of water as an analogy. Electrical current is analogous to the flow of water through a pipe or hose. Just as we can measure the amount of water that passes a given point in a pipe in a given period of time (e.g., 3.6 liters per minute), we can measure the amount of electricity that passes a given point in a conductor in a given period of time (e.g., 3.6 coulombs per second).

Voltage

People often get voltage and current mixed up, thinking that voltage is the actual flow of electricity. Current is the flow of electricity through a conductor, and voltage is the pressure that pushes the electrical current through the conductor. A more precise term for voltage is *electrical potential*, because it is the potential for electrical current to flow from one place to another (and this is why ERPs are event-related *potentials*). As an analogy, consider a tank of water at the top of a hill. There is a lot of potential for the water to flow from the tank to the bottom of the hill, but little potential for the water to flow from the bottom to the top. Importantly, the potential for water to flow downhill is present even if no water is flowing at a given moment (e.g., because a valve is closed). Similarly, there is potential for electrical current to flow from one terminal of a car battery to the other even if no current is flowing. Electrical potential is closely analogous to water pressure: there can be a lot of water pressure in a hose even if the end of the hose is closed and no water is actually flowing. However, once the end of the hose is opened, the pressure will cause water to flow. Also, no water will flow out of the end of the hose unless there is sufficient water pressure, just as no electrical current will flow without an electrical potential to push it through the conductor.

Electrical potential is measured in units of volts (V). ERPs are so small that they are usually quantified in microvolts (μV), where 1 microvolt is 1 millionth of a volt. You can imagine that the 120 V running through the video monitor in front of a subject could lead to significant interference when you are looking for a 1 μV experimental effect. This kind of interference will be discussed in more detail in chapter 5.

Resistance

Resistance is the ability of a substance to keep charged particles from passing. It is the inverse of *conductance*, which is the ability of a substance to allow charged particles to pass through it. Three main factors contribute to resistance: (1) the composition of the substance, (2) its length, and (3) its diameter. Because of their molecular properties, some substances conduct electricity better than others (e.g., copper is a better conductor than zinc). However, the ability of any substance to conduct electricity will be reduced if it is very thin or very long. Resistance is measured in ohms (Ω).

To use yet another hydraulic example, consider a water filtration system in which the water supply for a house passes through a large tank filled with carbon. If the carbon is tightly packed, water will not easily flow through the tank, but if the carbon is loosely packed, water will flow easily. This is analogous to the dependence of electrical resistance on the properties of the substance. Now imagine water passing through a hose. If the hose is 100 m long and only 1 cm wide, it will resist the flow of water, and a great deal of pressure will be necessary to fill a bucket in a short amount of time. However, if the hose is shorter (e.g., 1 m) or wider (e.g., 10 cm), the bucket will fill quickly with only a moderate amount of water pressure. This is analogous to the dependence of electrical resistance on the length and diameter of the conductor.

This last analogy also illustrates the relationship between voltage, current, and resistance. If a thin hose is used, the volume of water that passes out of the end of the hose will be small relative to what would be obtained with a wider hose and the same water pressure. Similarly, if voltage stays the same and the resistance increases, the current will decrease. However, if a thin hose is used, a large volume of water can be obtained in a given time period by increasing the water pressure. Similarly, it is possible to maintain a constant current when the resistance is increased by increasing the voltage.

We will talk more about how resistance and its close cousin *impedance* influence EEG recordings in chapter 5.

Electricity and Magnetism

Electricity and magnetism are fundamentally related to each other, and it is important to understand this relationship to understand how electrical noise is picked up in ERP recordings and how MEG recordings are related to EEG recordings (which will be described in more detail later). The flow of current through a conductor is always accompanied by a magnetic field that flows around the conductor. Moreover, if a magnetic field passes through a conductor, it induces an electrical current. These two principles are illustrated in figure 2.1, which shows what happens when a current is passed through one of two nearby conductors. The flow of current through one of the conductors generates a magnetic field, which in turn induces current flow in the other conductor. This is how electrical noise in the environment (e.g., the 120 V in the video display)

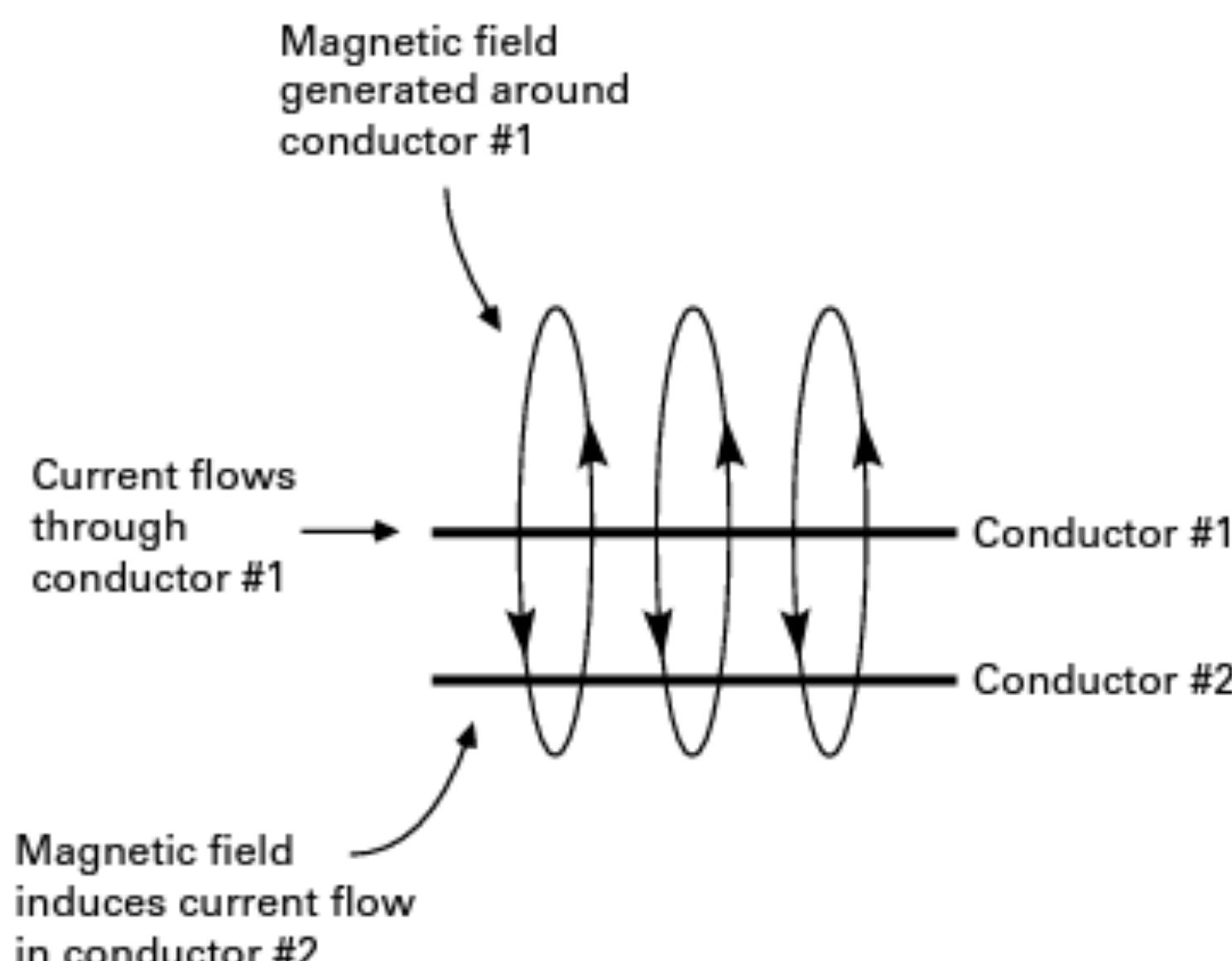


Figure 2.1

Relationship between electricity and magnetism. A current is passed through conductor #1, and this generates a magnetic field that circles around conductor #1. As this magnetic field passes through conductor #2, it induces a small current in conductor #2. This is how electrical devices located near the subject can induce artifactual electrical “noise” in the electrodes or electrode wires. It is also the basic principle underlying magnetoencephalogram (MEG) recordings.

can induce electrical activity in an ERP subject, in the electrodes, or in the wires leading from the electrodes to the amplifier (see chapter 5 for details).

The Neural Origins of ERPs

The neural origins of ERPs were described briefly in chapter 1, and here we take a much closer look. We will also discuss why it is so difficult to localize ERPs on the basis of scalp recordings (an even more detailed discussion of ERP localization is provided in online chapter 14). For a more detailed description of the neural and biophysical events underlying the generation of EEG and ERP signals, see the review by Buzsáki, Anastassiou, and Koch (2012).

Electrical Activity in Individual Neurons

Neurons produce two main types of electrical activity, *action potentials* and *postsynaptic potentials*. Action potentials are discrete voltage spikes that travel from the beginning of the axon at the cell body to the axon terminals, where neurotransmitters are released. Postsynaptic potentials are the voltages that arise when the neurotransmitters bind to receptors on the membrane of the postsynaptic cell, causing ion channels to open or close and leading to a graded change in the voltage across the cell membrane. It is fairly easy to isolate the action potentials arising from a single neuron by inserting a microelectrode into the brain, but it is virtually impossible to completely isolate a single neuron's postsynaptic potentials in an *in vivo* extracellular recording (because PSPs from different neurons become mixed together in the extracellular space). Consequently, *in vivo* recordings of individual neurons ("single-unit" recordings) measure action potentials rather than postsynaptic potentials. When many neurons are recorded simultaneously, however, it is possible to measure either their summed postsynaptic potentials or their action potentials. Recordings of action potentials from large groups of neurons are called *multi-unit* recordings, and recordings of postsynaptic potentials from large groups of neurons are called *local field potential* recordings.¹

In the vast majority of cases, action potentials cannot be detected by surface (scalp) electrodes because of the timing of the action potentials and the physical arrangement of axons. When an action potential is generated, current flows rapidly into and then out of the axon at one point along the axon, and then this same inflow and outflow occur at the next point along the axon, and so on until the action potential reaches a terminal. If two neurons send their action potentials down axons that run parallel to each other, and the action potentials occur at exactly the same time, the voltages from the two neurons will summate. However, if one neuron fires slightly after the other, current will be flowing into one axon at the same time that it is flowing out of the adjacent location on the other axon, and these signals will cancel. Because large populations of neurons do not usually fire at precisely the same time (i.e., within microseconds of each other), action potentials cannot usually be recorded from the scalp. As a result, ERPs almost always reflect postsynaptic potentials rather than action potentials. The main exceptions to this rule are peaks I and II of the brainstem auditory evoked response, which reflect precisely

synchronized action potentials generated in the cochlea and passing through the auditory nerve within a few milliseconds after a sudden sound onset (Pratt, 2012). You can safely assume that any ERPs recorded from the scalp more than 20 ms after stimulus onset reflect postsynaptic potentials rather than action potentials.

Notably, the neural events leading to the fMRI BOLD signal are more heterogeneous. Anything that increases glucose or oxygen utilization can potentially lead to a change in regional cerebral blood flow and impact the BOLD signal, whereas ERPs solely reflect postsynaptic potentials. I like to think about this fact when I'm talking to a neuroimaging researcher who is smug about having millimeter-level spatial resolution, but I try not to say it aloud.

Summation of Postsynaptic Potentials

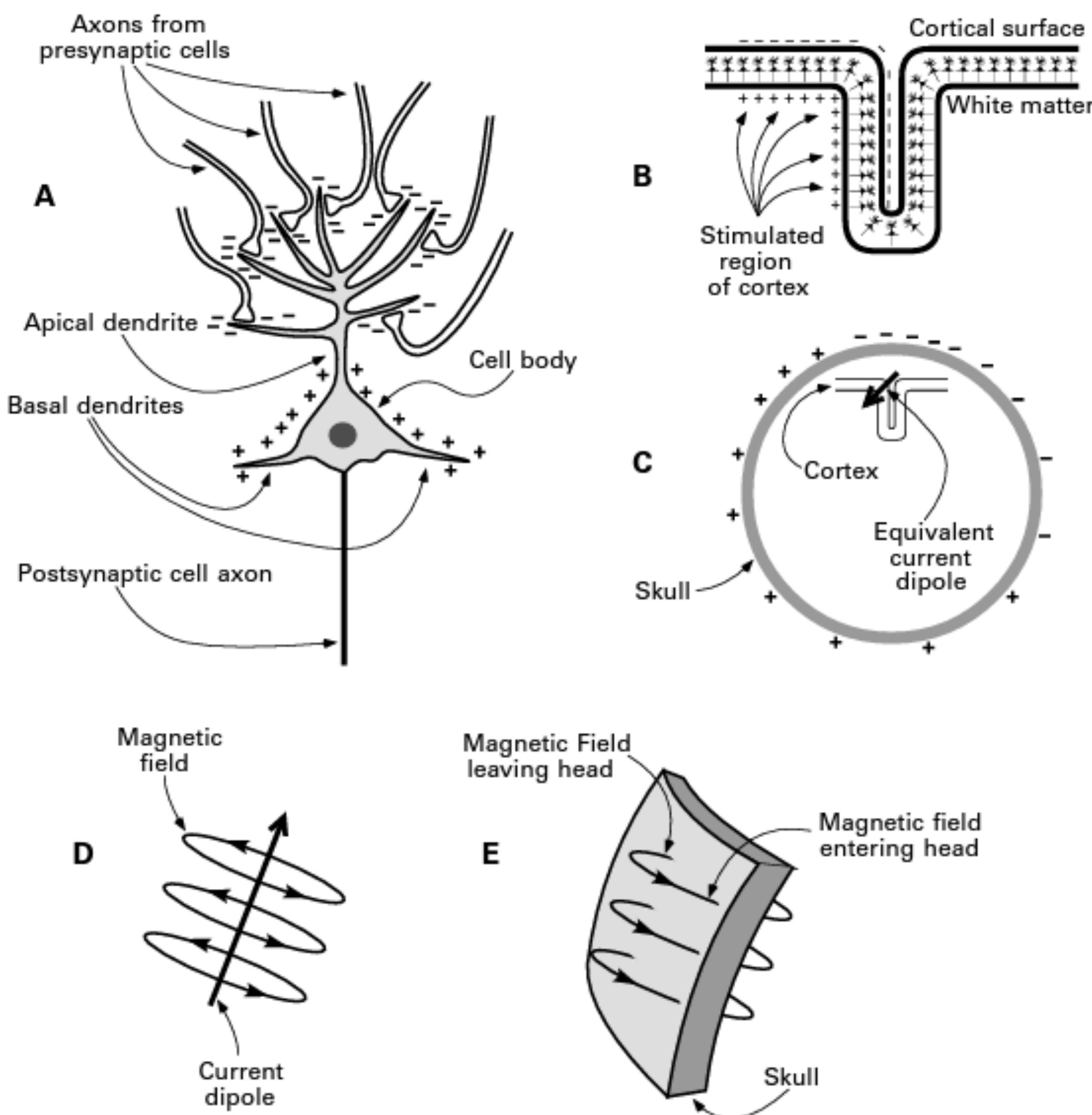
Whereas the duration of an action potential is only about a millisecond, postsynaptic potentials typically last tens or even hundreds of milliseconds. In addition, postsynaptic potentials are largely confined to the dendrites and cell body. Under certain conditions, these factors allow postsynaptic potentials from multiple neurons to summate, making it possible to record them at a great distance (i.e., at the scalp).

Figure 2.2 shows how postsynaptic potentials are thought to lead to electrical potentials that can be recorded on the scalp.² Scalp ERPs are thought to arise mainly from *pyramidal cells*, the main input–output cells of the cerebral cortex. These cells have a set of basal dendrites and a single apical dendrite (all of which branch out after leaving the cell body; see figure 2.2A). The overall spatial configuration of the cell body and dendrites looks like a pyramid (if you use a lot of imagination). Cortical pyramidal cells are all oriented perpendicular to the cortical surface, with the apical dendrite heading in the direction of the cortical surface and the cell body and basal dendrites located closer to the white matter (see figure 2.2B).

If an excitatory neurotransmitter is released at the apical dendrite of a cortical pyramidal cell, as shown in figure 2.2A, an electrical current (in the form of positively charged ions) will flow from the extracellular space into the cell, yielding a net negativity on the outside of the cell in the region of the apical dendrites. To complete the circuit, current will also flow out of the cell body and basal dendrites, yielding a net positivity in this area. This flow of current creates a tiny *dipole* (a pair of positive and negative electrical charges separated by a small distance).

If the postsynaptic potential is inhibitory rather than excitatory, this reverses the flow of current and changes the polarity of the signal recorded on the scalp. If the postsynaptic potential occurs at the cell body or basal dendrites rather than at the apical dendrite, this also changes the polarity (see box 2.1 for a discussion of the meaning of an ERP component's polarity).

The dipole from a single neuron is so small that it cannot be recorded from a scalp electrode, but the dipoles from many neurons will sum together, making it possible to measure the resulting voltage at the scalp. For the voltages from the individual neurons to summate and be recordable at the scalp, they must be present at the same time across thousands or millions of neurons, and the dipoles from the individual neurons must be spatially aligned. If the neurons are at random orientations with respect to each other, then the positivity from one neuron may be adjacent to

**Figure 2.2**

Principles of ERP generation. (A) Schematic pyramidal cell during neurotransmission. An excitatory neurotransmitter is released from the presynaptic terminals in the apical dendrite, causing positive ions to flow into this region of the postsynaptic neuron. This creates a net negative extracellular voltage (represented by the “-” symbols) just outside the apical dendrite. To complete the circuit, voltage will flow through the neuron and then exit in the region of the cell body and basal dendrites (represented by the “+” symbols). This flow of current forms a small dipole. The polarity of this dipole would be inverted if an inhibitory neurotransmitter were released rather than an excitatory neurotransmitter. It would also be inverted if the neurotransmission occurred at the cell body or basal dendrites rather than at the apical dendrite. (B) Folded sheet of cortex containing many pyramidal cells. When a region of this sheet is stimulated, the dipoles from the individual neurons summate. (C) The summated dipoles from the individual neurons can be approximated by a single equivalent current dipole, shown here as an arrow. By convention, the arrowhead indicates the positive end of the dipole. The position and orientation of this dipole determine the distribution of positive and negative voltages recorded at the surface of the head. (D) Example of a current dipole with a magnetic field traveling around it. (E) Example of the magnetic field generated by a dipole that lies just inside the surface of the skull. If the dipole is roughly parallel to the surface, the magnetic field can be recorded as it leaves and enters the head; no field can be recorded if the dipole is oriented radially (perpendicular to the surface). Reprinted with permission from Luck and Girelli (1998). Copyright 1998 MIT Press.

Box 2.1

What Does the Polarity of an ERP Component Mean?

I am often asked whether it “means something” if a component is positive or negative. My response is that polarity depends on a combination of four factors:

- Whether the postsynaptic potential is excitatory or inhibitory
- Whether the postsynaptic potential is occurring in the apical dendrite or the basal dendrites and cell body
- The location and orientation of the generator dipole with respect to the active recording electrode
- The location of the reference electrode (which will be discussed in chapter 5)

If you know three of these factors, then the polarity of the ERP can be used to infer the fourth factor. But we don’t usually know three of these factors, so the polarity doesn’t usually tell us anything. Polarity at a given site is meaningful only insofar as most components will have a constant polarity over a given region of the head, and the polarity of a component can help us determine which component we are seeing. But it cannot ordinarily be used to determine whether the component reflects excitation or inhibition.

the negativity from the next neuron, leading to cancellation. Similarly, if one neuron receives an excitatory neurotransmitter and another receives an inhibitory neurotransmitter, the dipoles of the neurons will be in opposite directions and will cancel. However, if the neurons all have a similar orientation and all receive the same type of input, their dipoles will summate and may be measurable at the scalp. This is much more likely to happen in cortical pyramidal cells than in other cell types or in other brain structures, so ERPs mainly arise from the pyramidal cells.

The summation of the individual dipoles is complicated by the fact that the cortex is not flat, but instead has many folds. Fortunately, however, physicists have demonstrated that the summation of many nearby dipoles is essentially equivalent to a single dipole formed by averaging the orientations of the individual dipoles.³ This averaged dipole is called an *equivalent current dipole*. It is important to note, however, that whenever the individual dipoles are more than 90° from each other, they will cancel each other to some extent, with complete cancellation at 180°. For example, the orientation of the neurons in the basal ganglia is largely random, making it difficult or impossible to record basal ganglia activity from the scalp.

An important consequence of these facts about ERP generation is that only a fraction of brain processes will produce a scalp ERP “signature.” To produce a measurable signal on the scalp, the following conditions must be met:

- Large numbers of neurons must be activated at the same time.
- The individual neurons must have approximately the same orientation.
- The postsynaptic potentials for the majority of the neurons must arise from the same part of the neurons (either the apical dendrite or the cell body and basal dendrites).
- The majority of the neurons must have the same direction of current flow to avoid cancellation.

Volume Conduction

When a dipole is present in a conductive medium such as the brain, current is conducted through that medium until it reaches the surface. This is called *volume conduction* and is illustrated in figure 2.2C. I should note, however, that I don't like the term *volume conduction* very much because it might be taken to imply that we are recording charged particles that pass from the neurons all the way to the scalp electrodes. That isn't the way it works. By analogy, when electricity is generated in a power plant and flows through power lines, the electrons don't go all the way from the power plant to your house. Instead, one electron pushes the next one, which pushes the next one, and so forth. Similarly, when a dipole is active in the brain, you don't have to wait for charged particles to move all the way from the dipole to the surface. Instead, a postsynaptic potential in a set of neurons creates an essentially instantaneous voltage field throughout the entirety of the head, with no meaningful delay. And don't forget that you are measuring voltage, which is the potential for current to flow and not the actual flow of current.

Electricity does not just run directly between the two poles of a dipole in a conductive medium, but instead spreads out across the conductor. Consequently, ERPs do not appear only at an electrode located directly above the dipole but are instead picked up by electrodes located all over the head. The high resistance of the skull causes the voltage to be even more widely distributed. Consequently, the scalp distribution of an ERP component is usually very broad.

Figure 2.2C illustrates a very important fact about ERP scalp distributions. For any dipole location, the voltage will be positive over one portion of the scalp and negative over the remainder of the scalp, with an infinitesimally narrow band of zero that separates the positive and negative portions. In many cases, one of these portions will fall over a part of the head where you don't have any electrodes (e.g., the face or the bottom of the brain), so you might not see both sides of the dipole. In other cases, you will be able to see both the positive and negative sides of the dipoles.⁴ The zero band that separates the positive and negative sides of the head will be in a different place for each different dipole, and no single zero band will be present when multiple dipoles are active. Thus, there is no place on the head that consistently has zero voltage (see chapter 5 for additional discussion).

Relationship between Dipoles and Components

An equivalent current dipole represents the summed activity of a large number of nearby neurons. How is this related to the concept of an *ERP component*? We will define the term *ERP component* more carefully later in this chapter, but we can make a simple link to the concept of a dipole at this time. Specifically, when an equivalent current dipole represents the activity of a single functional brain region, this dipole can be considered to be the same thing as an ERP component. The moment-by-moment changes in the magnitude of the dipole (sometimes called the dipole's *source waveform*) constitute the time course of the ERP component. As will be described soon, all of the different dipoles in the brain sum together to give us the complex pattern of positive and negative peaks that we record from our scalp electrodes.

Magnetic Fields

The blurring of voltage caused by the high resistance of the skull can be largely circumvented by recording magnetic fields instead of electrical potentials. As illustrated in figure 2.2D, an electrical dipole is always surrounded by a magnetic field of proportionate strength, and these fields summate in the same manner as voltages. Thus, whenever an ERP is generated, a magnetic field is also generated, running around the ERP dipole. Moreover, the skull is transparent to magnetism, so the magnetic fields are not blurred by the skull,⁵ leading to much greater spatial resolution than is possible with electrical potentials. The magnetic equivalent of the EEG is called the *magnetoencephalogram* (MEG), and the magnetic equivalent of an ERP is an *event-related magnetic field* (ERMF).

As illustrated in figure 2.2E, a dipole that is parallel (*tangential*) to the surface of the scalp will be accompanied by a magnetic field that leaves the head on one side of the dipole and enters back again on the other side. If a highly sensitive probe called a SQUID (superconducting quantum interference device) is placed next to the head, it is possible to measure the magnetic field as it leaves and reenters the head. However, if the dipole is perpendicular to the surface of the head (a *radial* dipole), the magnetic field running around the dipole will not leave the head, and it will be “invisible” to the SQUID. For orientations that are between tangential and radial, the strength of the magnetic field that is recorded from outside the head gets weaker and weaker the more radial the dipole is. Similarly, the strength of the extracranial magnetic field becomes very weak for deep dipoles. Thus, MEG recordings are primarily sensitive to superficial, tangential dipoles.

Because magnetic fields are not as widely dispersed as electrical potentials, they can provide more precise localization. However, as will be discussed in online chapter 14, the combination of ERP and ERMF recordings provides even better localization than ERMF recordings alone. Unfortunately, three factors make magnetic recordings very expensive: the SQUID is expensive; the coolant must be continually replenished; and an expensive magnetically shielded recording chamber is necessary to attenuate the earth’s magnetic field, which is orders of magnitude larger than the MEG signal. Thus, MEG/ERMF recordings are much less common than EEG/ERP recordings.

The Forward Problem and the Superposition of Components on the Scalp

If I tell you the locations and orientations of a set of dipoles in a brain, along with the shape and conductances of the brain, skull, and scalp, then it would be possible for you to use a relatively simple set of equations to compute the distribution of voltage that would be observed for those dipoles. This is called the *forward problem*, and it is relatively easy to solve. In this section, I will spend some time explaining how the forward problem is solved in a little bit of detail, because it will help you to understand exactly how the ERP components generated in the brain become mixed together in the scalp electrodes. This creates the superposition problem, which I described briefly in chapter 1 and which is often the biggest impediment in ERP studies.

Box 2.2

Four Kinds of Math

ERP waveforms are sequences of numbers, so you can't escape a little bit of math if you want to understand ERPs. If you are a "math person," then you are probably looking forward to seeing some mathematical formalisms as you read the book. But if you are not a math person, the last thing you'll want to see is a lot of equations. There will be some equations in the following chapters, but they will be very simple. And I promise not to write something like "As will be obvious from equation 6.4 ..." because I don't usually find that an equation makes something obvious.

I am not a math person. I managed to get through a year of calculus in my freshman year of college, but that's as far as I got. And I remember almost nothing I learned that year. So this book contains no calculus.

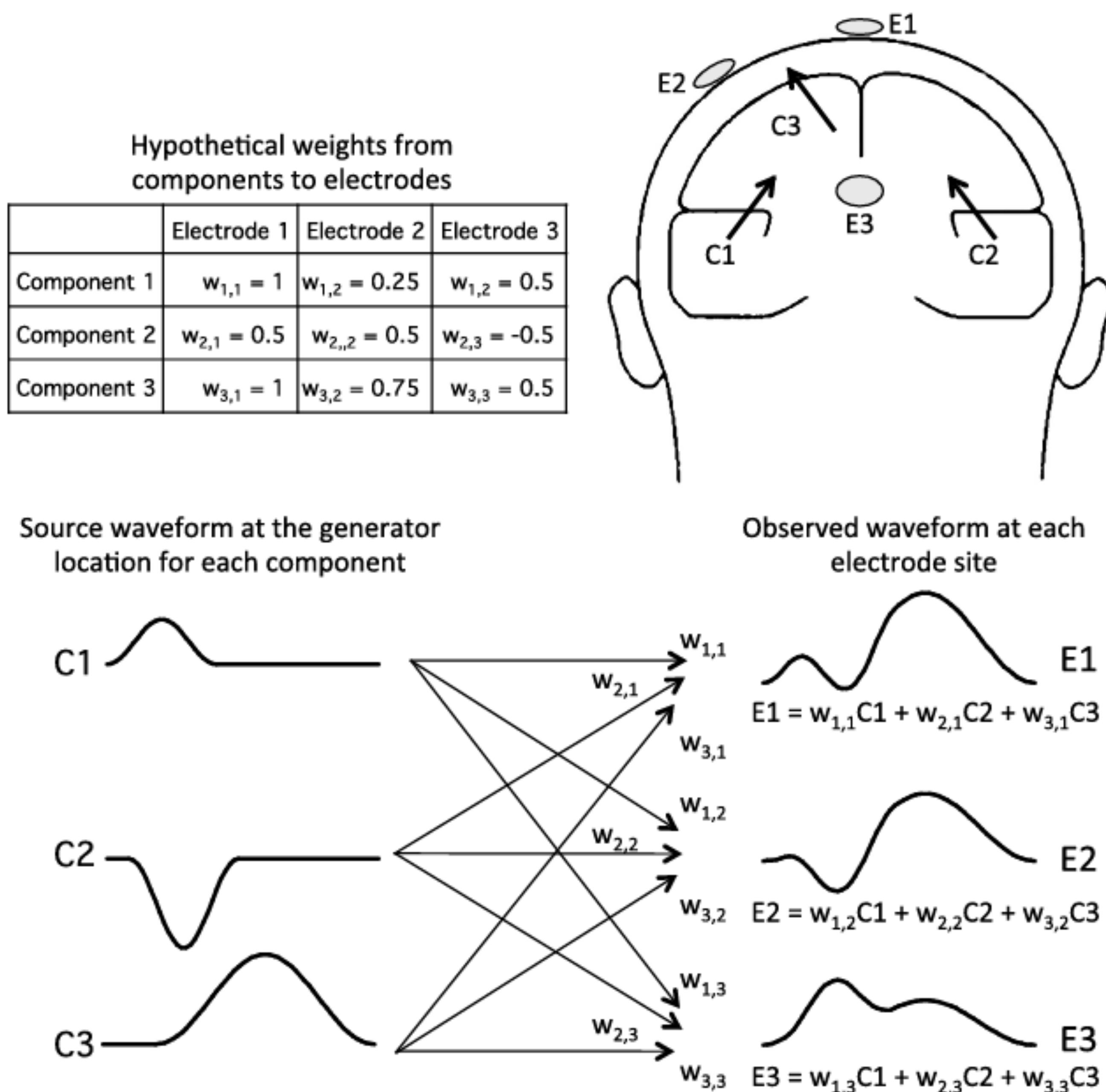
It turns out that you can understand all the key mathematical concepts involved in ERP research without any calculus. In fact, everything I will describe can be boiled down to addition, subtraction, multiplication, and division. If you are not a math person, you can use these four simple mathematical operations to understand things like Fourier analysis, time-frequency analysis, and how filters work. This will require that you spend some time looking at simple equations that combine these four simple operations in interesting ways, but ultimately it's all just arithmetic that anyone can understand.

If you are a math person, I think you will find that boiling things down in this way allows you to find a new appreciation for the logic that underlies the mathematics. And you will probably discover that there are some important things about Fourier analysis, time-frequency analysis, and filtering that you did not fully appreciate before.

Describing the forward problem in detail requires me to introduce a little bit of math, but only a very little bit (see box 2.2).

The forward problem is illustrated in figure 2.3, which shows the ERP waveforms for three hypothetical generator locations. These are called *source waveforms*, and they show the time course of voltage for the components. For any given electrode location on the scalp, a fixed percentage of the source waveform from a given internal generator will propagate to the electrode. That is, X% of the voltage from a given generator will be propagated to a given electrode site, where X has a different value for each combination of internal generator and external scalp electrode. The percentage of the voltage that is propagated will depend on the position and orientation of the generator with respect to the position of the electrode, along with the conductivity of the various tissues within the head. For example, a high percentage of the voltage from a superficial radial dipole will propagate to an electrode on the scalp right over the top of the generator, and a smaller (and inverted) percentage will propagate to an electrode on the opposite side of the head.

It's actually possible to estimate the percentage of propagation from each possible generator location to each electrode site in a given subject by creating a model of the subject's head from a structural MRI scan, combined with normative conductivity values for the different tissues that constitute the head (e.g., brain, skull, scalp). There are software packages that can provide the propagation factors if you provide a structural MRI scan.

**Figure 2.3**

Relation between the underlying component waveforms and the observed scalp waveforms. In this example, three components are present (C_1 , C_2 , C_3), each of which has a source waveform (time course of voltage, shown at the bottom left) and a generator location (represented by the arrows in the head). The contribution of each component waveform to the observed waveform at a given electrode site is determined by a weighting factor that reflects the location and orientation of the generator relative to that electrode, along with the conductivity of the tissues that form the head. The table shows the weighting factors between the three components, and the three electrode sites are given in the table (but note that these are made-up values, not the actual weighting factors from a real head). The observed waveform at a given electrode site (shown at the bottom right) is equal to the sum of each of the component waveforms, multiplied by the weighting factor between each component and that electrode site. The weights are indicated by the w 's on the arrows between the component waveforms and the observed waveforms (e.g., $w_{2,3}$ represents the weighting factor between component 2 and electrode 3). Adapted with permission from Kappenman and Luck (2012). Copyright 2012 Oxford University Press.

The proportion of the voltage that is propagated from a given generator location to a given electrode site is called the *weight* between the generator and the electrode. There is a separate weight for each combination of generator location and electrode site. In figure 2.3, the weights are denoted as $w_{x,y}$, where x is the generator location and y is the electrode site. For example, the weight from generator 2 to electrode 1 is denoted $w_{2,1}$. I just made up the weights shown in figure 2.3—they are not the actual weights. For example, real weights would be much less than 1.0, because only a small proportion of the generator voltage makes it all the way out to the scalp electrodes. The real weights would be provided by a software package on the basis of a subject's structural MRI data. Note that the weights are proportions (between -1 and +1), not percentages.

The “fake” weights shown in figure 2.3 make it easy to see how the waveforms at a given electrode site reflect the weighted sum of the internal underlying components. For example, the waveform at electrode E1 is simply the C1 waveform plus 25% of the C2 waveform plus 50% of the C3 waveform (because the weights from components C1–C3 to electrode E1 are 1.0, 0.25, and 0.50, respectively). If you think this seems very simple, you’re right! The waveform at a given electrode site is always just the weighted sum of all the source waveforms. This simplicity arises from the fact that voltages simply add together in a simple conductor like the human head.

Note that the voltage at a given electrode site is a weighted sum of *all* the underlying components. The weights will be negative on one side of the head and positive on the other, with a narrow band where the weights are zero at the transition between the positive and negative sides of the dipoles. And the weights may be quite small near this band. However, a given electrode site picks up at least some voltage from almost every component in the brain. This means that almost all of the components are mixed together at every electrode site. How many different components are likely to be mixed together in a given experiment? It is difficult to know for sure, but dozens may be present in a typical experiment. For example, evidence for at least 10 different sources was found in the brief period from 50 to 200 ms after the onset of an auditory stimulus in a simple target detection task (Picton et al, 1999), and many more are presumably active when a longer time range is examined and when the subject is engaged in a complex task.

In most cases, we are interested in measuring individual components, not the mixture that we record at a given scalp electrode. Unfortunately, there is no foolproof way to recover the underlying components from the recordings obtained at the scalp. There are many different methods that attempt to recover the underlying components (see box 2.3), but all of them are based on assumptions that are either known to be false or are not known to be true. The mere fact that each of these techniques will arrive at a different solution is an indication that most (or all) of them are incorrect.

As this chapter progresses, we will see why this superposition problem makes life so difficult for ERP researchers. You may find this depressing, but keep in mind that we will eventually discuss a set of strategies for overcoming the superposition problem. And the online supplement to chapter 4 describes some excellent examples of previous studies that have overcome the

Box 2.3
Unmixing the Components

The mixing of underlying components in scalp recordings is such an important problem that many different mathematical procedures have been developed to unmix them. The best known and most widely used procedures are dipole localization methods, principal component analysis, independent component analysis, Fourier analysis, and time-frequency analysis. All of these will be covered in some detail later in the book.

Although these techniques seem very different from each other, they all share a fundamental underlying structure, and it is worth understanding this structure. Specifically, they all assume that the waveforms recorded at the scalp consist of the weighted sum of a set of underlying *basis functions*. However, they make different assumptions about the nature of these basis functions. For example, Fourier analysis assumes that the basis functions are sine waves, but it makes no assumptions about the pattern across the scalp; in contrast, dipole localization methods make no assumptions about the time course of the basis functions, but they assume that the scalp distribution reflects the conductivity of the brain, skull, and scalp. These techniques also differ widely in the mathematical approach that is used to unmix the observed waveforms. However, it is useful to keep in mind that they all assume that the observed waveforms consist of the sum of a relatively small set of basis functions.

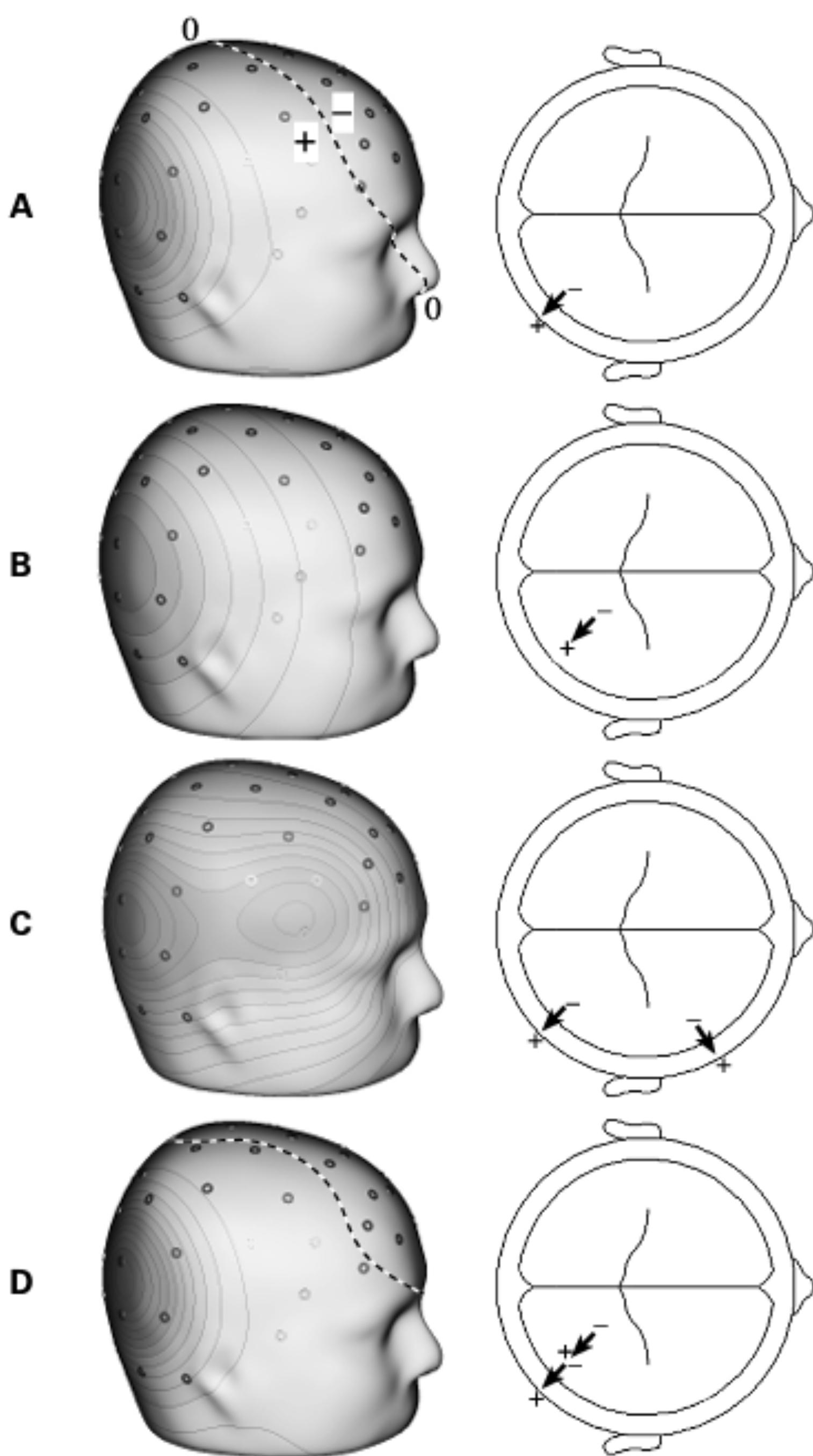
superposition problem and made important contributions to our understanding of the mind and brain.

The Challenges of ERP Localization

This section provides a brief discussion of the challenges involved in localizing ERPs. A more complete discussion is provided in online chapter 14.

As noted in the description of the forward problem, it is relatively easy to compute the distribution of voltage on the scalp if you know the locations and orientations of the dipoles (and have a structural MRI scan). However, if I provide you with an observed voltage distribution from the scalp and ask you to tell me the locations and orientations of the dipoles, you will not be able to provide an answer with 100% confidence. This is the *inverse problem*, and it is what mathematicians call an “ill-posed” or “underdetermined” problem. This simply means that there are multiple different sets of dipoles that can perfectly explain a given voltage distribution, and there is no way to tell which is the correct one. In fact, it has been known for more than 150 years that an infinite number of different dipole configurations can produce any given voltage distribution (Helmholtz, 1853; Nunez & Srinivasan, 2006; see also Plonsey, 1963). It is impossible to know with certainty which one of these configurations is the one that is actually responsible for producing the observed voltage distribution (unless you have other sources of information, such as lesion data).

Figure 2.4 illustrates some of the challenges involved in localizing ERPs. When a single dipole is present just under the skull and points directly outward (a superficial, radial dipole), a very

**Figure 2.4**

Scalp distributions (left) produced by different dipole configurations (right). See the text for descriptions of panels A–D of the figure. Images courtesy of J. Bengson. Reprinted with permission from Luck (2012a). Copyright 2012 American Psychological Association.

focal voltage distribution is observed on the scalp, with the maximum voltage directly over the location of the dipole (figure 2.4A). If this dipole is moved laterally even a small amount (e.g., 1 cm), the voltage distribution will be noticeably different. Consequently, a dipole such as this can be localized quite accurately simply by comparing the observed voltage distribution with the distribution that would be produced by a single hypothetical dipole with various different positions and orientations and selecting the dipole that best fits the observed data. Noise in the data will distort the observed scalp distribution somewhat, but it is still possible to localize a single superficial dipole like the one shown in figure 2.4A with reasonable accuracy as long as the noise is not too large (and assuming you know for certain that it *is* a single superficial dipole). Multiple-dipole configurations also exist that can produce exactly the same distribution of voltage as a single superficial dipole. Thus, we can localize a single superficial dipole with considerable precision (assuming very low levels of noise in the average ERP waveforms), but we cannot know from the scalp distribution that only a single superficial dipole is present.

Now consider the somewhat deeper dipole shown in figure 2.4B. The distribution of voltage over the scalp is broader than that observed with the superficial dipole, and moving the dipole laterally by a given amount won't have as large of an effect on the scalp distribution for the deeper dipole as it would for the superficial dipole. All else being equal, the deeper the dipole, the smaller and more broadly distributed the voltage will be on the scalp, and the less accurately it can be localized. An even more important problem arises in this situation, because it becomes difficult to tell the difference between a deep but focal generator and a superficial generator that extends across a large region of cortex. For example, the error-related negativity has a fairly broad distribution that is consistent with a single deep generator in the anterior cingulate cortex (Dehaene, Posner, & Tucker, 1994), but it is also consistent with the activation of a large patch of superficial cortex.

Figure 2.4C shows a situation in which two dipoles are simultaneously active. Voltages arising from different generators simply sum together, so the scalp distribution of the two simultaneous dipoles is simply equal to the sum of the scalp distributions of the individual dipoles. In this particular example, the two dipoles are both superficial, and they are quite far apart. It would be possible for you to localize the dipoles quite accurately in this situation, assuming that the data were not distorted by much noise and that you already knew that exactly two dipoles were active.

Figure 2.4D shows a different situation in which two dipoles are simultaneously active (the dipoles from figure 2.4A and B). This is a “nightmare scenario” for people who want to localize ERPs, because the scalp distribution of the sum of the two dipoles is nearly indistinguishable from the scalp distribution of the superficial dipole alone. Given even a small amount of noise, it would be impossible to know whether the data were the result of a single superficial dipole or two dipoles that are aligned in this fashion. The problem would still be bad even if the two dipoles were not perfectly aligned. Moreover, imagine an experiment in which these two dipoles were present, and an experimental manipulation led to a change in the amplitude of the deep dipole with no effect in the superficial dipole. It is very likely that an experimental effect of this nature would be attributed to the superficial dipole rather than the deep dipole.

As more and more simultaneous dipoles are added, the likelihood of dipoles aligning in this manner increases, and it becomes more and more difficult to determine how many dipoles are present and to localize them accurately. This problem becomes even worse when the data are noisy. Under these conditions, a set of estimated dipole locations that matches the observed scalp distribution can be quite far from the actual locations.

The examples shown in figure 2.4 are cause for both optimism and pessimism. You should be optimistic because ERPs can be localized accurately if you can be certain that you have a single dipole or that you have two to three dipoles that are not aligned in a way that makes them difficult to localize. But you should also be pessimistic because it will be difficult to localize ERPs unless you *know* that you have a single dipole or that you have two to three dipoles that are not aligned in a way that makes them difficult to localize. Fortunately, there are some things you can do to increase the likelihood that only a single dipole is active (e.g., performing localization on difference waves that isolate a single component).

In many experiments, the number of dipoles could be very large (>10), and localizing ERPs solely on the basis of the observed scalp distribution would be impossible to do with confidence. The only way to localize ERPs in this case is to add external constraints, and this is how existing procedures for localizing ERPs solve the non-uniqueness problem. As will be discussed in detail in online chapter 14, some common procedures allow the user to specify a fixed number of dipoles (Scherg, 1990), whereas other procedures use structural MRI scans and constrain the dipoles to be in the gray matter (Dale & Sereno, 1993; Hämäläinen, Hari, Ilmonieni, Knuutila, & Lounasmaa, 1993) or choose the solution that best minimizes sudden changes from one patch of cortex to the next (Pascual-Marqui, Esslen, Kochi, & Lehmann, 2002). Although each of these methods produces a unique solution, they do not necessarily produce the correct solution. And they may produce quite different solutions, further reducing our confidence that any of them has found the correct solution.

The most significant shortcoming of mathematical procedures for localizing ERPs is that they do not typically provide a well-justified margin of error. That is, they do not indicate the probability that the estimated location falls within some number of millimeters from the actual location. For example, I would like to be able to say that the N2pc component in a particular experiment was generated within 9 mm of the center of the lateral occipital complex and that the probability that this localization is incorrect is less than 0.05. I am aware of no mathematical localization technique that is regularly used to provide this kind of information.⁶ Without a margin of error, it is difficult to judge the credibility of a given localization estimate. In most cases, the strongest claim that can be made is that the observed data are consistent with a given generator location.

Although it is usually impossible to definitively localize ERPs solely on the basis of the observed scalp distributions, this does not mean that ERPs can never be localized. Specifically, ERPs can be localized using the general hypothetico-deductive approach that is used throughout science. That is, a hypothesis about the generator location for a given ERP effect leads to a set of predictions, which are then tested by means of experiments. One prediction, of course, is that

the observed scalp distribution will be consistent with the hypothesized generator location. However, confirming this prediction is not usually sufficient to have strong confidence that the hypothesis about the generator location is correct. Thus, it is important to test additional predictions. For example, one could test the prediction that damage to the hypothesized generator location eliminates the ERP component. Indeed, researchers initially hypothesized that the P3 component was generated in the hippocampus, and this hypothesis was rejected when experiments demonstrated that the P3 is largely intact in individuals with medial temporal lobe lesions (Polich, 2012). Similarly, one could predict that an fMRI experiment should show activation in the hypothesized generator location under the conditions that produce the ERP component (see, e.g., Hopf et al., 2006). It is also possible to record ERPs from the surface of the cortex in neurosurgery patients, and this can be used to test predictions about ERP generators (see, e.g., Allison, McCarthy, Nobre, Puce, & Belger, 1994). This hypothesis-testing approach has been quite successful in localizing some ERP components.

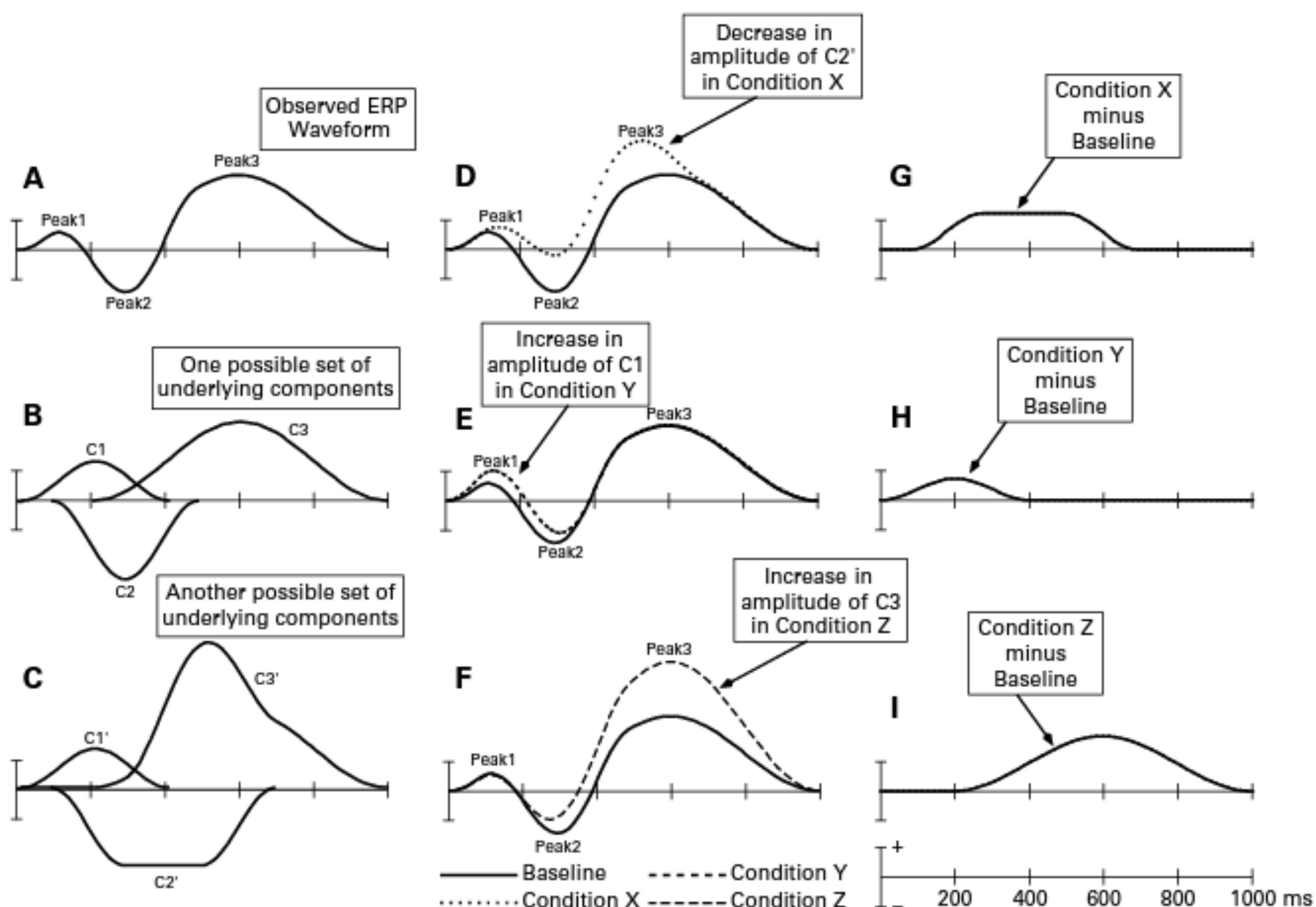
As was discussed in chapter 1, the main advantages of the ERP technique are its high temporal resolution, its relatively low cost, its noninvasiveness, and its ability to provide a covert and continuous measure of processing. Spatial resolution is simply not one of the strengths of the ERP technique, and it is therefore sensible that this technique should mainly be used in studies designed to take advantage of its strengths and that are not limited by its weaknesses.

Waveform Peaks versus Underlying ERP Components

Now that you understand how the underlying components become mixed together in scalp electrodes—and why it is so difficult to recover the underlying components from the observed scalp waveforms—it is time to consider why this is such a big problem in most ERP studies. In this section, I will show a set of simple artificial waveforms that demonstrate how the superposition problem can easily lead to misinterpretations of ERP data, along with a set of “rules” for avoiding these misinterpretations. In general, the goal of this section is to get you to look beyond the ERP waveforms that you have recorded from the scalp and think about the underlying components that might give rise to these surface waveforms. Even though you cannot usually localize the underlying components, you can learn to make educated guesses about the underlying components from the observed scalp waveforms.

The term *ERP component* will be described more formally later in this chapter. For now, you can just think of a component as electrical activity within a given region of the brain that reflects some neural process occurring in that region, which then propagates to our scalp electrodes.

To understand the underlying “deep structure” of a set of ERP waveforms, the first thing you need to do is understand how the peaks in the observed ERP waveforms can provide a misleading representation of the underlying components. To make this clear, I created some simple simulated components using Excel and then summed them together to create simulated scalp ERP waveforms. The results are shown in figure 2.5. This is a busy and complicated figure, but

**Figure 2.5**

Examples of the complications that arise when underlying components sum together to form an observed ERP waveform. Panels B and C show two different sets of underlying components that sum together to produce the observed waveform shown in panel A. Panels D, E, and F show three simulated experiments in which one component differs between a baseline condition and three comparison conditions. In panel D, component C2' is decreased in condition X compared to the baseline condition. In panel E, component C1 is increased in condition Y compared to the baseline condition, which creates an apparent shift in the latencies of both peak 1 and peak 2. In panel F, component C3 is increased in condition Z relative to the baseline condition, influencing both the amplitude and the latency of peak 2. Panels G, H, and I illustrate difference waves for conditions X, Y, and Z, respectively.

the next several sections will walk you through the different parts. This is probably the most important figure in the whole book, so it's worth taking your time and understanding each panel of the figure.

Voltage Peaks Are Not Special

Our eyes are naturally drawn to the peaks in a waveform, but the peaks often encourage incorrect conclusions about the underlying components. This is illustrated in panels A and B of figure 2.5, which show how three very reasonable components sum together to create the ERP waveform that we observe at the scalp. If you look carefully, you can see how the peaks in the observed waveform do a poor job of representing the underlying components. First, notice that the first positive deflection in the observed waveform (panel A) peaks at 50 ms, whereas the first underlying component (C1 in panel B) peaks at 100 ms. Similarly, the third underlying component (C3 in panel B) begins at 100 ms, but there is no obvious sign of this component in the observed waveform until approximately 200 ms.

It is natural for the human visual system to focus on the peaks in the waveform. However, the points in an ERP waveform where the voltage reaches a maximally positive or maximally negative value do not usually have any particular physiological or psychological meaning, and they are often completely unrelated to the time course of any individual underlying component. The peaks in the observed waveform are a consequence of the mixture of components, and they typically occur at a different time than the peaks of the underlying components. For example, the latency of a given peak in the observed waveform may differ across electrode sites (because of the different weights from the underlying components at the different electrode sites), whereas an underlying component has exactly the same time course at every electrode site (because the voltage propagates instantaneously to all electrodes). Sometimes the peak in the observed waveform occurs at the same time as the peak in an underlying component (e.g., when the underlying component is much larger than the other components). However, even in these cases it is not clear that the peak of activity tells us anything special about the underlying process. That is, theories of cognition or brain processes do not usually say much about when a process peaks. Instead, these theories usually focus on the onset of a process, the duration of the process, or the integrated activity over time (see, e.g., Pashler, 1994; Usher & McClelland, 2001).

This leads to our first and most important “rule” about interpreting ERP data:

Rule 1: Peaks and components are not the same thing. There is nothing special about the point at which the voltage in the observed waveform reaches a local maximum.

In light of this fundamental rule, I am always amazed at how often peak amplitude and peak latency are used to measure the magnitude and timing of ERP components. These measures often provide a highly distorted view of the amplitude and timing of the underlying components. Chapter 9 will describe better techniques for quantifying ERP data that do not rely on peaks.

Peak Shapes Are Not the Same as Component Shapes

Panel C of figure 2.5 shows another set of underlying components that also sum together to equal the ERP waveform shown in panel A. These three components are labeled C1', C2', and C3'. From the single observed waveform in panel A, there is no way to tell whether it was actually created from components C1, C2, and C3 in panel B or from C1', C2', and C3' (or from some other set of underlying components). There are infinitely many sets of underlying components that could sum together to produce the ERP waveform in panel A (or any other ERP waveform).

If the observed waveform in panel A actually consisted of the sum of C1', C2', and C3', the peaks in the observed panel would be a very poor indicator of the shapes of the underlying components. For example, the relatively short duration of peak 2 in panel A bears little resemblance to the long duration of component C2' in panel C. If you saw a waveform like panel A in an actual experiment, you probably wouldn't guess that a very long-duration negative component like C2' was a major contributor to the waveform.

This leads to our second rule:

Rule 2: It is impossible to estimate the time course or peak latency of an underlying ERP component by looking at a single ERP waveform—there may be no obvious relationship between the shape of a local part of the waveform and the underlying components.

In a little bit, we will talk about how difference waves can sometimes be used to determine the shape of an underlying ERP component. You can also gain a lot of information by looking at the waveforms from multiple scalp sites because the time course of a given component's contribution to one electrode site will be the same as the time course of its contribution to the other electrode sites (because ERPs propagate to all electrodes instantaneously).

The Time Course and Scalp Distribution of an Effect

Panels D–F of figure 2.5 show three simulated experiments in which a “baseline” condition is compared with three other conditions, named X, Y, and Z. The waveform for the baseline condition is the same as that shown in panel A, which could be the sum of either components C1, C2, and C3 from panel B or components C1', C2', and C3' from panel C. I am calling this a “baseline” condition only because I am using it for comparison with conditions X, Y, and Z.

In the simulated experiment shown in panel D, we are assuming that the observed waveform for the baseline condition is the sum of components C1', C2', and C3' and that component C2' is decreased by 50% in condition X relative to the baseline condition. However, if you just saw the waveforms in this panel, and you didn't know the shapes of the underlying components, you might be tempted to conclude that at least two different components differ between the baseline condition and condition X. That is, it looks like condition X has a decrease in the amplitude of a negative component peaking at 300 ms and an increase in the amplitude of a positive component peaking at 500 ms. You might even conclude that condition X had a larger positive component peaking at 100 ms. This would be a very misleading set of conclusions about the

underlying components because the effect actually consists entirely of a decrease in the amplitude of a single, broad, negative component ($C2'$). These incorrect conclusions arise from our natural inclination to assume that the peaks in the observed waveform have a simple and direct relationship to the unknown underlying components. This leads us to conclude that the increased amplitude in peak 3 in panel D reflects an increase in the amplitude of a long-latency positive component, when in fact it is a result in of a decrease in the amplitude of an intermediate-latency negative component.

Panel E shows a simulated experiment comparing the baseline condition with condition Y. This time, we're assuming that the underlying components are $C1$, $C2$, and $C3$ (rather than $C1'$, $C2'$, and $C3'$). Condition Y is the same as the baseline condition except for an increase in the amplitude of component $C1$. However, if you saw these observed waveforms, you might be tempted to conclude that condition Y has an increase in the amplitude of an early positive component peaking at 100 ms followed by a decrease in a negative component that peaks at 300 ms.

Similarly, panel F shows a simulation in which the amplitude of component $C3$ is increased in condition Z compared to the baseline condition. Although only this late positive component differs across conditions, the observed waveform for condition Z appears to exhibit a reduction of a negative component at 300 ms as well. However, this is just a consequence of the fact that component $C3$ overlaps in time with component $C2$.

In panels D–F, a change in the amplitude of a single component caused a change in the amplitude of multiple peaks, making it likely that the researcher will falsely conclude that multiple underlying components differ across conditions. I have seen this general pattern of waveforms countless times, and people often misinterpret the effects in exactly this way. This leads to our third rule:

Rule 3: An effect during the time period of a particular peak may not reflect a modulation of the underlying component that is usually associated with that peak.

Difference Waves as a Solution

Difference waves can often be used to provide a better estimate of the time course and scalp distribution of the underlying components. Difference waves are a very simple concept: You simply take the voltage at each time point in one ERP waveform and subtract the voltage from a different ERP waveform at the corresponding time points. The result gives you the difference in voltage between the two waveforms at each time point. In an oddball experiment, for example, you can subtract the frequent-trial waveform from the rare-trial waveform (rare-minus-frequent), and the resulting difference wave will show the difference in voltage between these trial types at each point in time (see, e.g., figure 1.4 in chapter 1). The difference wave from a given electrode site is analogous to a difference image in an fMRI experiment, except that differences are computed at each time point in an ERP difference wave and at each voxel in an fMRI difference image.

Panels G–I of figure 2.5 show difference waves from the three simulated experiments shown in panels D–F. The baseline waveform has been subtracted from the waveforms for conditions

X, Y, and Z. These difference waves are very helpful in showing us the nature of the experimental effects. They make the time course of the effects very clear, showing that they are different from the time course of the peaks in the observed waveforms. Indeed, under these conditions—in which the experimental effects consist entirely of a change in the amplitude of a single underlying component—the difference waves reveal the time course and scalp distribution of the underlying component that differs across conditions. That is, if you compare the difference wave in panel G to the underlying components in panel C, you will see that the difference wave has exactly the same time course as component C2'. And because the difference waves in these examples subtract away everything except the one component that differs across conditions, the difference waves will have the same topography as the underlying component.

You cannot be guaranteed that a difference wave will contain only a single component. For example, the rare-minus-frequent difference waves from the oddball paradigm that were discussed in chapter 1 (see figure 1.4) contained both an N2 wave and a P3 wave. However, there is a good chance that you will have a single component in your difference waves if you compare conditions that are very subtly different.

How can you know if a broad effect in a difference wave consists of a change in a single underlying component or a sequence of two or more components? First, you can look at the scalp distribution of the difference wave, collapsed across the entire duration of the effect, to see if the scalp distribution is too complex to be explained by a single dipole. Second, you can compare the scalp distributions of the early and later parts of the difference wave. If they are the same, then you probably have a single component; if they are different, then you have at least two components. Difference waves are discussed in more detail later in this chapter.

Interactions between Amplitude and Latency

Although the amplitude and latency of an underlying component are conceptually independent, they can become confounded when the underlying components become mixed together at the scalp. For example, panel F of figure 2.5 illustrates the effect of increasing the amplitude of component C3. Because component C3 overlaps with peak 2, this change in the amplitude of component C3 causes a shift of approximately 20 ms in the peak latency of peak 2 in condition Z relative to the baseline condition. This leads to our next rule:

Rule 4: Differences in peak amplitude do not necessarily correspond with differences in component size, and differences in peak latency do not necessarily correspond with changes in component timing.

This is a somewhat depressing rule, because the most obvious virtue of the ERP technique is its temporal resolution, and it is unpleasant to realize that estimates of component timing can be distorted by changes in the amplitude of temporally overlapping components. Keep in mind, however, that this sort of temporal distortion mainly happens when a large change in a large component overlaps with a smaller component, leading to a small latency change in the smaller component. If you think carefully about a given effect and spend some time looking at the

difference waves, you should be able to determine whether the latency differences could plausibly be a result of amplitude changes (or vice versa). In addition, chapters 3 and 4 will discuss how this problem can be completely avoided by looking at the onset time of a difference wave.

Distortions Caused by Averaging

In the vast majority of ERP experiments, the ERP waveforms are isolated from the background EEG by means of signal averaging. It's tempting to think of averaging as a process that simply attenuates the nonspecific EEG, allowing us to see what the single-trial ERP waveforms look like. However, to the extent that the single-trial waveform varies from trial to trial, the averaged ERP may provide a distorted view of the single-trial waveforms, particularly when component latencies vary from trial to trial. This is illustrated in figure 2.6. Panel A illustrates three single-trial ERP waveforms (without any EEG noise), with significant latency differences across trials, and panel B shows the average of those three single-trial waveforms. The averaged waveform differs from the single-trial waveforms in two significant ways. First, it is smaller in peak amplitude. Second, it is more spread out in time. As a result, even though the waveform in panel B is the average of the waveforms in panel A, the onset time of the averaged waveform in panel B reflects the onset time of the earliest single-trial waveform and not the average onset time. In other words, the onset time in the average waveform is not equal to the average of the single-trial onset times (see chapter 8 and online chapter 11 for additional discussion). This leads to our next rule:

Rule 5: Never assume that an averaged ERP waveform directly represents the individual waveforms that were averaged together. In particular, the onset and offset times in the averaged waveform represent the earliest onsets and latest offsets from the individual trials or individual subjects that contribute to the average.

Fortunately, it is often possible to measure ERPs in a way that avoids the distortions created by the averaging process. For example, the area under the curve in the averaged waveform shown in figure 2.6A is equal to the average of the area under the single-trial curves in figure 2.6B. Similarly, it is possible to find the time point that divides the area into two equal halves, and this can be a better measurement of latency than peak measures. These methods are described in detail in chapter 9.

Comparisons across Experiments

It can be very difficult to determine whether an ERP effect in one experiment reflects the same underlying component as an ERP effect in another experiment. For example, imagine that you've conducted an experiment in which you recorded ERPs from bilingual speakers of two languages, Xtrinqua and Kirbish, focusing on the N400 component elicited by words in these two languages. You found that the N400 was larger (more negative) for proper nouns in Xtrinqua than for proper nouns in Kirbish. You therefore conclude that processing proper nouns requires more work in Xtrinqua than in Kirbish. However, this assumes that the effect you have observed actually reflects a change in the same N400 component that was observed in prior studies of semantic

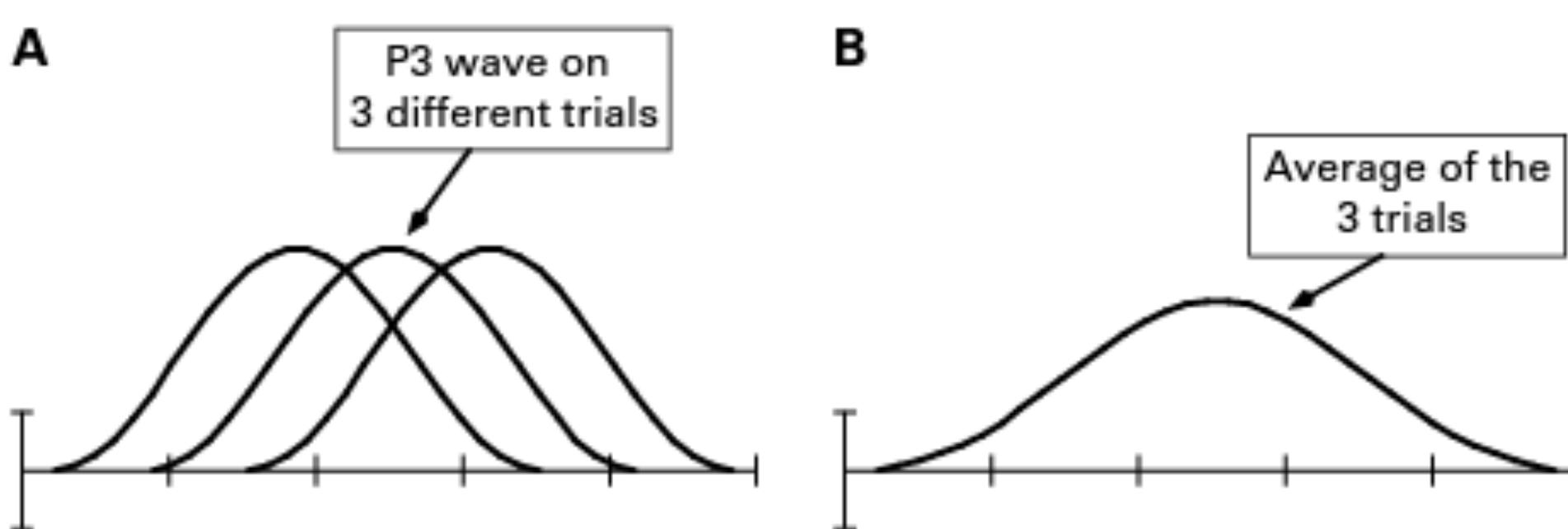
**Figure 2.6**

Illustration of the distortions in an averaged ERP waveform that arise from trial-to-trial latency variation. (A) A single-trial component at three different latencies, representing trial-to-trial variations in timing. (B) The average of these three single-trial waveforms. The average waveform is broader than the single-trial waveforms and has a smaller peak amplitude. In addition, the onset time and offset time of the average waveform reflect the earliest onset and latest offset times, not the average onset and offset times.

integration. Perhaps you are instead seeing a smaller P3 rather than a larger N400. Because the P3 is related to the amount of cognitive resources devoted to processing a stimulus, this would suggest that it is actually easier to process Xtrinqua proper nouns than Kirbish proper nouns. This is nearly the opposite of the conclusion that you would draw if the effect was an increase in N400 amplitude rather than a decrease in P3 amplitude. This type of problem has come up many times in the language ERP literature (see review by Swaab, Ledoux, Camblin, & Boudewyn, 2012), and analogous problems arise in other ERP domains. Scalp distribution can sometimes be used to rule out a given component, but this only works when the scalp distributions of two components are easily distinguished (which is not the case for P3 and N400).

This leads to our final rule of ERP interpretation:

Rule 6: An ERP effect observed in one experiment may not reflect the same underlying brain activity as an effect of the same polarity and timing in previous experiments.

Solutions to this problem will be described in the final section of this chapter.

Some General Comments about the Component Structure of ERP Waveforms

The six rules of ERP interpretation presented in this chapter have been violated in a very large number of published ERP experiments (including some of my own papers!). Violations of these rules significantly undermine the strength of the conclusions that can be drawn from these experiments, so you should look for violations when you read ERP papers. If you are relatively new to the ERP technique, it would be worth looking back through old ERP papers that you've previously read and identifying any violations of these rules. This will be good practice, and it may cause you to reevaluate your conclusions about some prior findings.

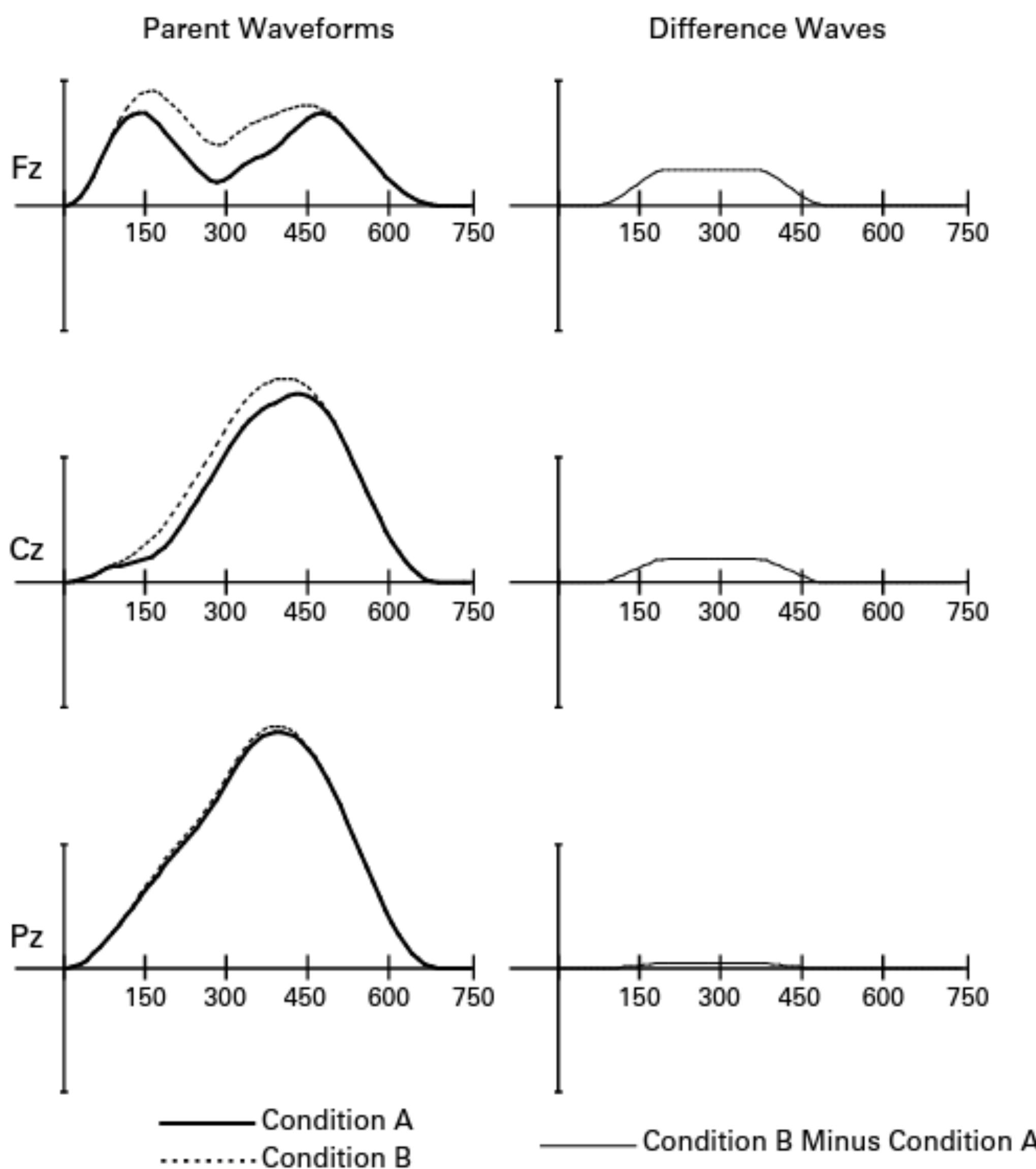
This section of the book can be depressing, because it focuses on the most difficult challenges that face ERP researchers. But don't despair! Chapter 4 provides some strategies for overcoming these challenges.

Also, many of these problems are not nearly as bad when you consider the waveforms recorded at multiple scalp sites. Because the ERP waveforms at different scalp sites reflect exactly the same components, but scaled by different weighting factors (as shown in figure 2.3), you can rule out many alternative explanations by looking at the data from multiple electrodes. Consider, for example, the simulated experiment shown in figure 2.7 (which is based on the C1', C2', and C3' components in figure 2.5). In this imaginary experiment, ERPs were recorded from the Fz, Cz, and Pz electrode sites in condition A and condition B. If you just saw the data from the Cz electrode site, you might conclude that the P3 wave was larger and earlier for condition B than for condition A. However, you can rule out this conclusion by looking at the scalp distribution of the waveforms (both the parent waveforms and the difference waves). From the whole set of data, you can see that the P3 wave is largest at Pz, a little smaller at Cz, and quite a bit smaller at Fz (which is the usual pattern). The experimental effect, however, is largest at Fz, smaller at Cz, and near zero at Pz, and it extends from approximately 150 to 450 ms. Both the timing and the scalp distribution of the experimental effect are inconsistent with a modulation of the P3 wave and are more consistent with a frontal N2 effect. You should also note that the scalp distribution of the effect is the same throughout the time course of the effect, suggesting that it really does consist of a single component that extends from approximately 150 to 450 ms, rather than consisting of separate early and late effects. Thus, a careful examination of the data from multiple electrode sites, including the difference waves, will allow you to avoid making naïve mistakes in interpreting your data. Moreover, as you gain more experience with ERPs, you will be able to do a better job of figuring out the underlying components (see box 2.4).

Although I am not a big fan of mathematical techniques for determining the underlying components in ERP experiments, they can certainly be useful for generating plausible hypotheses and for showing that some hypotheses are inconsistent with the data. For example, if you were to perform source localization on the difference waves shown in figure 2.7 (with many more electrode sites, of course), this would make it clear that the effect is not consistent with the likely generators of the P3 wave. Source localization would also make it clear that a single generator source could account for both the early and late portions of the effect. Thus, even though you should be skeptical about the three-dimensional coordinates of the effect that would be provided by source localization techniques, these techniques are still valuable for testing more general hypotheses about the component structure of your data. This is especially true if you combine source localization with the use of difference waves (see box 2.5 for an example of my own rather lame attempt at using math to understand the underlying component structure of an experiment).

Difference Waves as a Tool for Isolating Components

In this section, I want to spend some additional time discussing the value of difference waves in addressing the problems caused by the mixing of components in our observed ERP waveforms. As shown in figures 2.5 and 2.7, difference waves can sometimes reveal the time course

**Figure 2.7**

Simulated experiment in which three underlying components (similar to components C1', C2', and C3' in figure 2.5) propagate to electrode sites Fz, Cz, and Pz with different weighting factors. The amplitude of a negative-going component (C2') is reduced in condition B compared to condition A. Because the weighting from this component is greatest at Fz, intermediate at Cz, and smallest at Pz, the difference between conditions A and B is greatest at Fz, intermediate at Cz, and smallest at Pz. This can be seen in the parent waveforms from the individual conditions (left column) and in the difference waves (right column). Note that because the difference waves were formed by subtracting condition A from condition B rather than vice versa, the difference waves show a positive deflection rather than a negative deflection.

Box 2.4

Experience Matters

It appears that people can learn to make good inferences about the underlying components when examining ERP data. Many years ago, Art Kramer conducted a study in which he created artificial ERPs from a set of realistic underlying components (Kramer, 1985). He then gave these waveforms (from multiple conditions at multiple electrode sites) to eight graduate students and two research associates who had between 1 and 10 years of experience with ERPs. There was a strong effect of experience: the experienced ERP researchers were able to figure out the nature of the underlying components, whereas the people who were new to ERPs could not reliably determine the underlying component structure of the data. Of course, there are limits to this conclusion. It was based on a small sample of researchers from one particular lab who were shown one type of data, and there is no guarantee that a given experienced researcher will always (or even usually) reach a correct interpretation. When writing a journal article, you couldn't cite your years of experience with ERPs as evidence that your interpretation of the underlying component structure is correct. However, once you gain enough experience with ERPs (and learn to apply everything you have read in this chapter), you should be able to figure out the likely pattern of underlying ERP components from a given experiment with some confidence.

and scalp distribution of an underlying ERP component. A well-constructed difference wave (i.e., one based on a well-controlled and relatively subtle experimental manipulation) will always contain fewer components than the *parent* waveforms from which the difference wave was constructed. And fewer components means less opportunity for confusion due to the mixing of components.

Given that I'm a big fan of difference waves, it's a bit ironic that the first published use of difference waves to assess the component structure of an experiment were in a paper by Risto Näätänen and his colleagues (Näätänen, Gaillard, & Mantysalo, 1978) that was designed to question the interpretation of a previous study by my graduate mentor, Steve Hillyard (Hillyard, Hink, Schwent, & Picton, 1973). However, Jon Hansen and Steve Hillyard responded with a paper in which they embraced the difference wave approach and fought back with their own difference waves (Hansen & Hillyard, 1980).

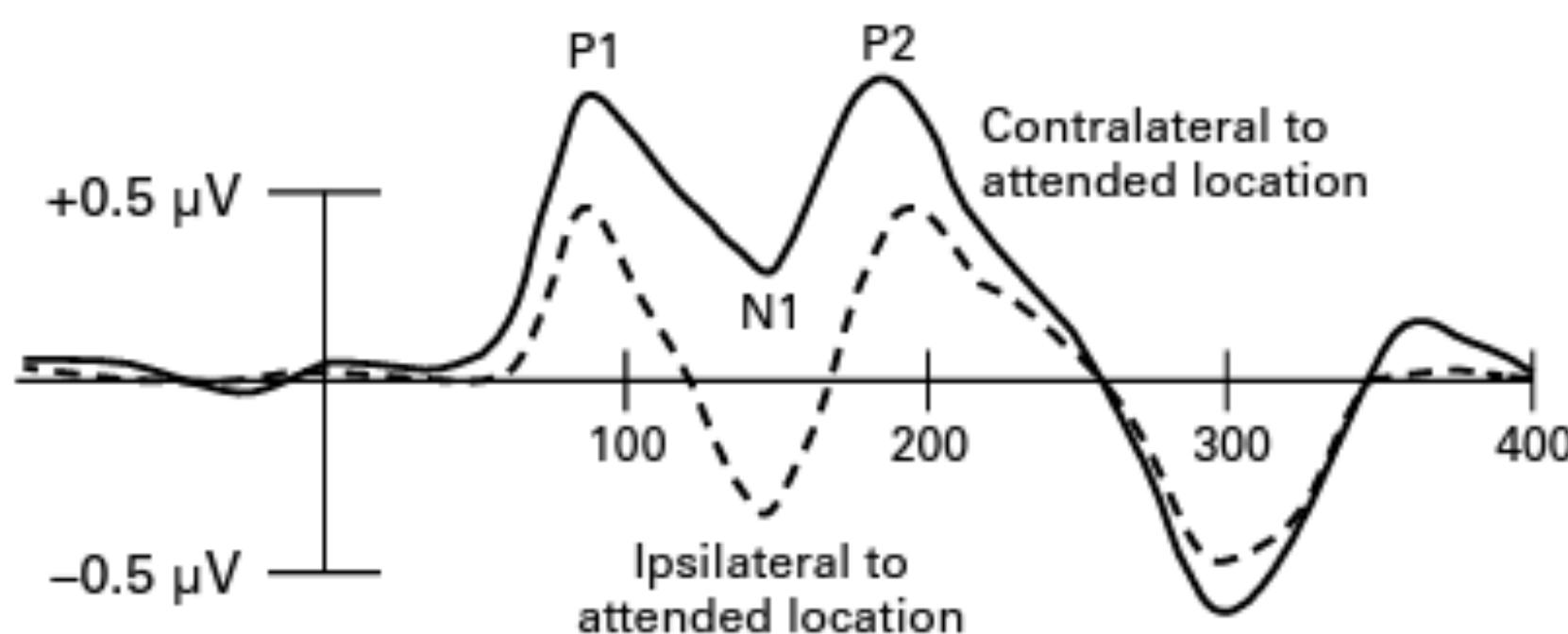
The logic behind difference waves is very simple. As shown in figure 2.3, the ERP waveform at a given electrode site is the weighted sum of a set of underlying source waveforms (recall that *source waveform* is just another term for the time course of an ERP component at the generator site). If two conditions differ in some of the source waveforms and not in others, then the difference wave created by subtracting one condition from the other will eliminate the source waveforms that are identical in the two conditions, making it possible to isolate the components that differ. This is completely reasonable because ERPs from different sources simply sum together.

As described earlier in this chapter, figures 2.5 and 2.7 show how difference waves can help reveal the time course of an effect. To see how difference waves can help reveal the scalp

Box 2.5

My Own Experience with Mathematical Approaches

When I was making the simulated waveforms shown in figure 2.7, I realized that these waveforms looked a lot like the data from one of the first experiments I conducted in graduate school (Luck, Heinze, Mangun, & Hillyard, 1990). In this experiment, subjects attended either to the left or the right side of a bilateral visual display, and we wanted to see if the P1 and N1 components would be larger over the hemisphere contralateral to the attended side (relative to the ipsilateral hemisphere). The waveforms are shown in the illustration that follows.



As you can see, we found that the waveform was more positive over the contralateral hemisphere from approximately 80 to 200 ms, including the time ranges of the P1, N1, and P2 components. From visual inspection of the data, it was not clear whether this broad attention effect was a single component or a modulation of separate P1 and P2 components. Because I thought of myself as a statistics hotshot at that time, I decided that I would use principal component analysis (PCA) to answer this question. PCA produced nice results indicating that the attention effect consisted of modulations of separate P1 and P2 components. However, the more I thought about the results, the more I realized that they could be an artifact of PCA assumptions. Also, Steve Hillyard was not as impressed by fancy mathematical techniques as I was (for reasons that I now appreciate). Our compromise was to put the PCA results into an appendix in the published paper. Fortunately, the conclusions of the paper did not hinge on the PCA results.

distribution of an effect, consider the N170 component shown in figure 2.8. As discussed in chapter 1, the N170 is larger in response to pictures of faces than pictures of non-face objects such as cars (for a review, see Rossion & Jacques, 2012). If you simply measure the scalp distribution at 170 ms for trials on which faces were presented, the distribution will reflect face-specific processing plus all of the nonspecific activity that is present at 170 ms. However, if you first construct face-minus-nonface difference waves and then measure the scalp distribution, you will see the topography of face-specific brain activity, uncontaminated by the nonspecific activity.

Bruno Rossion's lab conducted a study in which they examined the development of the N170 (Kuefner, de Heering, Jacques, Palmero-Soler, & Rossion, 2010), and this study showed the importance of measuring scalp distributions from difference waves. In this study, ERPs were recorded from children between 4 and 17 years of age while they viewed images of faces,

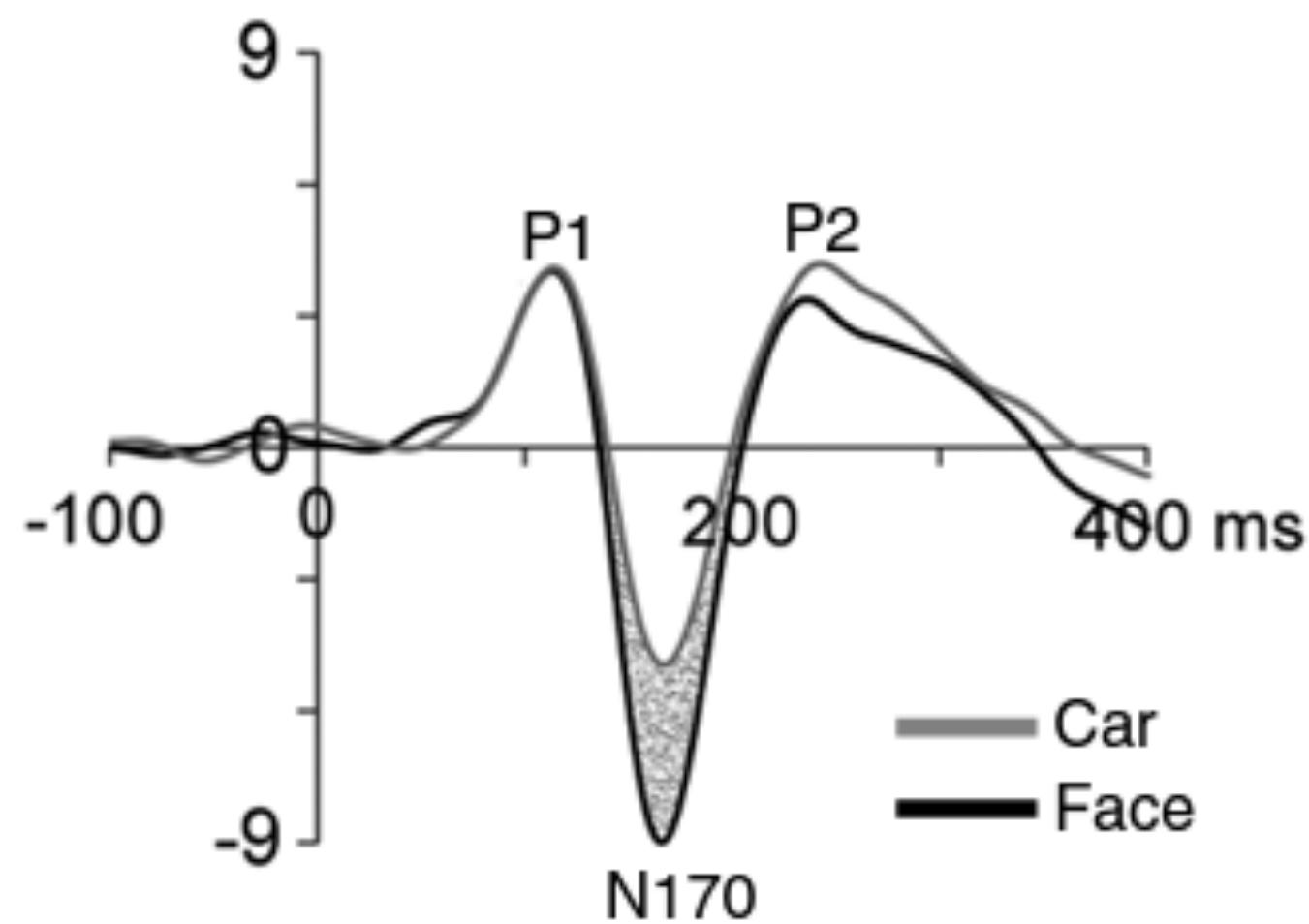


Figure 2.8

ERPs elicited over visual cortex by car and face stimuli, with the N170 effect highlighted by the shaded region. Adapted with permission from Rossion and Jacques (2012). Copyright 2012 Oxford University Press.

scrambled faces, cars, and scrambled cars. When the scalp distribution was measured at the time of the N170 component from the ERPs elicited by faces, the scalp distribution changed markedly over the course of development. Previous studies had found similar effects and concluded that the neuroanatomy of face processing changed during this period of development. However, these changes in scalp distribution could instead be a result of distortion from other ERP components that are also present at 170 ms and that change in relative amplitude over the course of development. To test this, Kuefner et al. constructed difference waves in which they subtracted the ERPs elicited by scrambled faces from the ERPs elicited by intact faces, removing any activity that was not face specific. The scalp distribution of the resulting difference wave was virtually identical from 4 to 17 years, indicating that the face-specific processing had the same neuroanatomical locus across this developmental period.

Difference waves can also help you avoid a visual illusion that sometimes causes people to misperceive ERP effects. Figure 2.9 shows a simulated experiment in which this illusion arises. In this experiment, the difference between condition A and condition B is exactly the same at the Fz and Cz electrode sites. However, because this effect is superimposed on the steeply rising edge of the P3 wave at the Cz site, the effect looks smaller at Cz than at Fz. The difference wave shows that the effect is exactly the same at these sites. The illusion arises because our visual system tends to focus on the distance between two curves along an axis that is approximately perpendicular to the curves (e.g., the horizontal difference between the condition A and condition B waveforms at the Cz site). However, the difference in amplitude at a given time point is the vertical distance between the two waveforms at that time point. The steeper the slope of two overlaid waveforms, the more our visual system focuses on the horizontal difference between the waveforms rather than the vertical distance, and this leads us to underestimate the true

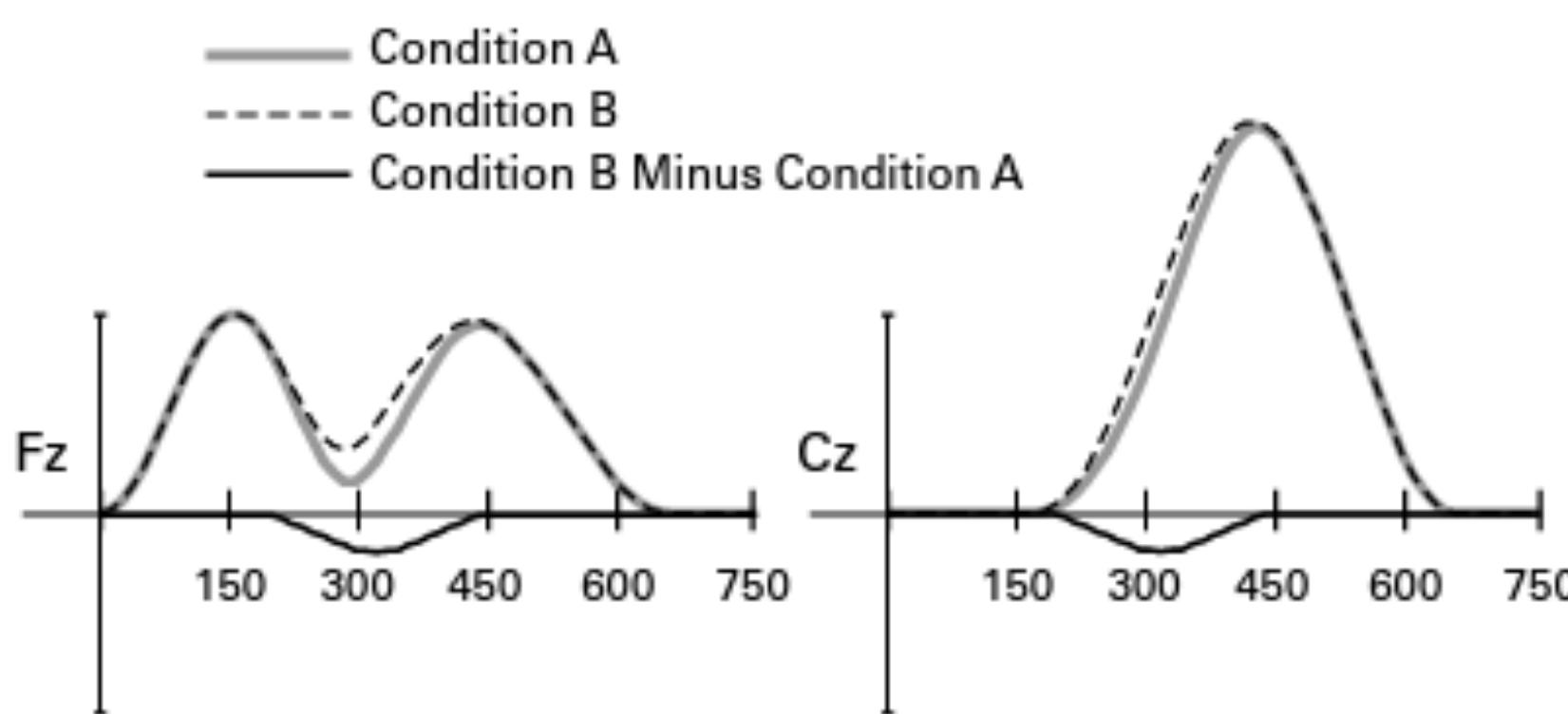


Figure 2.9

Visual illusion in which the effect of an experimental manipulation appears to be smaller when it is superimposed on a steeply sloped ERP wave. In this example, the difference between conditions A and B is exactly the same size at the Fz and Cz scalp sites (as shown by the difference waves). However, because this difference is superimposed on a steeply sloped P3 wave at the Cz site, but not at the Fz site, the effect looks smaller at Cz than at Fz when judged by looking at the parent waveforms rather than by looking at the difference waves.

difference in amplitude between the two conditions. Once you look at the difference waves in figure 2.9, you can see that the difference between conditions A and B is exactly the same at Fz and Cz in this experiment. This is yet one more advantage of difference waves.

Although difference waves are an incredibly useful way to isolate the underlying components from the mixture of components in the parent waveforms, they do have some limitations. First, you are making implicit assumptions about the nature of the difference between conditions A and B when you choose whether to compute A minus B or to compute B minus A. Consider, for example, the simulated experiment shown in figure 2.7. The difference waves in this experiment make it look as if a frontal positive component is larger in condition B than in condition A, but the effect was actually created (in my simulations) by decreasing the amplitude of a frontal negative component. Thus, you need to be careful about the implicit assumptions you are making about the direction of the effect when you subtract one waveform from another.

Another important issue is that the difference wave will always be noisier than the parent waveforms. To understand why this is true, consider what happens when you add two waveforms rather than subtract two waveforms. When you add two waveforms, A and B, some of the noise in A cancels out noise in B, but mostly the noise increases rather than canceling, and the overall noise in the summed waveform increases (although it doesn't double). It turns out that exactly the same thing happens when you subtract one waveform from the other instead of adding the two waveforms. The reason for this is that the noise at a given point in the waveform can be either positive-going or negative-going, so it doesn't matter whether you add or subtract pure noise (on average). The end result will be a noisier waveform. However, this is not usually a problem in practice. If you do a statistical analysis on the difference waves, the *p* value may be exactly the same as if you did the analysis on the parent waveforms (this is true for linear measures, such as mean amplitude, as will be discussed in chapter 9). For example, if you have

waveforms for conditions A and B in two groups of subjects, you could do a two-way analysis of variance (ANOVA) on the mean amplitude from 400 to 600 ms with factors of condition and group. Alternatively, you could measure the mean amplitude from 400 to 600 ms in difference waves formed by subtracting the condition B waveforms from the condition A waveforms and then do a *t* test comparing these values for the two groups. The *p* value from this *t* test will be identical to the *p* value from the group × condition interaction in the ANOVA.

What Is an ERP Component?

A Conceptual Definition

We are now ready to provide a formal definition of *ERP component*. In the early days of ERP research, a component was defined primarily on the basis of its polarity, latency, and general scalp distribution. For example, the P3a and P3b components were differentiated on the basis of the earlier peak latency and more frontal distribution of the P3a component relative to the P3b component (Squires, Squires, & Hillyard, 1975). However, polarity, latency, and scalp distribution are superficial features that don't really capture the essence of a component. For example, the peak latency of the P3b component may vary by hundreds of milliseconds depending on the difficulty of the target–nontarget discrimination (Johnson, 1986), and the scalp distribution of the auditory N1 wave depends on the pitch of the eliciting stimulus in a manner that corresponds with the tonotopic map of auditory cortex (Bertrand, Perrin, & Pernier, 1991). Even polarity may vary: the C1 wave, which is generated in primary visual cortex, is negative for upper-field stimuli and positive for lower-field stimuli due to the folding pattern of this cortical area (Clark, Fan, & Hillyard, 1995). The difficulty of using latency, scalp distribution, and polarity to identify components becomes even greater when multiple components are mixed together at a given electrode site. For example, the N2 elicited by an oddball is superimposed on top of P2 and P3 waves, so the overall voltage during the N2 time range is often positive.

I do not mean to imply that you should not use latency, scalp distribution, and polarity to help identify ERP components. In fact, these factors are extremely useful in determining whether a given experimental effect reflects, for example, a P3a or P3b component. However, these factors do not *define* an ERP component; they are merely superficial consequences of the nature of the component. Instead, a component should be defined by the factors that are intrinsic to the component. For example, an influential discussion of ERP components by Manny Donchin, Walter Ritter, and Cheyne McCallum noted that, “an ERP component is a subsegment of the ERP whose activity represents a functionally distinct neuronal aggregate” (Donchin, Ritter, & McCallum, 1978, p. 353). My own, very similar definition is this:

Conceptually, an ERP component is a scalp-recorded neural signal that is generated in a specific neuroanatomical module when a specific computational operation is performed.

By this definition, a component may occur at different times under different conditions, as long as it arises from the same module and represents the same computational operation (e.g.,

the encoding of an item into working memory in a given brain area may occur at different delays after the onset of a stimulus because of differences in the amount of time required to identify the stimulus and decide that it is worth storing in working memory). The scalp distribution and polarity of a component may also vary according to this definition, because the same cognitive function may occur in different parts of a cortical module under different conditions (e.g., when a visual stimulus occurs at different locations and therefore stimulates different portions of a topographically mapped area of visual cortex). It is logically possible for two different cortical areas to accomplish exactly the same cognitive process, but this probably occurs only rarely and would lead to a very different pattern of voltages, and so this would not usually be considered a single ERP component (except in the case of mirror-image regions in the left and right hemispheres).

Although this definition captures the essence of an ERP component, it is completely useless as an operational definition. That is, because we are recording the mixed signals from multiple generators at every electrode site, we have no way of directly determining the contribution of each neuroanatomical module to the observed waveform. And we don't ordinarily know the computational operation reflected by a scalp voltage. So we cannot use this definition to determine which component is being influenced by a given experimental manipulation or to determine whether the same component is active in multiple experiments. However, this definition is useful insofar as it helps to formalize what we believe is going on under the skull.

You should also keep in mind that many well-known ERP components (e.g., N400, mismatch negativity, P3b) are probably not individual components according to this definition. That is, multiple brain areas that are carrying out similar but somewhat different computations likely contribute to these scalp-recorded voltage deflections (see, e.g., the chapters on these components in Luck & Kappenman, 2012b). As research progresses, we gain the ability to subdivide these multicomponent conglomerations into their parts. In some cases, this leads to new names for the individual components. For example, the “N2 component” that was identified in early ERP studies turned out to consist of a set of many different individual components that can be separated by means of various experimental manipulations, and these individual components (sometimes called *subcomponents*) were given new names (e.g., *anterior N2*, *N2c*, *N2pc*). In some cases, these subcomponents have been divided even further (see, e.g., Luck, 2012b). In other cases, we still use a single name to refer to something that likely consists of multiple similar components, especially when we don't yet have good methods for isolating the individual subcomponents (e.g., *N400* is still used even though there are probably at least two neurally distinct subcomponents that contribute to it).

An Operational Definition

Manny Donchin provided an alternative definition that is more like an operational definition: “A component is a set of potential changes that can be shown to be functionally related to an experimental variable or to a combination of experimental variables” (Donchin et al., 1978, p. 353). They summarized this idea more compactly by saying that, “an ERP component is a source

of *controlled, observable variability*" (Donchin et al., 1978, p. 354). This is very similar to the idea, illustrated in figures 2.5 and 2.7, that difference waves can be used to isolate ERP components. Donchin et al. noted that electrode site is one key source of variability, which corresponds to the idea that changes in the scalp distribution of a difference wave between the early and late parts of the effect mean that different components are active in the early and late parts of the effect. Thus, by this definition, any consistent difference between the waveforms in different experimental conditions is an ERP component. This is a clear and easily applied operational definition of *ERP component*.

However, there are two shortcomings of this operational definition. First, it ignores the key idea that an ERP component is generated by a specific neuroanatomical module (or "neural aggregate" to use the terminology of Donchin et al., 1978). That is, even if the scalp distribution of an experimental effect did not vary over time or over the conditions of a particular experiment, the scalp distribution might clearly indicate that more than one dipole was active (e.g., if the scalp distribution did not follow a simple dipolar pattern). In such a case, we would want to conclude that multiple components were active, but tightly interlinked. And we could reasonably assume that these components could be shown to be functionally distinct in future experiments.

Second, Donchin's operational definition focuses exclusively on *experimental* (controlled) manipulations, completely ignoring variations that are spontaneous or correlational in nature. To take an obvious example of why this is an unnecessary limitation, consider a case in which a patient group and a control group differ in terms of the voltage between 150 and 250 ms over lateral frontal electrode sites. In this case, there must be at least one ERP component (according to my conceptual definition) that varies between these groups. This is just as convincing as an experimentally controlled within-subject difference in the voltage between 150 and 250 ms over lateral frontal electrode sites. Subtler examples are also important to consider. For example, if you look at the distribution of voltage over the scalp from moment to moment as the EEG spontaneously varies, it is possible to use advanced statistical techniques (e.g., principal component analysis, independent component analysis) to isolate systematic patterns of covariation across electrode sites that reflect spontaneous fluctuations in the amplitude of underlying ERP components.

When taking these factors into consideration, we can update Donchin's operational definition as follows:

An ERP component can be operationally defined as a set of voltage changes that are consistent with a single neural generator site and that systematically vary in amplitude across conditions, time, individuals, and so forth. That is, an ERP component is a source of systematic and reliable variability in an ERP data set.

This should not be taken to imply that we cannot isolate a component until we have determined its generator. If the scalp distribution of a putative component has a complex structure that is inconsistent with a single dipole, then this should not be considered a single component. But if

it has a simple structure that is consistent with a single dipole (or with a pair of mirror-symmetric dipoles in the left and right hemispheres), then we can provisionally accept it as a single component.

How Can We Identify Specific ERP Components?

Now that we have both a conceptual definition and an operational definition for ERP components, we can consider in more detail a question that has come up many times in this chapter: when we see differences in the ERPs between different conditions or different groups in a given study, how can we determine which underlying components are responsible for these differences?

This is still not an easy question to answer, because our operational definition applies to a single data set and cannot be used to determine if the components (sources of consistent variability) that we see in one experiment are the same as the components that were observed in another experiment. Scalp distributions can be helpful, especially when derived from difference waves to eliminate the contribution of other overlapping components. If the scalp distribution of the effect in the new experiment is the same as the scalp distribution observed in previous experiments, then this is one piece of evidence in favor of it being the same component; if the scalp distribution is different, then this is evidence against the hypothesis. In practice, this can provide strong evidence *against* the hypothesis that two effects reflect the same component, but it cannot provide strong evidence *in favor* of the hypothesis. First, it is often impossible to provide direct quantitative comparisons of scalp distributions across experiments (e.g., when you are comparing your data with published data from another lab), and this will make it difficult to rule out the possibility that the scalp distribution in the new experiment is subtly but significantly different from the scalp distribution in a previous experiment. Second, concluding that two scalp distributions are the same requires accepting the null hypothesis, and conclusions of this sort are almost always weak. Source localization techniques can also provide evidence about whether generator sources are the same for ERP effects observed in different experiments, but this is essentially equivalent to asking whether the scalp distributions are the same and therefore has the same limitations.

We can also ask whether the component that we isolate in one experiment shows the same pattern of interaction with other factors as the component that was isolated in prior experiments. For example, if we believe we are seeing a P3b effect, we can ask whether it interacts with the probability of the stimulus category (see Luck et al., 2009; and see Experiment 4 in Vogel, Luck, & Shapiro, 1998). This can be a useful adjunct to comparisons of scalp distribution, but it requires a very solid theory of the interactions that should occur. Some of the clearest cases involve combinations of experimental factors and scalp distribution; as will be described in chapter 3, the N2pc, contralateral delay activity (CDA), and LRP components are isolated by computing a difference wave in which the waveforms recorded over the ipsilateral hemisphere (relative to an attended location or a response hand) are subtracted from the waveforms recorded

over the contralateral hemisphere. These components can be very easily isolated from other ERP components, and they have been particularly useful for testing precise hypotheses about attention, working memory, and response selection.

In general, the difficult problem of identifying ERP components is solved in the same way that every other difficult problem in cognitive neuroscience is solved: with converging evidence. If you make a slight change in an experimental paradigm and you find the same effects as before (in terms of latency and scalp distribution), it is very likely that you have isolated the same underlying ERP components. If you then make a very large change in the paradigm, and now you find a very different latency or a somewhat different scalp distribution, you have to do some further research to determine whether you are still looking at the same component. If the latency is quite different, you can look for other evidence that the timing of the relevant process has changed. If the scalp distribution is a little different, you can look at whether the scalp distribution changes over the time course of the effect, suggesting that you now have two components contributing to the effect. If the scalp distribution is approximately the same as in your prior research, you can run additional experiments to see if the effect interacts with other manipulations in a way that is predicted by your hypothesis about the nature of the underlying component. You could also ask whether subject-to-subject differences in the scalp distribution of your new experimental effect are correlated with subject-to-subject differences in your previous effect.

The bottom line is that it is more difficult to isolate and identify specific ERP components than people typically realize, but this challenge can be overcome if you think carefully about the problem and come up with clever ways to test your hypotheses. Chapter 4 will describe a variety of strategies for overcoming this challenge, including circumventing the problem entirely by designing experiments that do not depend on identifying a specific ERP component.

Suggestions for Further Reading

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