

5 Basic Principles of ERP Recording

Overview

This chapter describes how electrodes, amplifiers, filters, and analog-to-digital converters work together to record the EEG. The main goal of this chapter is to help you record clean data so that your results are valid and statistically significant.

The first section of this chapter will describe why clean data are so important. We will then discuss how EEG amplifiers work and why you need both a ground electrode and a reference electrode (in most systems). This includes a discussion of how to choose a reference electrode location and how to re-reference your data offline. We will then discuss how electrodes work and how the impedance of the electrode–skin connection can have an enormous impact on the quality of your data and the probability that your effects will be statistically significant. We will then finish the chapter by discussing how the continuous EEG signal is amplified and then converted into a set of discrete voltage samples that can be stored in your computer and why filters must be applied to your data prior to this conversion.

This chapter provides information that will be relevant if you are deciding what kind of EEG recording system to purchase for your laboratory. However, I have not tested every system on the market, and I have not done extensive side-by-side comparisons of different systems, so I will not recommend specific systems. Nonetheless, I will provide some useful information that you can use when evaluating different systems. Box 5.1 provides financial disclosures that you may want to read when you consider my advice.

The Importance of Clean Data

Before I get into the details of how to record the EEG, I want to convince you that it is worthwhile to spend some significant time and effort making sure that you are recording the cleanest data possible. This is the reason in a nutshell: The cleaner your data are, the fewer trials you will need per subject and the fewer subjects you will need to obtain clear and reliable results in a given experiment. If you don't need as many trials and subjects in each experiment, you can run more experiments per year that yield publishable results. By recording cleaner data, you can

Box 5.1

Money

Whenever someone publishes a book or journal article that includes information or data that you might use in making decisions about spending money, you should ask whether the author has any financial incentives that might lead to intentional or unintentional biases. I am therefore disclosing my (meager) financial interests that are related to ERPs so you can decide if I might be biased.

I receive honoraria for providing Mini ERP Boot Camp workshops at universities, conferences, and industry sites. I receive royalties from publishers for books, such as this one (although this is no way to get rich!).

My laboratory uses EEG recording systems manufactured by BioSemi but has not received any free or discounted equipment or any other financial considerations from BioSemi or from any other manufacturers. The UC-Davis ERP Boot Camp was given electrode caps and a small amount of money by Cortech Solutions, the U.S. distributor for BioSemi. The ERP Boot Camp has also received financial support from several other vendors of ERP recording and analysis systems, including Brain Products GmbH, EasyCap GmbH, and Advanced Neuro Technologies, and software has been provided for the ERP Boot Camp by Compumedics Neuroscan, Megis GmbH, and Brain Products GmbH. The cash donations from these companies have been used to support Boot Camp activities (e.g., group meals). I receive no personal income from any manufacturers or distributors of ERP-related products. I don't think I have any financial incentives that might bias my advice, but now you can decide for yourself.

publish more (and better) papers. This will also increase the likelihood that you will get a great postdoc/faculty position, large grants, awards, fame, and fortune. If you're not interested in publishing a lot of high-quality journal articles, then go ahead and record noisy data. But if you would like to have a successful career and make important contributions to science, then you will want to record clean data. This may seem obvious, but I often find that people spend much more time on applying fancy analyses to their data than on making sure the data they are analyzing is clean.

The background EEG obscures the ERPs on individual trials, and the ERPs are isolated from the EEG noise by means of averaging across multiple trials. As you average together more and more trials, the amount of residual EEG noise in the averages will become progressively smaller, and it is therefore crucial to include a sufficient number of trials in your ERP averages. However, increasing the number of trials eventually has diminishing returns because the effect of averaging on noise is not linearly proportional to the number of trials; instead, the noise decreases as a function of the square root of the number of trials in the average. As a result, you won't be able to cut the noise in half by doubling the number of trials. In fact, doubling the number of trials decreases the noise only about 30%, and you have to quadruple the number of trials to reduce the noise by 50%. This will be discussed in more detail in chapter 8.

It should be obvious that you can quadruple the number of trials only so many times before your experiments will become absurdly long, so increasing the number of trials is only one part of the solution. The other part is to reduce the noise before it is picked up by the electrodes.

Much of the noise in an ERP recording arises not from the EEG, but from other biological signals such as skin potentials and from nonbiological electrical noise sources in the environment. It is possible to reduce these sources of noise directly. In fact, if you spend a few days tracking down and eliminating these sources of noise, the resulting improvement in your averaged ERPs could be equivalent to doubling the number of trials for each subject. This initial effort will be well rewarded in every experiment you conduct.

In addition to tracking down noise sources and eliminating them before they contaminate your recordings, it is possible to reduce noise by the use of data-processing techniques such as filtering. As will be discussed in chapter 7, these techniques are essential in ERP recordings. However, it is important not to depend too much on postprocessing techniques to “clean up” a set of noisy ERP data because these techniques are effective only under limited conditions and because they almost always distort the data in significant ways. This leads us to an important principle that I call *Hansen’s axiom*:

Hansen’s axiom There is no substitute for good data.

The name of this principle derives from Jon Hansen, who was the technical guru in Steve Hill-
yard’s lab when I was a graduate student at UCSD. As Jon put it in the documentation for a set
of artifact rejection procedures:

There is no substitute for good data. It is folly to believe that artifact rejection is going to transform bad data into good data; it can reject occasional artifactual trials allowing good data to be better. There is no way that artifact rejection can compensate for a subject who consistently blinks in response to particular events of interest or who emits continuous high-amplitude alpha activity. In other words, data that are consistently noisy or have systematic artifacts are not likely to be much improved by artifact rejection. (J. C. Hansen, unpublished software documentation)

Jon made this point in the context of artifact rejection, but it applies broadly to all postprocessing procedures that are designed to clean up the data, ranging from averaging to filtering to independent component analysis. Some postprocessing procedures are essential, but they cannot turn bad data into good data. You will save a great deal of time in the long run by eliminating electrical noise at the source, by encouraging subjects to minimize bioelectric artifacts, and by designing experiments in a way that maximizes the size of the effects relative to the amount of noise.

Online chapter 16 describes a practical approach for finding and eliminating sources of electrical noise in your laboratory. However, you need to understand how the noise is picked up by your recording system before you can effectively eliminate it. A key goal of this chapter is to provide you with this understanding.

Active, Reference, and Ground

Before I can discuss noise in detail, I need to describe one of the most basic aspects of ERP recording; namely, the use of three electrodes (active, reference, and ground) to record the signal

from a single scalp site. These three electrodes are combined to provide a single *channel* of EEG. The reference electrode plays a particularly important role that is not always appreciated by ERP researchers. I will provide a fairly detailed description of how the reference electrode works, because this is an absolutely fundamental aspect of EEG/ERP recordings. If you don't fully understand referencing, you won't understand the signal that you are recording. So bear with me as I describe the details of active, reference, and ground electrodes. Note that all of the following information is relevant even if your system does referencing in software rather than during the recording.

Voltage as a Potential between Two Sites

As described in chapter 2, voltage is the potential for current to move from one place to another (if you did not read the section “Basic Electrical Concepts” at the beginning of chapter 2, this would be a good time to go back and read that section). As a result, there is no such thing as a voltage at a single electrode.

Consider, for example, a typical 120-V household electrical outlet, which has two main terminals. The voltage measurement of 120 V represents the potential for current to move between the two terminals, and it doesn't make sense to talk about the voltage at one terminal in isolation. For example, you could touch one terminal without being shocked (assuming you weren't touching any other conductors), but if you touch both terminals at the same time, you will allow the outlet's potential to be realized as a strong current that passes from one terminal through your body into the other terminal. Similarly, you can never record the voltage at a single scalp electrode. Rather, the EEG is always recorded as a potential for current to pass from one electrode (called the *active* electrode) to some other specific place. This “other specific place” is usually a *ground* electrode (see box 5.2 if you'd like to know why this is called the “ground”).

Although voltage is always recorded between two sites and there is no such thing as a voltage at a single electrode site, we can use the term *absolute voltage* to refer to the potential between a given active site and the average of the rest of the head (because physics dictates that the average of the EEG activity across the entire surface of the head must be 0 μ V). This allows us to use some very simple math to describe how the active and ground electrodes work. We will use *A* to refer to the absolute voltage at the active electrode (i.e., the potential between the active electrode and the average of the scalp), and we will use *G* to refer to the absolute voltage at the ground electrode (i.e., the potential between the ground electrode and the average of the scalp). The potential between the active electrode and the ground electrode is simply the difference between these two absolute electrodes. In other words, the voltage recorded between an active site and a ground site is simply $A - G$. Note that neural activity will be present in both *A* and *G*, not just in *A*, and that anything that is equivalent in *A* and *G* will be subtracted away.

There is a practical problem that arises in the design of an EEG amplifier: To create a working amplifier, the ground electrode must be connected to a *ground circuit*, which is necessarily connected to other parts of the amplifier that generate electrical noise. This noise—which is an inevitable fact of electrical circuits—is present in the *G* signal but not in the *A* signal. Conse-

Box 5.2

Ground and Earth

You've probably heard the term *ground* used in the context of electrical systems, but most people don't know that this term originated from the actual ground (i.e., the dirt that covers much of the planet). Specifically, in household electrical systems, a metal stake is driven deep into the ground beneath the house and serves as an important reference point for electrical devices. To distinguish between the term *ground* as it is used in electrical circuits and the stake driven into the ground under a house or other building, I will use the term *earth* to refer to the stake that is driven into the physical ground.

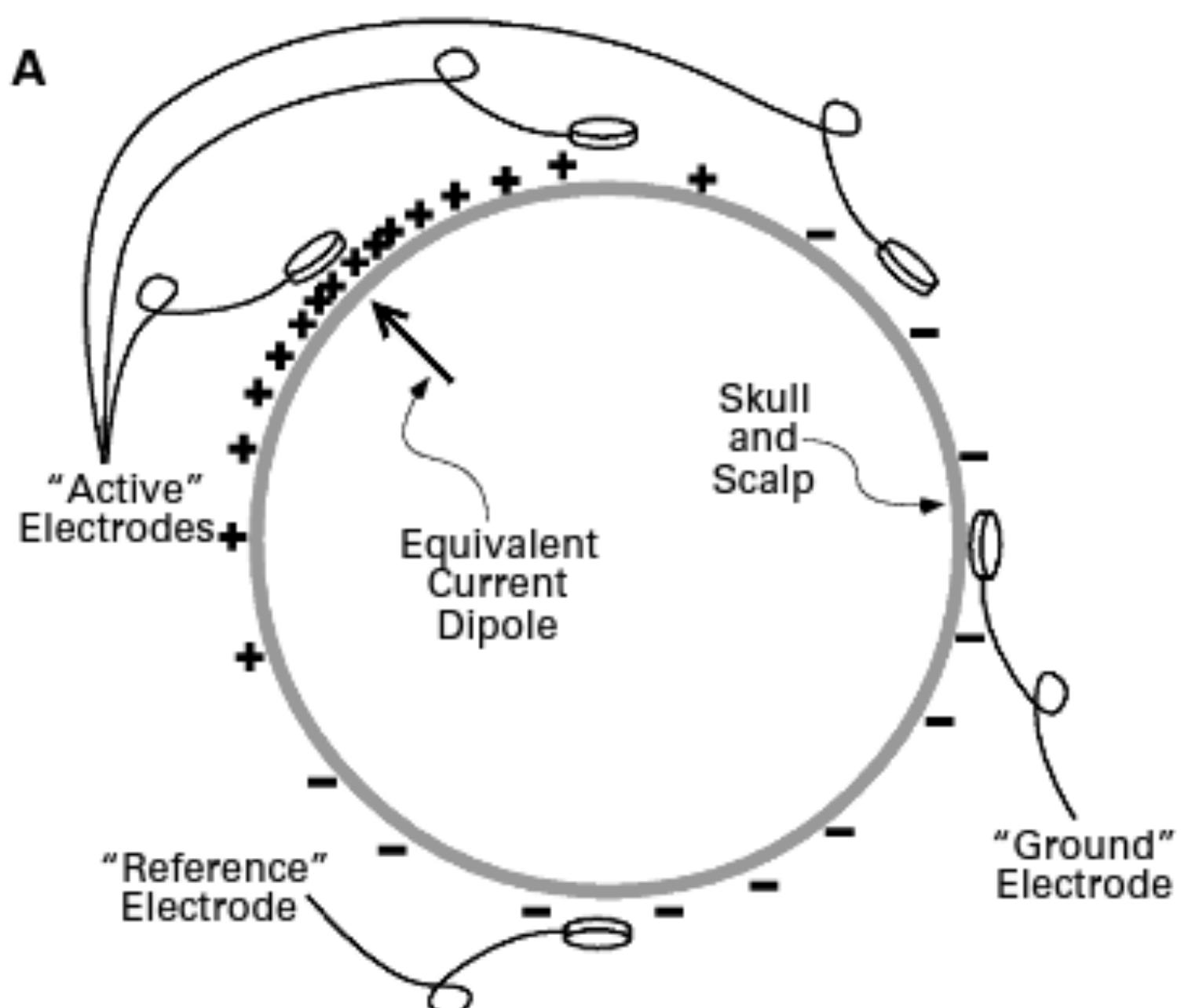
The earth is used in electrical systems, in part, to avoid the buildup of large static electrical charges between electrical devices inside a building and the rest of the world. If, for example, lightning strikes your house, the large current from the lightning will be discharged into the earth. The "ground pin" in a standard electrical outlet is therefore connected to the earth. The term *ground* is now used more generally to refer to a common reference point for all voltages in a system, whether or not this reference point is actually connected to a stake in the dirt, and this is how I will use this term. The term *common* is also sometimes used as a synonym for *ground*.

If we measured the electrical potential between an electrode on a subject's scalp and a stake driven into the earth, the voltage would reflect any surplus of electrical charges that had built up in the subject (assuming the subject was not touching a conductor that was connected to earth), and this static electricity would obscure any neural signals. We could put an electrode somewhere on the subject's body that was connected to earth, and this would cause any static electricity in the subject to be discharged into the earth, eliminating static differences and making it easier to measure changes in neural signals over time. However, it is dangerous to directly connect a subject to earth, because the subject might receive a shock if touched by an improperly grounded electrical device (like a button box used to collect behavioral responses). Thus, EEG amplifiers create a virtual ground that is used as a reference point but is not directly connected to earth. The virtual ground of the EEG amplifier is connected to a ground electrode located somewhere on the subject, and you record the voltage between each active electrode and this ground electrode.

quently, the measured potential between A and G will contain this noise along with electrical activity picked up from the scalp.

The Reference Electrode

As illustrated in figure 5.1A, EEG recording systems typically solve the problem of noise in the ground circuit by using *differential amplifiers*. With a differential amplifier, a *reference electrode* (R) is used along with the active (A) and ground (G) electrodes. The amplifier records the potential between A and G (which is equal to A – G) and the potential between R and G (which is equal to R – G). The output of the amplifier is the difference between these two voltages ([A – G] – [R – G]). This is equivalent to A – R (because the Gs cancel out), so any noise in G will be removed because it is the same for A – G and R – G. In other words, electrical noise from the amplifier's ground circuit will be the same for the A – G and R – G voltages and will therefore be eliminated by the (A – G) – (R – G) subtraction.



Voltage is measured between Active and Ground (A - G)

Voltage is measured between Reference and Ground (R - G)

Output is difference between these voltages

$$[A - G] - [R - G] = A - R$$

It's as if the ground does not exist

Any noise (or signals) in common to A and R will be eliminated

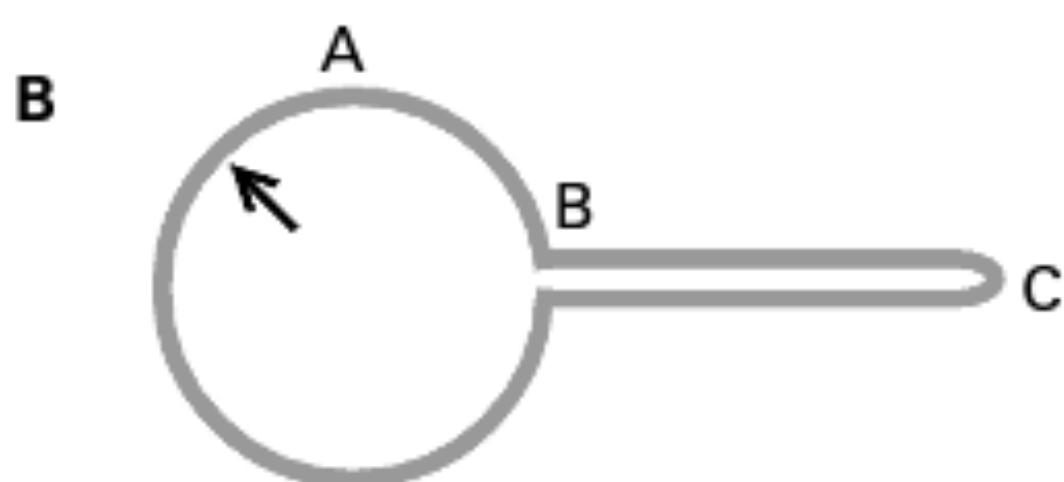


Figure 5.1

Active and reference electrodes. (A) Example of an equivalent current dipole (arrow) inside a spherical head, with the resulting surface voltages ("+" and "-" for positive and negative) on the surface. The recorded voltage will be the difference between the absolute voltage at the active and reference electrodes. (B) Example of the use of a distant reference source. If the active electrode is at point A, it will not matter whether point B or point C is used as the reference, because the absolute voltage at point C will be approximately the same as at point B despite its distance.

The output of a differential amplifier is equivalent to the electrical potential between the active and reference electrodes ($A - R$), as if the ground electrode does not exist (although a good electrical connection for the ground electrode is necessary for the amplifier to work correctly). Why, then, do we need a ground electrode? As mentioned in the previous paragraph, when voltage is initially measured between two electrodes, one of the two electrodes must be connected to the amplifier's ground circuit, and this circuit picks up noise from the amplifier circuitry. There is no way to record the voltage directly between A and R without connecting R to the ground circuit (in which case it would simply be the ground electrode). Thus, most systems use a differential amplifier to cancel out the noise in the ground circuit.

The electrical potential between the subject's body and the amplifier's ground circuit is called the *common mode* voltage (because it is in common with the active and reference electrodes). To achieve a clean EEG recording, this common mode voltage must be completely subtracted away. Although the subtraction seems like a perfect solution when it is written out as an equation (as in figure 5.1), the subtraction will not be perfect because the equation is implemented in physical electronic circuitry. For example, if the $A - G$ signal is amplified a little more strongly than the $R - G$ signal, the subtraction will not be perfect, and some of the noise in the ground circuit will remain in the amplifier's output. The ability of an amplifier to subtract away the common mode voltage accurately is called *common mode rejection*, and it is usually measured in decibels (dB; see the glossary). A good EEG amplifier will have a common mode rejection of at least 70 dB. As we will discuss in a little bit, electrode impedances can impact the common mode rejection.

Note that some systems work a little differently, and one of these (the BioSemi ActiveTwo EEG system) is described in box 5.3.

Box 5.3

The BioSemi ActiveTwo System

The BioSemi ActiveTwo system works a little bit differently from most EEG recording systems. First, instead of a single ground electrode, it includes a *common mode sense* (CMS) electrode and a *driven right leg* (DRL) electrode. CMS is much like a traditional ground electrode; the system records the potential between each active electrode and CMS. The DRL electrode is part of a feedback circuit that drives the potential of the subject very close to the potential of the amplifier's ground circuit, resulting in a very low common mode voltage. That is, it actually injects a small current into the head so that the average voltage is close to the potential of the ground circuit. This improves the effective common mode rejection of the system because there is less common mode voltage to be subtracted away (for the technically inclined reader, details can be found in Metting van Rijn, Peper, & Grimbergen, 1990). The second unusual thing about this system is that, because of optimized electronics, the BioSemi system does not need to subtract the reference signal from the active signal prior to digitizing the signal. That is, the system provides a *single-ended* recording rather than a *differential* recording (see the glossary). The subtraction of the reference ($[A - G] - [R - G]$) is conducted in software after the recording is complete. The end result is conceptually equivalent to a differential recording, but with lower noise and more flexibility.

The original idea behind the terms *active electrode* and *reference electrode* was that the active electrode was assumed to be near the active neural tissue, and the reference electrode was assumed to be at some distant site that doesn't pick up any brain activity, such as the earlobe. As the neural signals near the active electrode changed, it was assumed that this would influence the voltage at the active site but not at the reference site. This would work well if the earlobe contained no neurally generated activity. The problem is that neural activity is conducted to the earlobe (and to every other place on the head or body). Consequently, the voltage recorded between an active site and a so-called reference site will reflect neural activity at both of the sites. This leads to perhaps the most important thing you should remember from this chapter, which I call the *no-Switzerland principle* (because Switzerland is famous for being politically neutral):

The no-Switzerland principle There is no electrically neutral site on the head or body. An ERP waveform therefore reflects the difference in voltage between two sites that both contain neural activity.

Consider, for example, the tip of the nose. This seems like it ought to be a neutral site because it is separated from the brain by a bunch of non-neural tissue, but it's not. To make the example more extreme, imagine a head with an extremely long nose, like that of Pinocchio. Electrical activity from a dipole inside the head flows to the entire surface of the head, including the base of the nose (see figure 2.2C in chapter 2). Pinocchio's long and skinny nose is much like a wire, so neural activity generated in the brain flows readily from the base of the nose to the tip (see figure 5.1B). Consequently, the absolute voltage at the tip of the nose will be nearly identical to the absolute voltage at the base of the nose. It doesn't really matter, therefore, whether the reference electrode is placed at the tip of the nose or where the nose joins the head; either place will pick up neural activity, just like any other spot on the surface of the head. This is not to say that the tip of the nose is an inappropriate site for a reference electrode—it can work quite well. Rather, my point here is that there is no such thing as an electrically neutral reference site, so you must always keep in mind that an ERP waveform reflects contributions from both the active site and the reference site.

The choice of a reference electrode can be somewhat difficult, and some key factors will be described in the next two sections. Fortunately, choosing the location of the ground electrode is trivial: Because the signals at the ground electrode are subtracted out by the referencing process, you can put the ground electrode anywhere on the head that is convenient. The location of the ground electrode will not ordinarily influence your recordings.

Re-referencing Your Data Offline

The whole reference issue is a bit of a pain, but one nice thing is that you can easily change the reference offline, after the data have been recorded. And you can do this many times to see what your data look like with different references (which I highly recommend you do). An implication of this is that it doesn't really matter what reference site was used during recording, because

you can always re-reference offline. Some systems allow you to select any reference you like during recording, whereas other systems require that you use a particular location (e.g., Cz). Because you can easily re-reference offline, it's not a problem if your system forces you to use a location that is not optimal.

Re-referencing your data offline is very simple. Recall that hardware referencing is accomplished by taking the potential between A and G and subtracting the potential between R and G (i.e., $[A - G] - [R - G]$). The result is the potential between A and R ($A - R$). You can do the same type of thing in software by literally subtracting one channel from another. For example, if you've recorded the voltage at electrodes A and B using a differential amplifier, with R as the reference, you can compute the voltage between A and B by simply subtracting channel B from channel A ($A - B$). In other words, the output of your amplifier for channel A is equivalent to $A - R$, and the output of your amplifier for channel B is equivalent to $B - R$, so the potential between these channels ($A - B$) is equivalent to $(A - R) - (B - R)$.

Now let's take a more complicated example, where you want to re-reference using the average of the left and right mastoids (the bony protrusions behind the ears) as the new reference. In other words, you want to look at the potential between an active site, A, and the average of the left mastoid (Lm) and the right mastoid (Rm), which is $([Lm + Rm] \div 2)$. This is the same thing as $A - ([Lm + Rm] \div 2)$. Imagine that you've recorded from site A using a differential amplifier, with the Lm as the reference (which is $A - Lm$). You've also recorded the signal at the Rm electrode with Lm as the reference (which is $Rm - Lm$). After the data have been recorded, you can re-reference to the average of the two mastoids using the formula $a' = a - (r/2)$, where a' is the re-referenced waveform for site A (i.e., the waveform using the average of the two mastoids as the reference), a is the original waveform for channel A (recorded with an Lm reference), and r is the original waveform for the Rm channel (recorded with an Lm reference).

Here's how this formula works. Because we originally used Lm as the reference, the output of the amplifier for channel A is equal to $A - Lm$. Similarly, the voltage recorded from the Rm channel with an Lm reference is equal to $Rm - Lm$. We need to recombine these two recorded signals into something that equals $A - ([Lm + Rm] \div 2)$. This is achieved with some simple algebra:

$a = A - Lm$ The voltage recorded at site A is the absolute voltage at A minus the absolute voltage at Lm.

$r = Rm - Lm$ The voltage recorded at Rm is the absolute voltage at Rm minus the absolute voltage at Lm.

$a' = A - ([Lm + Rm] \div 2)$ This is what we are trying to compute (the potential between A and the average of Lm and Rm).

$a' = A - (Lm \div 2) - (Rm \div 2)$ This is just an algebraic reorganization of the preceding equation.

$a' = A - (Lm - [Lm \div 2]) - (Rm \div 2)$ This works because $Lm \div 2 = Lm - (Lm \div 2)$.

$a' = (A - Lm) - ([Rm - Lm] \div 2)$ This is just an algebraic reorganization of the preceding equation.

$a' = a - (r \div 2)$ Here we've taken the previous equation and replaced $(A - Lm)$ with a and replaced $(Rm - Lm)$ with r .

In other words, you can compute the voltage corresponding to an average mastoids reference for a given site simply by subtracting one-half of the voltage recorded from the other mastoid. The same thing can be done with earlobe reference electrodes.

If you have a system that does not use a reference during recording (e.g., BioSemi ActiveTwo), this is even easier. Imagine, for example, that you recorded signals from A, Lm, and Rm (each recorded relative to the ground electrode). To reference channel A to the average of the two mastoids, you would just use $a' = A - ([Lm + Rm] \div 2)$.

One convenient aspect of re-referencing is that you can re-reference your data as many times as you want. You can go back and forth between different reference schemes, with no loss of information. I highly recommend that you look at your data with multiple different references.

In most ERP experiments, the EEG electrodes are recorded with respect to a single common reference (which may be a single electrode or the average of two or more electrodes). These are sometimes called *monopolar recordings*, but this term is something of a misnomer because monopolar recordings reflect contributions from both the active and reference sites, not the absolute voltage at the active site. The term *bipolar recording* is typically used when each channel uses a different reference. In the clinical evaluation of epilepsy, for example, each electrode is typically referenced to an adjacent electrode. In cognitive and affective neuroscience experiments, bipolar recordings are often used to measure the electrooculogram (EOG), which is the electrical potential caused by blinks and eye movements. To measure horizontal eye movements, for example, the active electrode is usually placed adjacent to one eye, and the reference electrode is placed adjacent to the other eye (see chapter 6 for more details). However, all the scalp electrodes use the same reference site in most cases.

The Average Reference

It is possible to re-reference your data to the average of all of your scalp sites, which is often called the *average reference*. This is relatively easy to do, and it has become very common, but it has some conceptual complexities that I will describe after I explain the basics of how it works.

To understand how the average reference works, imagine that the head was not connected to the rest of the body so that you could place electrodes around the entire head (including the bottom, which is normally inaccessible because of the neck). By using the average voltage across all of the electrodes as the reference, you could obtain the absolute voltage at each electrode site. The mathematics of this would be trivial: The absolute voltage at a given site can be obtained by simply subtracting the average of all of the sites from each individual site, assuming that all sites were recorded with the same reference electrode. Although this would be ideal, it isn't practical for the simple reason that the neck and face get in the way of putting electrodes over

the entire surface of the head. Nonetheless, many researchers use the average of whatever scalp electrodes they happen to record as the reference.

The following list of equations provides the logic behind re-referencing to the average of all the electrodes. In this example, we have recorded from three active electrodes using Lm as the reference. In the equations, A1, A2, and A3 refer to the absolute voltage at these three active sites, and a1, a2, and a3 refer to the voltage actually recorded at these sites with the Lm reference. If we simply subtract the average of the recorded voltages (denoted $\text{avg}[a1, a2, a3]$) from each of the recorded voltages, this is equivalent to converting each recording into the difference in absolute voltage between each site and the average of the absolute voltage at each of the active sites. For example, the re-referenced version of a1 is equal to the potential between A1 and $\text{avg}(A1, A2, A3)$. Note that the original reference (Lm) no longer contributes to the reference. As an exercise, you can figure out how to re-reference the data so that the original reference is one of the sites that contributes to the average reference.

$$a1 = (A1 - \text{Lm})$$

$$a2 = (A2 - \text{Lm})$$

$$a3 = (A3 - \text{Lm})$$

$$\begin{aligned} \text{avg}(a1, a2, a3) &= (a1 + a2 + a3) \div 3 \\ &= [(A1 - \text{Lm}) + (A2 - \text{Lm}) + (A3 - \text{Lm})] \div 3 \\ &= [(A1 + A2 + A3) - 3\text{Lm}] \div 3 \\ &= \text{avg}(A1, A2, A3) - \text{Lm} \end{aligned}$$

$$\begin{aligned} a1 - \text{avg}(a1, a2, a3) &= (A1 - \text{Lm}) - (\text{avg}(A1, A2, A3) - \text{Lm}) \\ &= A1 - \text{avg}(A1, A2, A3) \end{aligned}$$

$$a2 - \text{avg}(a1, a2, a3) = A2 - \text{avg}(A1, A2, A3)$$

$$a3 - \text{avg}(a1, a2, a3) = A3 - \text{avg}(A1, A2, A3)$$

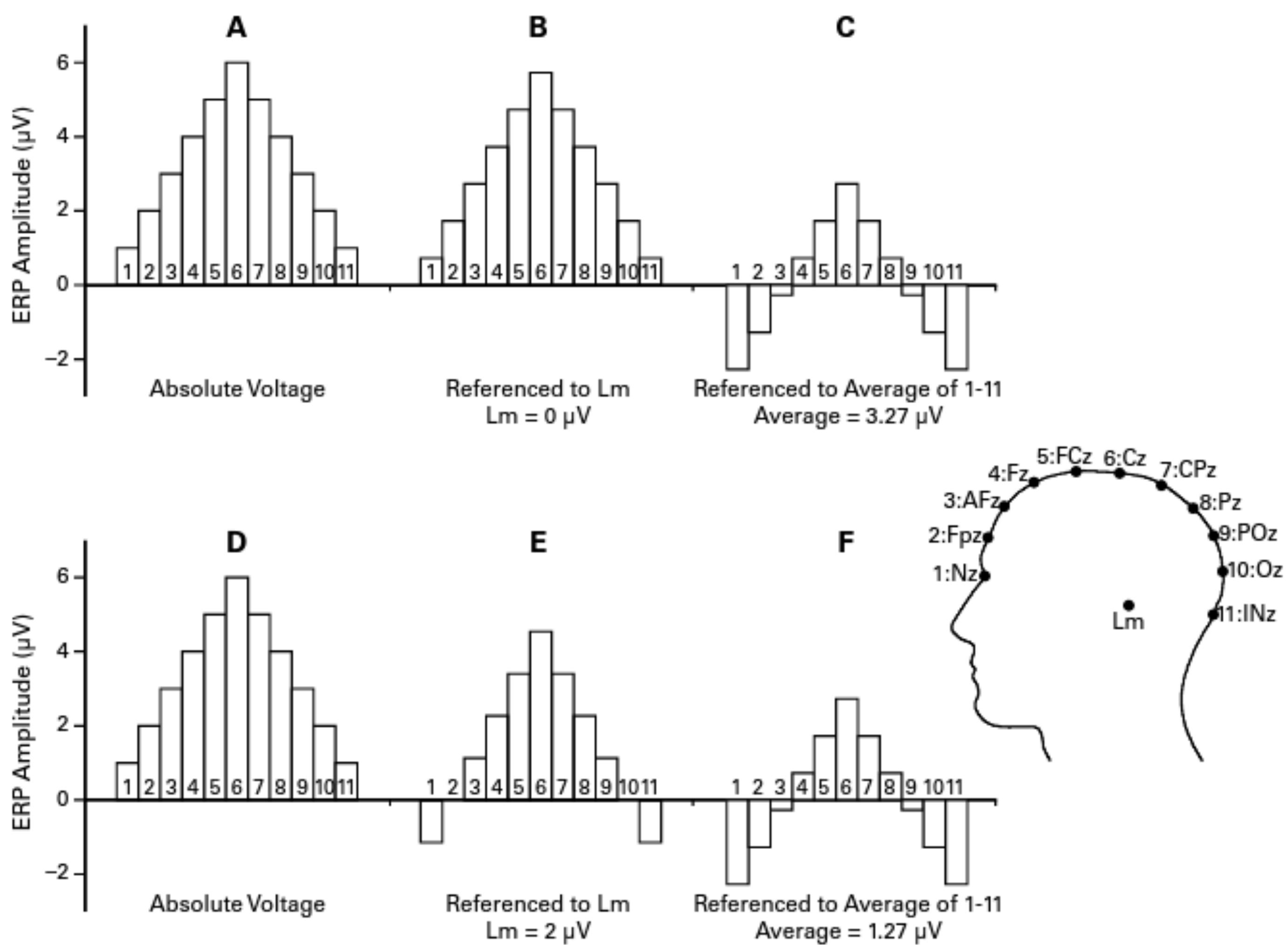
The average reference is quite appealing. First, it is convenient: You simply record from a large set of scalp electrodes and then re-reference to the average of all sites offline. Second, it is not biased toward a particular hemisphere (assuming that you use a symmetrical set of electrode locations). Third, because it reflects the average across a large number of sites, it will tend to minimize noise. Fourth, as long as the set of electrodes covers a very large proportion of the scalp, it is unlikely that the average reference will subtract away most of the voltage for a given component (as can happen for the average mastoids reference when the component is large near the mastoids).

However, the use of the average reference has several side effects that are not obvious (for additional discussion, see Dien, 1998). These side effects are not necessarily disadvantages, but they can lead to unexpected results and misinterpretations if they are not fully understood. To

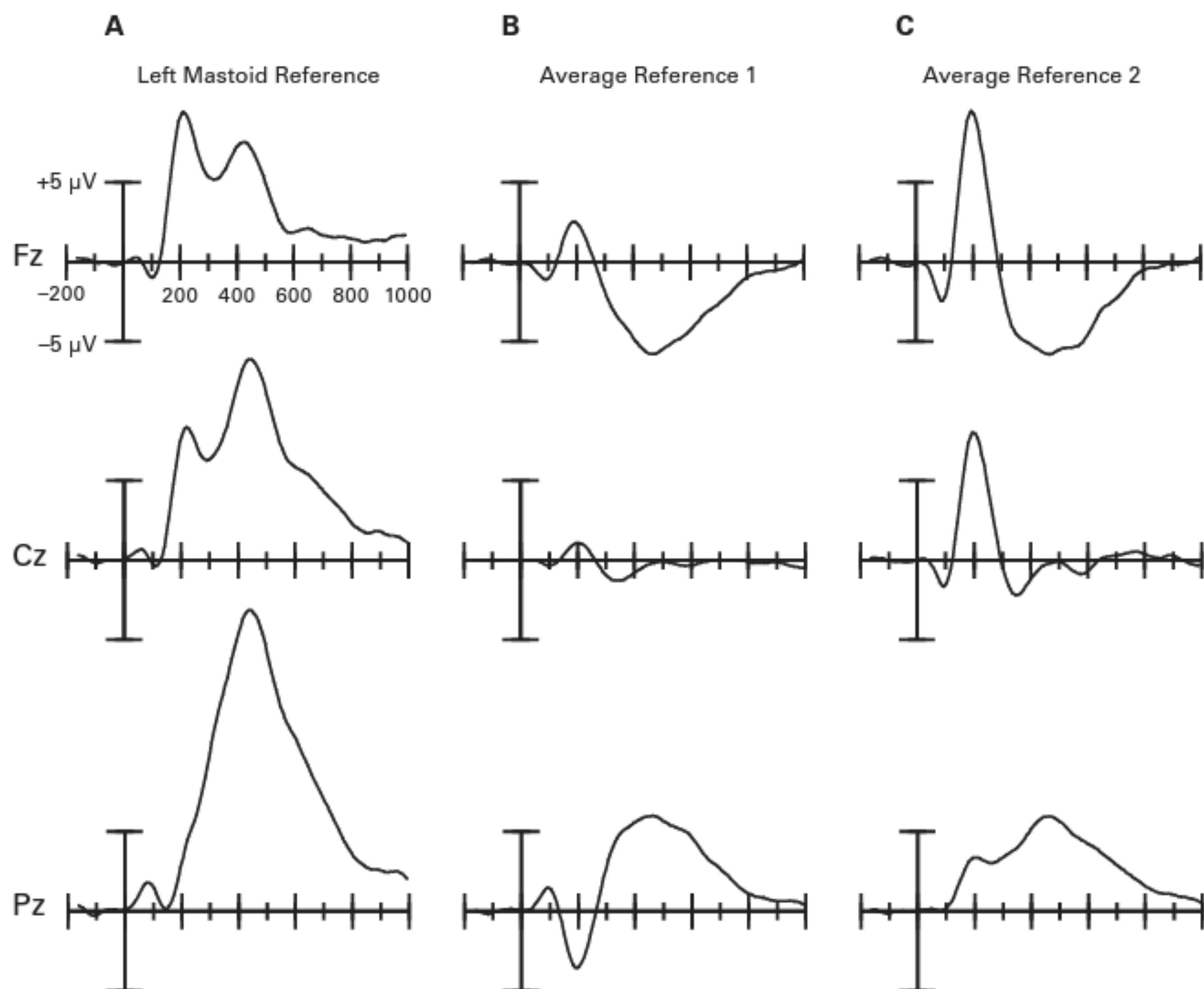
explain these side effects, let's take a closer look at what really happens when the average reference is used. Figure 5.2 illustrates the effect of taking recordings that were obtained using an Lm reference and re-referencing to the average of all sites. These are artificial data, designed to be similar to what one might expect for a broadly distributed positive component, such as the P3 wave. For the sake of simplicity, we are assuming that data were recorded only from 11 sites along the midline. Figure 5.2A shows the absolute voltage (the potential between each electrode and the average of the entire surface of the head, including the bottom side). Figure 5.2B shows what the data would look like in the original recordings, referenced to Lm, if we assume that the absolute voltage at Lm was zero (which could happen if the band of zero voltage for the dipole just happened to pass under the Lm electrode). In this unusual situation, the scalp distribution of the recorded voltage is simply equal to the absolute voltage, because 0 μ V (the voltage at Lm) is subtracted from each active site by the initial referencing process. Figure 5.2C shows the scalp distribution after we re-reference to the average reference by subtracting the average of all the original values (3.27 μ V) from each of the original values. Note that re-referencing all of the electrodes to a new value simply pushes the distribution of values upward or downward, without changing the relative differences in voltage between electrodes. Panels E and F of figure 5.2 show the same thing, but under the more realistic assumption that the absolute voltage at Lm is not zero. Instead, we are assuming that Lm was 2 μ V (which is just an arbitrary value). With this assumption, all the values are pushed downward by 2 μ V for the data recorded using the Lm reference, but we end up with the same values as before when we use the average reference.

This example shows the first problem with the average reference; namely, that researchers often assume that it provides a good estimate of the absolute voltage at each site. Although this will sometimes be true (in cases where the positive and negative sides of the dipole are captured equally by the set of recording electrodes), it will often be false. If your electrodes cover only a portion of the head, then you are missing much of the voltage that is needed to compute the average of the entire surface of the head. Moreover, even if you put electrodes everywhere you can, you will still be missing the bottom portion of the head (unless you figure out a way to insert electrodes through the neck to reach the bottom half of the head). Thus, even under the best of circumstances, the average reference yields an imperfect approximation of the absolute voltage. Dien (1998) provided examples in which the average reference led to a good approximation of the absolute voltage, but there is no guarantee that this will be true for a given ERP component. For example, it is clearly not true for the example shown in figure 5.2. Of course, the use of the mastoids, earlobes, or any other site also fails to yield the absolute voltage in most cases, but at least these references don't lead anyone to believe that they are recording an absolute voltage. Thus, the no-Switzerland principle arises even when the average reference is used.

A second side effect of the average reference is that the ERP waveforms and scalp distributions you will get when you use the average reference will change depending on what electrode sites you happened to record from. An extreme version of this problem is illustrated in figure 5.3, which shows waveforms from the Fz, Cz, and Pz electrode sites recorded with a left mastoid

**Figure 5.2**

Examples of how the reference configuration can influence the measured scalp distribution. In this made-up example, the amplitude is measured at a particular time point from 11 scalp electrodes, distributed along the midline between the nasion and the inion (see cartoon head on the right), using the left mastoid (Lm) as the reference. Panels A–C assume that the absolute voltage at Lm was 0 μV (a very unlikely occurrence). Panels D–E assume that the absolute voltage at Lm was 2 μV (a purely arbitrary but more realistic value used for the sake of this example). Panels A and D show the true absolute voltage (i.e., the difference in potential between each scalp site and the average of the entire surface of the head, including the part that is ordinarily obscured by the neck). This absolute voltage is purely theoretical; there is no way to actually measure it in a living person. Panels B and E show the voltage that would actually be recorded using the Lm reference. Panels C and F show the voltage that would be obtained if the recorded voltages in panels B and E, respectively, were re-referenced to the average voltage at sites 1–11 (eliminating any contribution from Lm). Even though the Lm value differs between panels B and E, the values in panels C and F are identical. Note that all six scalp distributions are exactly the same except for a vertical shift upward or downward. However, the actual value at some electrodes is positive for some reference configurations and negative for others. Thus, different references may make the scalp distributions look quite different, even though they differ only in terms of a vertical shift.

**Figure 5.3**

Effects of the average reference on ERP waveforms. (A) Voltage recorded at each of three sites (Fz, Cz, and Pz) using a left mastoid reference. (B) Waveforms obtained when the average of the three sites in column A is used as the reference. (C) Waveforms obtained when the average of these three sites and five additional occipital and temporal electrode sites was used as the reference.

reference (column A), the same data using the average of these three sites as the reference (column B), and the same data using the average of these three sites plus five occipital and temporal sites as the reference (column C). Even though the same Fz, Cz, and Pz signals were present in all three cases, the resulting waveforms look very different. For example, the large and broadly distributed P3 that can be seen with a left mastoid reference (column A) is converted by the use of an average reference into a medium-sized positive value at the Pz site, a flat line at the Cz site, and a medium-sized negative value at the Fz site (column B). Moreover, the shapes of the ERP waveforms at each site are very different for the average reference data shown in columns B and C, because the electrodes contributing to the average reference are different in these two columns.

To make this clear, imagine that you record ERPs from Fz, Cz, Pz, and 30 other electrodes, and I record ERPs in the same paradigm from Fz, Cz, Pz, and 30 other electrodes, but I don't use the same 30 other electrodes that you use. And imagine that we both publish papers showing the waveforms at Fz, Cz, and Pz, using an average reference. Your waveforms could look very different from mine if those "other electrodes" were quite different in my experiment than in your experiment. However, to someone casually reading the methods sections of our papers, it would sound as if our data should look the same. This is obviously a recipe for confusion. Many ERP researchers who use the average reference appear to be unaware of this problem, as I have seen many papers in which the researchers used the average reference but did not specify all of the electrodes that were used in the recordings (and that therefore contributed to the average reference and influenced the waveforms). That is, the researchers indicated which active electrode sites were used in the statistical analysis, but they said something vague like "recordings were obtained from a total of 33 scalp electrodes, using the average reference, but the analyses were limited to Fz, Cz, and Pz." This suggests that the researchers were unaware that the other, unspecified electrodes had a large effect on the data they analyzed from Fz, Cz, and Pz (because the unspecified electrodes contributed to the average reference).

A third side effect of the average reference is that the voltage will always sum to zero across all of the electrode sites at every point in time (which is a simple consequence of the math). This can be seen in figure 5.2, where several of the electrodes have a negative voltage after the data were re-referenced to the average reference. This can also be seen in the average reference waveforms in figure 5.3B, where the short-duration, positive-going peak at around 400 ms at the Fz electrode site in column A becomes a long-duration, negative-going peak in column B. This occurred because of the large P3 wave at Pz in the column A waveforms; to achieve a summed voltage of zero, a large negative voltage had to be added onto the Fz site in the average reference waveforms. To be fair, it is important to note that the dipolar nature of ERP components means that every component is actually positive over some parts of the head and negative over other parts, summing to zero over the entirety of the head (although you may not have electrodes over enough of the head to see both the positive and negative sides). The transition point between the positive and negative portions is influenced by the reference voltage, whether the absolute reference or some other reference is used (see, e.g., the artificial negative voltages at electrode

1 and electrode 11 in the left mastoid-referenced data in figure 5.2E). However, this distortion can be extreme when the average reference is used, especially when the electrodes cover less than half the head.

Many researchers do not appear to realize that the voltage will necessarily be positive at some electrode sites and negative at others when the average reference is used. For example, I have reviewed manuscripts in which an average reference was used and the authors made a great deal out of the finding that an experimental effect was reversed in polarity at some sites relative to others. But this is necessarily the case when the average across sites is used as the reference.

The fourth and biggest side effect of the average reference is that it makes it difficult to compare waveforms and scalp distributions across studies (as noted by Dien, 1998). This is truly a disadvantage. As I mentioned earlier, even when two researchers show data from the same active electrodes and say that they used the average reference, their waveforms and scalp distributions may look quite different if the entire set of electrodes was not the same across studies. Thus, unless everyone uses the same set of electrodes to form the average reference, the use of the average reference may lead to confusion and misinterpretations, with researchers thinking that the pattern of results differs across experiments when in fact only the set of recording electrodes differs. This problem does not arise when people use, for example, the mastoids as the reference, making it easy to compare results across experiments. The consistent use of exactly the same reference configuration across experiments is therefore quite beneficial to the field. Emerson famously wrote that “a foolish consistency is the hobgoblin of little minds,” but this particular consistency is not usually foolish.

Choosing a Reference Site

Now that we have discussed several different options for the reference, you probably want to know what you should use for the reference in your own experiments. There is no simple answer to this question, and you need to consider the following five factors.

First, given that no site is truly electrically neutral, you might as well choose a site that is convenient and comfortable. The tip of the nose, for example, is a somewhat distracting place for an electrode.

Second, you will want to avoid a reference site that is biased toward one hemisphere. For example, if you use the left earlobe as the reference, then people might be concerned that you have introduced an artificial asymmetry between the left and right hemispheres. This is not usually a real problem, but reviewers might hassle you about it, and it's always better to avoid this kind of hassle. To avoid the potential for a hemispheric bias, you could use a single electrode somewhere on the midline (e.g., Cz). Another option is to place two electrodes in mirror-image locations over the left and right hemispheres and then combine them as the reference. For example, sometimes people place electrodes on both the left mastoid and the right mastoid, physically connect the wires from these electrodes, and then use the combined signal as the reference (the same thing can be done with earlobe electrodes). This is called the *linked mastoids* (or linked earlobes) reference, and it is not biased toward either hemisphere. However, physically

linking the wires from these two electrodes creates a zero-resistance electrical bridge between the hemispheres, which may distort the distribution of voltage over the scalp and reduce hemispheric differences. This also invalidates the use of source localization techniques. Thus, I would advise against using linked mastoids (or linked earlobes) as the reference. It is better to re-reference the data offline to the average of the separately recorded left and right mastoids or earlobes, as described in the previous section, creating an *average mastoids* or *average earlobes* reference (Nunez, 1981). Note that some researchers use the term *linked mastoids* or *linked earlobes* to refer to the average of the mastoids or earlobes, but to avoid any ambiguities about what was actually done, the term *linked* should be used only when the two sides have been physically linked.

Third, you should avoid using a reference that introduces a lot of noise into your data. For example, a reference electrode near the temporalis muscle (a large muscle on the side of the head that is used during eating and talking to control the jaw) will pick up a lot of muscle-related activity, and this activity will then be present in all channels that use this reference (box 5.4). Averaging tends to reduce noise, so using the average of many electrode sites as the reference may lead to cleaner data.

Fourth, it is usually a good idea to avoid using a reference that is near the place on the scalp where the effect of interest will be largest. For example, the absolute voltage for the N170 component is largest over the lateral posterior scalp, near the mastoids. A large N170 is therefore present in the absolute voltage recorded at the mastoids, and this large N170 will be subtracted from all your electrodes if you use the mastoids as the reference. This will make the N170 appear to be relatively small in the region of the scalp where the absolute voltage is actually largest, and it will create a large positive voltage at distant sites (because subtracting a negative voltage from the reference electrodes creates a positive voltage). This may cause confusion about the scalp distribution of the N170, so the mastoid is not usually used as the reference in N170 experiments. Similarly, Cz is the default reference in systems made by Electrical Geodesics, and

Box 5.4

Where's That Noise Coming From?

Whether your system subtracts the reference in hardware or in software, any noise in the reference electrode will be present in all electrodes that use this reference (but will be upside down because it is being subtracted). Thus, if you see some noise in all the channels that share a particular reference site, then the noise is almost certainly coming from the reference site. This is a simple consequence of the fact that the referenced data is equal to the absolute voltage at the active site (A) minus the absolute voltage at the reference site (R). In other words, the referenced voltage is $A - R$. For example, a reference electrode on the mastoid may pick up the electrocardiogram (EKG) voltage from the heart, and an upside-down version of this EKG will then be present in all electrodes that use this reference. One implication of this is that you should avoid using as reference a site that is picking up a lot of noise. Another implication is that you can figure out where the noise is coming from by asking whether it is present in all channels that use a particular reference.

researchers who use these systems almost always re-reference offline to a different site, especially if they are looking at components like P3 and N400 that are very large at Cz.

The last and perhaps most important factor is that you want your ERP waveforms and scalp distributions to be comparable with those published by other researchers. That is, because an ERP waveform for a given active site will look different depending on the choice of the reference site, it is usually a good idea to use a site that is commonly used by other investigators in your area of research. Otherwise, you and others may incorrectly conclude that your data are inconsistent with previously published data.

Now that we've spelled out all the relevant factors, we can finally discuss what the "best" reference site actually is. Unfortunately, there is no single best site, and the best site according to one factor might not be the best according to another factor. My lab usually uses the average of the mastoids as the reference because it is convenient, unbiased, and widely used. The earlobes and mastoids are close enough to each other that the resulting ERP waveforms should look about the same no matter which is used. I prefer to use the mastoid rather than the earlobe because I find that an earclip electrode becomes uncomfortable after about an hour and because I find it easier to obtain a good electrical connection from the mastoid (because the skin is not so tough).

A downside of the mastoids is that they are near the neck muscles, and they therefore tend to pick up muscle-related artifacts. They are also more likely to pick up electrocardiogram (EKG) artifacts, although this is not usually a significant problem in practice (see chapter 6). As I mentioned earlier, the mastoids can also be problematic for the N170 and other components that are largest at lateral posterior electrode sites. However, for a large proportion of studies, the mastoids are the best option. A similar alternative is to use the average of the P9 and P10 electrodes, which are near the mastoids but don't pick up quite as much muscle noise from the neck.

My lab rarely uses the average reference. The main reason is that the average reference makes it difficult to compare waveforms across different laboratories that record from different electrode sites. Even within my lab, we use different electrode configurations for different experiments, and using the average reference would make it difficult to compare across experiments. In addition, I like to avoid encouraging the incorrect view that the average reference provides a means of recording the absolute voltage from each site. However, there are certainly situations in which the average reference is acceptable or even preferable.

Because there are many issues involved in choosing the reference, I will not make a single simple recommendation for your research. After all, I don't know what you are studying! However, I've created the following list, which provides several different pieces of advice that you can use to decide what reference is best for your research:

- Look at your data with multiple different references. This will keep the no-Switzerland principle active in your mind.
- Concentrate on the pattern of differences in voltage among electrodes, not on the specific voltage at each site.

- In many cases, you will want to use the average mastoids or average earlobes as the reference simply because this is the most common practice in your area of research.
- You will probably want to use something other than the mastoids or earlobes if some other reference is standard in your area of research or if the component of interest is largest near the mastoids and earlobes (as in the case of N170).
- If the data look noisy with a mastoid or earlobe reference, you may gain some statistical power by using the average reference.
- If you wish to use the average reference, you should use a large number of evenly spaced electrodes that cover more than 50% of the surface of the head, and you absolutely must report all electrodes that contributed to the average reference in the methods sections of your papers.

Current Density

It is possible to completely avoid the reference problem by transforming your data from voltage into *current density* (sometimes called *scalp current density* [SCD] or *current source density* [CSD]). Current density is the flow of current out of the scalp at each point on the scalp. Because current is the flow of charges past a single point, rather than the potential for charges to flow between two points, current is naturally defined at a single point and does not require a reference. Conveniently, it is possible to convert the distribution of voltage across the scalp into an estimate of the distribution of current. This is done by taking the second derivative of the distribution of voltage over the scalp (for a detailed description, see Pernier, Perrin, & Bertrand, 1988). This is often called the *surface Laplacian* (after the mathematician Pierre-Simon Laplace).

To understand what it means to take the second derivative of the voltage distribution, start by imagining that you have recorded data from thousands of tightly packed electrodes, so you have a nearly continuous measure of the voltage distribution over the scalp at each moment in time. Now imagine that you replace the voltage at each electrode with the difference in voltage between that electrode and the average of its nearest neighbors (at each moment in time). The result would be the first derivative of the voltage distribution. Now imagine that you repeat this process again, taking the difference between each newly computed difference value and the average of the difference values from the nearest neighbors. This would be the second derivative. Derivatives are ordinarily calculated from continuous data, but you could get a good approximation of the true derivative if you had thousands of tightly packed electrodes. In a real experiment, however, you might have only 32 electrodes, and taking differences between adjacent electrodes would not give you a very good estimate of the true derivative. The typical approach is therefore to use an interpolation algorithm that provides an estimate of the continuous voltage distribution and then use this continuous distribution to compute the second derivative (Perrin, Pernier, Bertrand, & Echallier, 1989). The accuracy of the interpolation will, of course, depend on how many electrodes you're using. In practice, a reasonably good estimate of current density can be obtained with 32 electrodes. However, the interpolation becomes less accurate near the edge of electrode array, so you shouldn't place much faith in the current density estimates at the outermost electrodes.

In addition to eliminating the reference issue, current density has the advantage of “sharpening” the scalp distributions of ERP components. In other words, current density is more focally distributed than voltage. This may help you to separately measure two different electrodes that overlap in time, because the current density transformation may make them more spatially distinct. You should also know that current density minimizes activity from dipoles that are deep in the brain and preferentially emphasizes superficial sources (this is because the current from a deep source dissipates widely over the entire scalp and is therefore not very dense). This can make broadly distributed components like P3 difficult to see. However, this can sometimes be a benefit because it reduces the number of overlapping components in your data. You should also keep in mind that current density is an estimated quantity that is one step removed from the actual data, and it is therefore usually a good idea to examine both the voltage waveforms and the current density waveforms. Current density can be a very valuable tool, and it is probably used less than it should be.

Electrodes and Impedance

Electrodes

Now that we’ve discussed the nature of the voltages that are present at the scalp, let’s discuss the electrodes that are used to pick up the voltages and deliver them to an amplifier. Basically, a scalp electrode is just a way of attaching a wire to the skin. You could just tape a wire to the skin, but that would not create a very stable electrical connection. The main consideration in selecting an electrode is to create a stable connection that does not vary rapidly over time (e.g., if the subject moves slightly).

Electrode Composition In most cases, an electrode is a metal disk or pellet that does not directly contact the scalp but instead makes an electrical connection to the scalp via a conductive gel or saline. The choice of metal is fairly important, because some metals quickly become corroded and lose their conductance. In addition, the circuit formed by the skin, the electrode gel, and the electrode can function as a capacitor that attenuates the transmission of low frequencies (i.e., slow voltage changes).

The most common choice of electrode material is silver covered with a thin coating of silver chloride (these are typically called Ag/AgCl electrodes). These electrodes have many nice electrical properties, and contemporary manufacturing methods lead to good reliability. In the 1980s, many investigators started using electrode caps made by Electro-Cap International, which feature tin electrodes. In theory, tin electrodes will tend to attenuate low frequencies more than Ag/AgCl electrodes (Picton, Lins, & Scherg, 1995), but Polich and Lawson (1985) found essentially no difference between these two electrode types when common ERP paradigms were tested, even for slow potentials such as the CNV and sustained changes in eye position. This may reflect the fact that the filtering caused by the electrodes is no more severe than the typical filter settings of an EEG amplifier (Picton et al., 1995). Either tin or Ag/AgCl

should be adequate for most purposes, but Ag/AgCl may be preferable when very slow potentials are being recorded.

Electrode Placement Figure 5.4 illustrates the most common system for defining and naming electrode positions (Jasper, 1958; American Encephalographic Society, 1994a). This system is called the *International 10–20 System* because the original version placed electrodes at 10% and 20% points along lines of latitude and longitude (5% points are now sometimes used). The first step in this system is to define an equator, which passes through the nasion (the depression between the eyes at the top of the nose, labeled Nz), the inion (the bump at the back of the head, labeled Iz), and the left and right pre-auricular points (depressions just anterior to the ears). A longitudinal midline is then drawn between Iz and Nz, and this line is then divided into 10 equal sections (defining the 10% points along the line). The equator is similarly broken up at the 10%

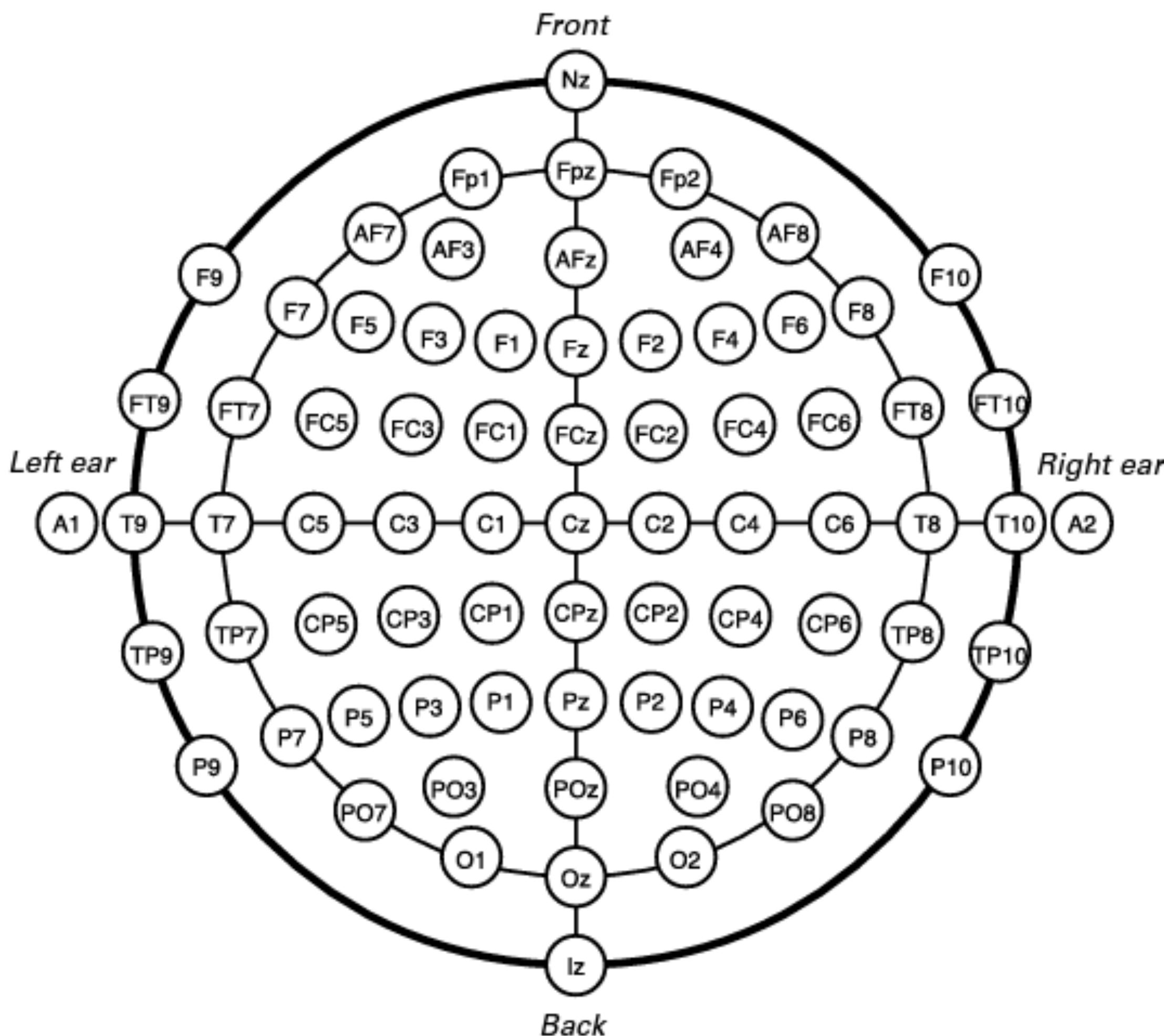


Figure 5.4
International 10/20 System for electrode placement. Note that earlier versions of this system used labels of T5 and T6 in place of P7 and P8 and used T3 and T4 in place of T7 and T8.

and 20% points, allowing electrodes such as F7, F8, P7, and P8 to be defined. Additional sites are then placed at equal distances along arcs between the midline sites and these equatorial sites.

Each electrode name begins with one or two letters to indicate the general region of the electrode (Fp = frontal pole; F = frontal; C = central; P = parietal; O = occipital; and T = temporal). Each electrode name ends with a number or letter indicating distance from the midline, with odd numbers in the left hemisphere and even numbers in the right hemisphere. Larger numbers indicate greater distances from the midline, with locations on the midline labeled with a “z” for zero (because the number 0 looks too much like the letter O).

Other systems are sometimes used, especially when very large numbers of electrodes are present. The most common alternative is a geodesic arrangement, which provides the same distance between any two adjacent electrodes. You can use any system you like, but you will need to be able to describe how your electrode sites are related to the 10/20 system.

How Many Electrodes Do You Need? You might think that it is always better to record from more electrodes and therefore obtain more information. However, it is very difficult to ensure that you are obtaining clean data when you record from more than 30–40 electrodes. It’s just too much information to monitor. My general advice is to record from between 16 and 32 active electrode sites in most experiments. You may want to go up to 64 electrodes on rare occasions, but I see very little value in going beyond 64 except in rare cases (e.g., when you are doing very serious source localization, including structural MRI scans from each subject). A more detailed discussion of this issue can be found in the online supplement to chapter 5.

Safety Precautions

EEG recordings carry a theoretical possibility of disease transmission between subjects via contaminated electrodes and between the subject and the experimenter during the electrode application and removal process. To my knowledge, there have been no reported cases of serious disease transmission in research studies using scalp electrodes. Risks are slightly greater in clinical practice (because of the greater possibility of people who have infectious diseases). A report from the American Encephalographic Society noted that “transmission of infection during routine EEG recording procedures is almost unheard of except under special conditions, such as depth electrode placement in patients with spongiform encephalopathy” (American Encephalographic Society, 1994b, p. 128). This reflects, in part, the fact that most EEG/ERP laboratories have implemented procedures to reduce the risk of disease transmission.

For many serious infectious diseases, such as hepatitis B, the risk comes from pathogens in the blood and other fluids. In most kinds of ERP research, risks of disease transmission can be nearly eliminated by thoroughly disinfecting the electrodes after each subject and by ensuring that the experimenter wears gloves when touching the subject (or touching the electrodes before they have been disinfected). There are many different ways of disinfecting electrodes, some of which may harm the electrodes. I therefore recommend that you follow the manufacturer’s instructions for disinfecting your electrodes. If you are working with high-risk groups (i.e.,

individuals who are likely to have infectious diseases or who may have compromised immune systems), you should take more extensive precautions. For a more extensive discussion and more detailed recommendations, see Sullivan and Altman (2008).

Impedance, Common Mode Rejection, and Skin Potentials

It is obviously important to have a good electrical connection between the electrode and the scalp. As described in chapter 2, the quality of the connection is usually quantified by the *impedance* of the electrode–scalp connection (the *electrode impedance*). Impedance is related to resistance, which was defined in chapter 2. Resistance is the tendency of a material to impede the flow of a constant current, whereas impedance is the tendency to impede the flow of an alternating current (a current that fluctuates rapidly over time). The EEG is an alternating current, so it makes more sense to measure impedance than resistance in EEG recordings. Impedance is actually a combination of resistance, capacitance, and inductance, and the properties of the skin, the electrode gel, and the electrode can influence all three of these quantities. Thus, to assess the extent to which current can flow between the scalp and the recording electrode, it is important to measure the impedance rather than the resistance. Impedance is typically denoted by the letter Z and is measured in units of ohms (Ω) or thousands of ohms (kilohms; $k\Omega$). As will be described in detail later in this chapter, the scalp is covered by a layer of dead skin cells and an oil called sebum, and these can dramatically increase electrode impedance, which can reduce the quality of the EEG recordings. You might think that a higher electrode impedance would make the recorded EEG voltages smaller, but this is not a problem with modern EEG amplifiers. Higher impedance may increase the noise in the data however, which is a problem.

Many EEG recording systems require the experimenter to lower the electrode impedance, which is typically achieved by cleaning and abrading the skin under each individual electrode. However, many newer EEG systems can tolerate high electrode impedances (these are often called *high-impedance systems*). I used low-impedance systems in my own lab for many years, and now I use a high-impedance system. Note that low-impedance systems require low electrode impedances to work properly, whereas high-impedance systems have special circuitry that allows them to work with either low or high electrode impedances.

High-impedance systems have three significant advantages. First, they reduce the amount of time required to prepare each subject (by eliminating the time involved in abrading the skin under each electrode, which can be considerable if you are recording from a lot of electrodes). Second, they reduce the likelihood of disease transmission between subjects because they eliminate abrasion of the skin (which may lead to a small amount of blood). Of course, disease transmission can be minimized by thoroughly disinfecting the electrodes between subjects, but it is even safer to avoid abrading the scalp at all. Third, because abrasion can be uncomfortable, high-impedance recordings may be more pleasant for the subject.

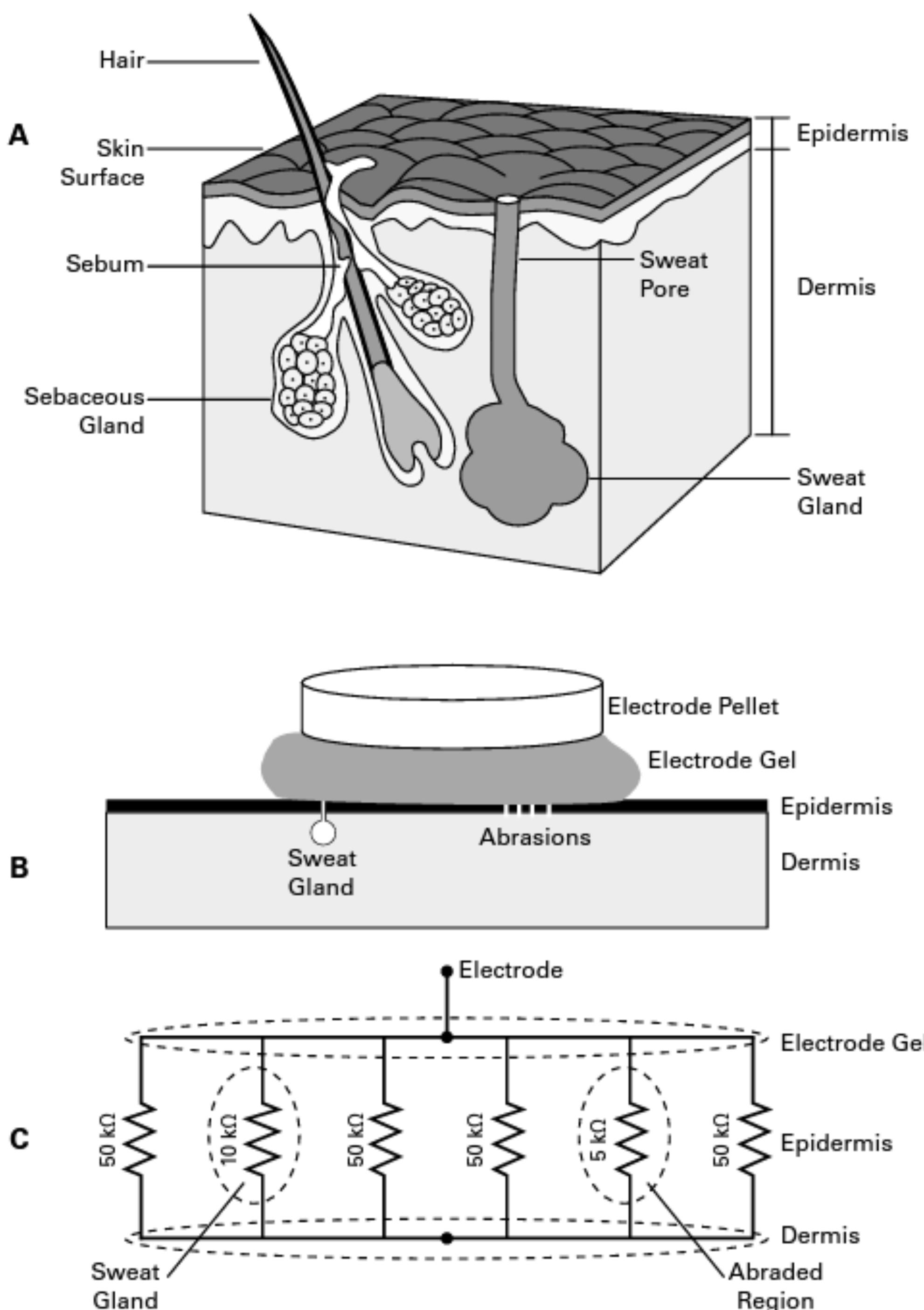
However, high electrode impedances can potentially lead to two problems. The first problem is poor common mode rejection. Recall from earlier in this chapter that common mode rejection is the ability of a differential amplifier to accurately subtract the noise that is present in the

amplifier's ground circuit. To do this subtraction accurately, the active and reference signals ($[A - G]$ and $[R - G]$) must be treated exactly equivalently. If the impedances differ among the active, ground, and reference electrodes, they may not be treated equivalently in the subtraction process, and some of the common mode noise may remain in the referenced data. Differences in impedance typically become more profound as the impedance increases. Thus, as the electrode impedance increases, the ability to reject common mode noise decreases. However, it is possible to design EEG amplifiers that are less prone to this problem (by increasing the *input impedance* of the amplifiers). Thus, if you have an amplifier that is designed to work with high electrode impedances, the effect of increased electrode impedance on common mode noise rejection may not have much impact on the quality of your data. In my lab's high-impedance system, we see very little common mode noise (but we also spend a lot of time making sure that we've eliminated sources of electrical noise).

The second problem associated with high electrode impedance is that this may increase skin potential artifacts. Unfortunately, high-impedance EEG recording systems do nothing to address this problem. Skin potentials are a very significant factor in ERP studies. As described in the online supplement to this chapter, the skin potentials in high-impedance recordings can add so much noise that you might need to double or triple the number of trials needed to get a statistically significant result. Consequently, it is worthwhile to understand how skin potentials are generated, which is described in detail in the next section. A later section will provide concrete advice about how to deal with skin potentials and whether you should use low- or high-impedance recordings.

Skin, Impedance, and Skin Potentials There is a tonic voltage between the inside and the outside of the skin, and the magnitude of this voltage changes as the impedance changes. Thus, if the electrode impedance goes up and down over time, this will lead to voltages that go up and down in your EEG recordings. These voltage changes are called *skin potentials*, and they are a major source of noise in ERP experiments. Understanding these skin potentials requires that you learn a little about the skin.

The skin is a very complex organ, and figure 5.5A provides a simplified diagram of some of the major components. The skin is divided into a thick lower layer called the *dermis* and a thin top layer called the *epidermis*. Skin cells die and are replaced at a rapid rate, and the top portion of the epidermis is a layer of dead skin cells. These dead skin cells flake off at a rapid rate (thousands of cells per minute, which is more than a little disgusting!). But before they flake off, they provide a very important layer of protection between the living skin below and the harsh, dangerous world around us. These dead skin cells are poor conductors of electricity, and they are a big part of the high impedance between the electrode and the living dermis (which itself has a very low impedance). A second major factor is that the outside of the skin is covered with a thin layer of an oil called *sebum* that is secreted by *sebaceous glands* in the dermis. Like the layer of dead skin cells, this oil serves to protect us from the surrounding environment but is a poor conductor of electricity.

**Figure 5.5**

(A) Major components of the skin. Adapted from a public-domain image provided by the National Institute of Arthritis and Musculoskeletal and Skin Diseases (www.niams.nih.gov/Health_Info/Acne/default.asp). (B) Cartoon of the skin and electrode after abrasion of the skin under the electrode. (C) Simplified electrical diagram of the skin's resistance. The “squiggly line” symbols represent resistors, and each resistor reflects the resistance or impedance of a small patch of the skin under the electrode.

The final major factor in determining the impedance between the outside of the skin and the electrode is sweat, which is generated in sweat glands and secreted through sweat pores on the surface of the skin (figure 5.5A). Sweat contains salt and is therefore highly conductive. When the sweat glands start filling with sweat, they become a means of conducting electricity between the outside of the skin and the dermis. This does not require that the sweat is actually pouring out onto the skin—the presence of sweat in the tube leading up to the sweat pore is sufficient to reduce the impedance of the skin at the location of that sweat pore. The amount of sweat in the sweat glands reflects both environmental factors (e.g., temperature and humidity) and psychological factors (e.g., stress). As these factors change, the level of sweat changes within the sweat glands, and this leads to changes in the impedance of the skin. These changes in impedance lead to changes in the standing voltage between the dermis and the outside of the skin, thus producing skin potentials.

To illustrate how sweat influences your EEG recordings, figure 5.5B shows an electrode pellet making an electrical connection with the epidermis via a conductive electrode gel. The epidermis ordinarily has a high impedance (due to oils and dead skin cells) that impedes the flow of brain-generated voltages through the dermis to the electrode gel and then to the electrode. The impedance may decrease gradually over time as the dead skin cells become hydrated by the electrode gel, because hydration makes the dead skin cells better conductors. This will lead to a very gradual shift in the voltage recorded by the electrode over a period of many minutes. In addition, the impedance will also decrease if a sweat gland in the skin under the electrode gel starts filling with sweat, providing a path for electricity to flow more readily across the epidermis. This will cause the recorded voltage to shift over a period of several seconds. In addition, the impedance will increase if the skin starts to become less hydrated or if the level of sweat in the sweat glands starts to decrease (e.g., if the subject begins to relax), and this will also cause changes in the skin potential. Thus, as the impedance shifts up and down over time, this creates a voltage that shifts up and down over time in the recording electrode. The very gradual shifts caused by hydration of the skin are not ordinarily a problem, but the faster changes caused by the sweat glands can add random variance to the EEG and reduce your ability to find statistically significant effects.

You can think of the electrode, electrode gel, epidermis, and dermis as a simple electrical circuit consisting of several resistors in parallel. As illustrated in figure 5.5C, each tiny patch of epidermis serves as a resistor. The impedances of the electrode, electrode gel, and dermis are negligible, so they are just represented as wires and dots. The overall impedance between the electrode and the dermis is mainly determined by the impedance of the little patches of epidermis between the electrode gel and the dermis. Because electricity follows the path of least resistance (and least impedance), decreasing the impedance of one little patch allows current to flow more easily from the dermis to the electrode pellet, changing the overall impedance for that electrode. More formally, the impedances of the little patches combine according to a basic principle of electricity: When multiple resistors are arranged in parallel, the overall resistance (e.g., the resistance between the electrode gel and the dermis in the figure) is less than the smallest of the

individual resistances. This is just a simple consequence of the fact that electricity tends to follow the path of least resistance. Thus, if each patch of epidermis has an impedance of about $50\text{ k}\Omega$, but a sweat gland starts filling with sweat and its impedance decreases to $10\text{ k}\Omega$, the overall resistance between the electrode gel and the epidermis will be a little less than $10\text{ k}\Omega$. This is why tiny sweat glands can have such a large impact on the overall impedance for a given electrode.

We can use the same basic principle of electricity to minimize the effect of the sweat glands on impedance. Specifically, if we abrade the skin under the electrode (by making tiny scratches), this will disrupt some of the dead skin cells and oils on the surface of the skin, providing a low-impedance path for electricity to travel through the epidermis. If the abraded region has a lower impedance than a filled sweat gland, then the overall impedance between the electrode gel and the dermis will be determined almost entirely by the impedance of the abraded region, and changes in the impedance of the sweat gland will not have much impact on the overall impedance. Box 5.5 describes some methods for reducing impedance.

Advantages and Disadvantages of High-Impedance Systems The online supplement to this chapter describes a study that Emily Kappenman conducted in my lab to determine whether skin potentials are actually a significant problem in high-impedance recordings (Kappenman & Luck, 2010). She ran an oddball paradigm and recorded the EEG with a high-impedance system, but she abraded half of the electrodes to reduce the impedance for those electrodes. She found that the high-impedance (unabraded) electrodes contained much more low-frequency noise than the low-impedance (abraded) electrodes, which reduced the statistical power by a large amount in an analysis of P3 amplitude. Thus, many more trials or subjects may be needed to obtain statistically significant effects if you use high electrode impedances than if you abrade the skin to provide low electrode impedances. However, impedance had much less impact on statistical power in analysis of the N1 wave (see the online supplement to this chapter for details).

It would be tempting to conclude from Emily's study that high-impedance systems are a bad idea and that everyone should rely on old-fashioned low-impedance systems. However, this would be a mistake. In fact, after we collected the data and saw the initial results, I bought a second high-impedance system that was identical to the first, and my lab has conducted and published many ERP studies using these high-impedance systems over the past several years. However, it is important for you to carefully consider the pros and cons of high-impedance systems, and if you use a high-impedance system, you need to take steps to minimize the problem of skin potential artifacts.

A very important thing to keep in mind is that different EEG recording systems typically vary along many dimensions that may influence data quality, and a high-impedance system from manufacturer A is not ordinarily inferior to a low-impedance system from manufacturer B. In fact, it is not the recording system that is the issue, but the actual electrode impedances in your subjects (which is a consequence of how you prepare the subject, not the recording system itself). All else being equal, including the actual electrode impedances, recordings from

Box 5.5

Reducing Electrode Impedances

There are several ways to reduce the electrode impedance. Some can be done before the electrodes are applied. For example, you can rub the skin with alcohol to reduce oils (or ask your subjects to wash their hair immediately before coming to the lab). You can also rub an abrasive paste or gel on the skin using a cotton-tipped swab. A product called Nuprep (made by Weaver and Company) is widely used for this purpose. Some labs ask subjects to comb or brush their hair vigorously when they arrive at the lab. These are good things to do even if you have a high-impedance system.

To get the impedance low enough for a traditional low-impedance system, it is almost always necessary to abrade the skin individually at each electrode site, but you don't know where the scalp electrodes will be until you've placed the electrode cap on the subject's head. Each electrode has a hole for squirting electrode gel into the space between the electrode and the skin, and you can lower something through this hole to abrade the skin. The goal of this is to disrupt some of the dead skin cells and expose the living skin cells below. One common method is to use a blunt, sterile needle to squirt the gel into the hole and then rub the tip of this blunt needle against the skin. I don't like this method because a blunt needle isn't very good for displacing the top layer of dead skin cells, and you have to rub pretty hard to get the impedance down to an acceptable level. When I've had this done to me, I found it quite unpleasant.

A better alternative is to put a drop of Nuprep on the end of a thin wooden dowel (e.g., the wooden end of a cotton-tipped swab), lower it into the electrode, and twirl it on the skin.

My favorite technique uses a sharp, sterile hypodermic needle. You lower it into the electrode hole, sweeping it back and forth as you are lowering it so that you don't poke directly into the skin. When you feel some resistance to the back-and-forth sweeping motion, you know that you're starting to touch the skin. You can also have the subject tell you when the needle is contacting the skin. Once the tip of the needle has contacted the skin, you just drag it lightly across the skin a few times. Remember, your goal is to disrupt the dead skin cells, not to puncture this skin. In my experience, this does a great job of reducing the impedance with minimal discomfort. However, it requires considerable practice to do this without occasionally poking the subject. You can practice on yourself first, then try a few friends or labmates before you start working with real subjects. This approach is a little scary (and also increases the risk of disease transmission), and you need a biohazard waste disposal container, so you might just want to use the wooden dowel with Nuprep.

Whatever you do, the method should be clearly stated in your ethics approval form and on your consent form.

a high-impedance system should be as good as or better than recordings from a low-impedance system. Although I haven't done a formal assessment, I think the data quality from my current high-impedance recordings is nearly as good as the data quality from my previous low-impedance recordings (from a traditional low-impedance system). In addition, my informal observations of a variety of EEG recording systems suggests that some high-impedance systems yield much higher data quality than others. I won't "name names," because I haven't formally compared different systems, but you should certainly compare systems carefully before purchasing one (for a brief direct comparison, see Kayser, Tenke, & Bruder, 2003).

When deciding what kind of system to use, it is important to remember that abrading the skin carries a slight risk of disease transmission, and the reduction in this risk is a benefit of high-impedance recordings. This was a factor in my decision to buy a high-impedance system.

High-impedance recordings also mean that you will save time when preparing the subject, because you won't need to abrade the skin under each electrode. However, it is not clear that this will save you any time in the long run, because you may need many more subjects or trials per subject to obtain statistical significance in high-impedance recordings. Moreover, as discussed in the online supplement to this chapter, you may not really need to record from a large number of electrodes. Thus, it's not clear that high-impedance recordings really save you any time.

An exception to this arises in recordings from infants and small children, who cannot tolerate a long period of electrode preparation. It is very difficult to record from these subjects if you need to abrade the skin under each electrode. Moreover, parents are not happy when their children have a red spot or a scab at the electrode locations at the end of the recording session. Consequently, the advantages of high-impedance recordings are very important in studies with infants and small children. However, not all high-impedance systems are the same, and if you are doing this type of research, I would encourage you to think carefully about data quality when selecting a recording system and when developing your electrode application procedures. In particular, I suspect that the use of an electrode gel to make an electrical connection between the electrode and the scalp will lead to more stable impedance levels—and therefore fewer artifactual voltage fluctuations—than will the use of saline to make this connection, especially in subjects who move a lot. Again, I have not formally compared electrode gels and saline, so I cannot make a strong claim here. I would strongly recommend talking to people who use multiple different systems before choosing a particular system (and talk to the people who actually record and analyze the data, not the lab chief who sits in his or her office drinking coffee and writing grants and papers all day long).

If you decide to use a high-impedance system, there are several things you can do to minimize skin potentials and their effects on statistical power. First, many labs ask subjects to wash their hair on the day of the recording, which will decrease the oils on the surface of the skin that contribute to the electrode impedance. Some labs even have subjects comb or brush their hair vigorously immediately prior to electrode application, which may displace some of the dead skin cells on the surface of the epidermis, decreasing the impedance. This seems like a reasonable

idea (as long as the comb or brush is disinfected after each use), and my lab has recently started doing it. Second, many high-impedance systems provide a measure (e.g., an impedance value or offset value) for each electrode that you can use to make sure that the impedance is within a reasonable range. Spending some time checking these values and monitoring them over the course of each session will save you a lot of time in the long run. Third, you should make sure that your recording environment is cool, because this will tend to reduce sweating. Chapter 16 provides some specific advice about this. Fourth, if you are running an experiment in which you need extra statistical power, you may want to abrade the skin a little bit to keep the impedances reasonably low (e.g., $<20\text{ k}\Omega$). In some cases, you can do this just for the electrodes that will be contributing to the main statistical analyses (along with the ground and reference electrodes). Finally, you should do all the other small and large things that I describe in this book that influence data quality and statistical power. For example, you should track down and eliminate sources of electrical noise and follow the advice that I provide in online chapter 16 about monitoring subjects and keeping them happy.

Amplifying, Filtering, and Digitizing the Signal

Once the EEG has been picked up by the electrodes, it must be amplified and then converted from a continuous, analog voltage into a discrete, digital form that can be stored in a computer. Fortunately, these processes are relatively straightforward, although there are a few important issues that must be considered, such as choosing an amplifier gain and a digitization rate.

Analog-to-Digital Conversion and High-Pass Filters

The EEG is an analog signal that varies continuously over a range of voltages over time, and it must be converted into a set of discrete *samples* to be stored on a computer. This is called *digitizing* the EEG. As illustrated in figure 5.6, the samples are discrete in terms of both voltage and time (i.e., there are a fixed set of possible voltage values at a fixed set of time points). The continuous EEG is converted into these discrete samples by a device called an *analog-to-digital converter* (ADC). In older EEG digitization systems, the ADC had a resolution of 12 bits. A 12-bit ADC can code 2^{12} , or 4096, different voltage values (intermediate values are simply rounded to the nearest whole number). For example, if the ADC has a range of -5 V to $+5\text{ V}$, a voltage of -5 V would be coded as 0, a voltage of $+5\text{ V}$ would be coded as 4096,¹ and the intermediate voltages would be coded in discrete steps of 0.00244 V (because the 10-V range of values is divided into 4096 equal steps, and $10 \div 4096 = 0.00244$).

The EEG is amplified before being digitized, which provides much smaller steps between values. For example, if the EEG is amplified by a factor of 10,000 before being digitized, your ADC will have an effective range of $\pm 500\text{ }\mu\text{V}$ and a step size of $0.244\text{ }\mu\text{V}$. This amplification factor is called the *gain* of the amplifier. Amplification is necessary to bring the EEG voltage into the appropriate range for the ADC.

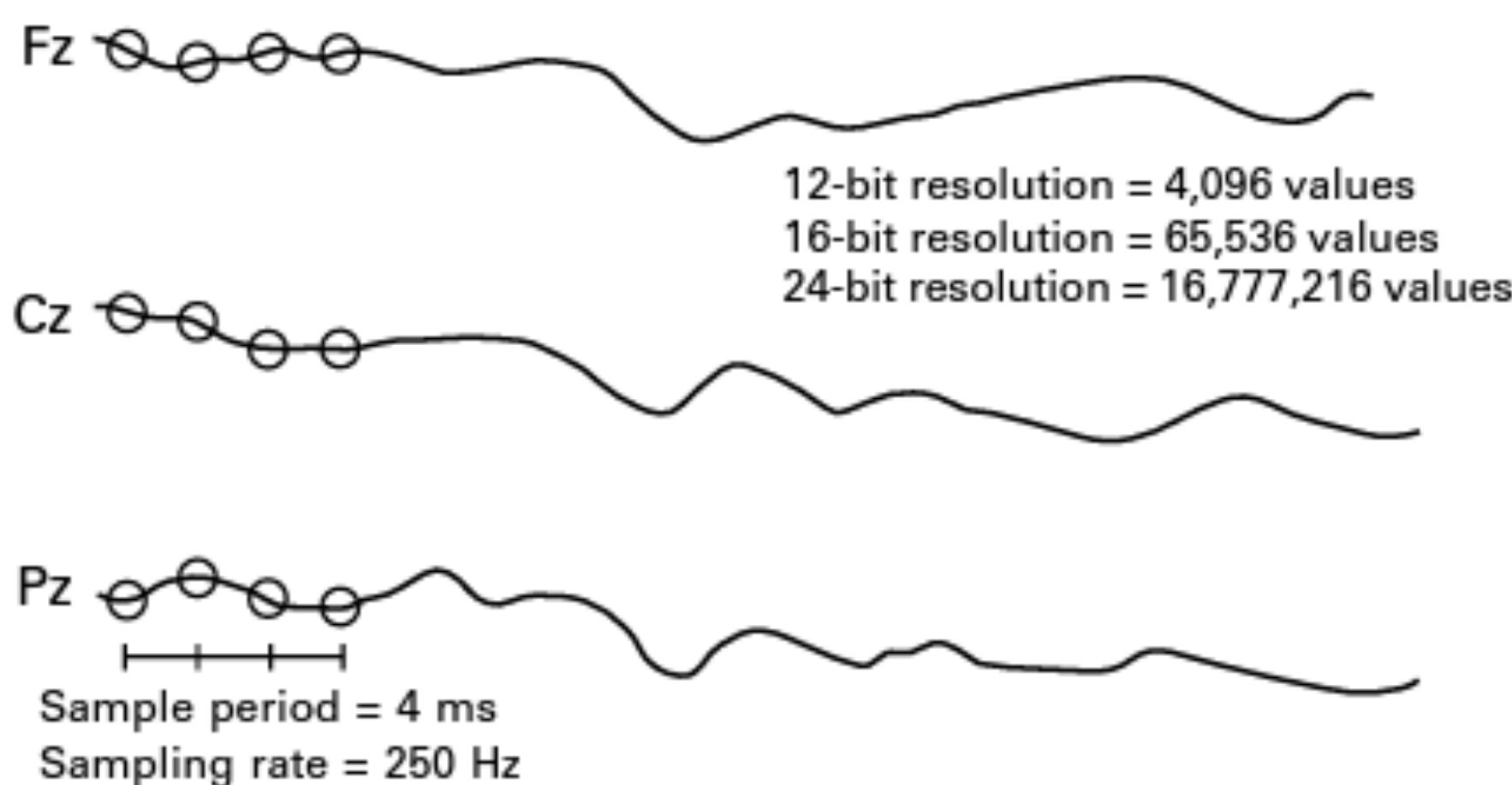


Figure 5.6

Digitization (sampling) of the EEG. A discrete sample is taken from each channel every 4 ms in this example, so the sample period is 4 ms. This is the same as 250 samples per second in each channel, so the sampling rate is 250 Hz.

Most modern EEG recording systems use the gain of the amplifier and the properties of the ADC to recode the discrete ADC values into units of microvolts. In the bad old days, the raw EEG was stored in the original ADC units, and we had to go through a series of extra steps to convert these values into microvolts.

Newer EEG systems typically use ADCs with 16–32 bits. This provides both greater resolution (smaller differences in voltage between each possible ADC value) and a broader range of possible values. The broader range is actually more important than the increased resolution. If your ADC has a resolution (step size) of $0.244 \mu\text{V}$, you might think you would be unable to detect an experimental effect of $0.2 \mu\text{V}$. But you would be wrong. When you average together many trials to create averaged ERP waveforms, you effectively increase your resolution. For example, even though the set of numbers {1, 2, 2, 2, 1, 1, 1, 1} contains only 1s and 2s, the average of this set is 1.375. Thus, a resolution of a quarter of a microvolt is sufficient for almost any ERP experiment. Most newer EEG recording systems provide a far greater resolution than this. You shouldn't worry about the resolution, and you certainly shouldn't choose one system over another because of differences in voltage resolution.

However, a broad range of values is very useful. If you have a 12-bit ADC with an effective range of $\pm 500 \mu\text{V}$, the EEG will often drift past the range of values. This drift can occur because of skin potentials and because of small static charges in the electrodes. If you are using a 12-bit or 16-bit ADC, you will need to filter out low frequencies to make sure that the voltages don't drift outside the ADC range. You will also need to make sure that the gain of your amplifier is low enough that you don't exceed the ADC range very often (and that you reject trials when this happens, as will be discussed in chapter 6). However, you should make sure that the gain of your amplifier is high enough that your voltage resolution is reasonably good (at least a quarter of a microvolt).

Filters are described in more detail in chapter 7 and online chapter 12, but I will say a few words about them in this chapter so that you know how to set the filters in your EEG acquisition system. To avoid drift, you can use a *high-pass* filter (a filter that passes high frequencies and suppresses low frequencies). You will definitely want to use a high-pass filter during data acquisition if you are using a 12- or 16-bit ADC (with a half-amplitude cutoff of between 0.01 and 0.1 Hz; see chapter 7 for details). However, the high-pass filters that are implemented in EEG amplifiers are inferior to the filters that you can apply in software. Consequently, if your ADC has a resolution of at least 24 bits, you can record without a high-pass filter (assuming that your system allows you to turn off the high-pass filter). This is called a *direct coupled* (DC) recording, because the EEG signal is directly coupled to the amplifier rather than being coupled through a capacitor. You can then filter out the low frequencies offline with a superior software filter.

If you are shopping for an EEG recording system, I recommend that you get a system with at least 20 bits of ADC resolution if you can afford it. If you can't afford it, you can live with 12 or 16 bits as long as you filter out the low frequencies prior to digitization. If a system has 12–16 bits of ADC resolution, the gain should be adjustable, with a minimum gain of 1000 or less and a maximum gain of 20,000 or more. In addition, a system like this should allow you to select among several high-pass cutoffs, including 0.01 Hz, 0.1 Hz, and 0.5 Hz (or nearby frequencies). These options will give you the ability to do many different kinds of ERP experiments. Systems with at least 20 bits of ADC resolution do not need to have a user-adjustable amplifier gain because they have enough range and resolution to deal with virtually any imaginable ERP experiment. These systems also do not need to include high-pass filters that operate prior to digitization because the EEG will never exceed the amplifier range (unless an electrode becomes disconnected) and the low frequencies can be filtered offline. I don't think there is any value in going beyond 24 bits of ADC resolution, although I won't be surprised if manufacturers someday start advertising that they are using 64-bit ADCs.

Discrete Time Sampling and Low-Pass Filters

The ADC takes samples of the continuous EEG signal at regularly spaced time points and converts the measured voltage into a number at each time point. As illustrated in figure 5.6, the *sampling period* is the amount of time between consecutive samples (e.g., 4 ms), and the *sampling rate* is the number of samples taken per second (e.g., 250 Hz). When multiple channels are sampled, most systems sample the channels sequentially rather than simultaneously; however, the digitization process is so fast that you can think of the channels as being sampled simultaneously (unless you are examining extremely high frequency components, such as brainstem evoked responses). Some systems contain a separate ADC for each channel, but this seems like an unnecessary expense for the vast majority of experiments.

How do you decide what sampling rate to use? To decide, you need to know about the *Nyquist theorem*, which states that all of the information in an analog signal such as the EEG can be captured digitally as long as the sampling rate is more than twice as great as the highest frequency in the signal. You should avoid sampling at lower rates because you will be losing information.

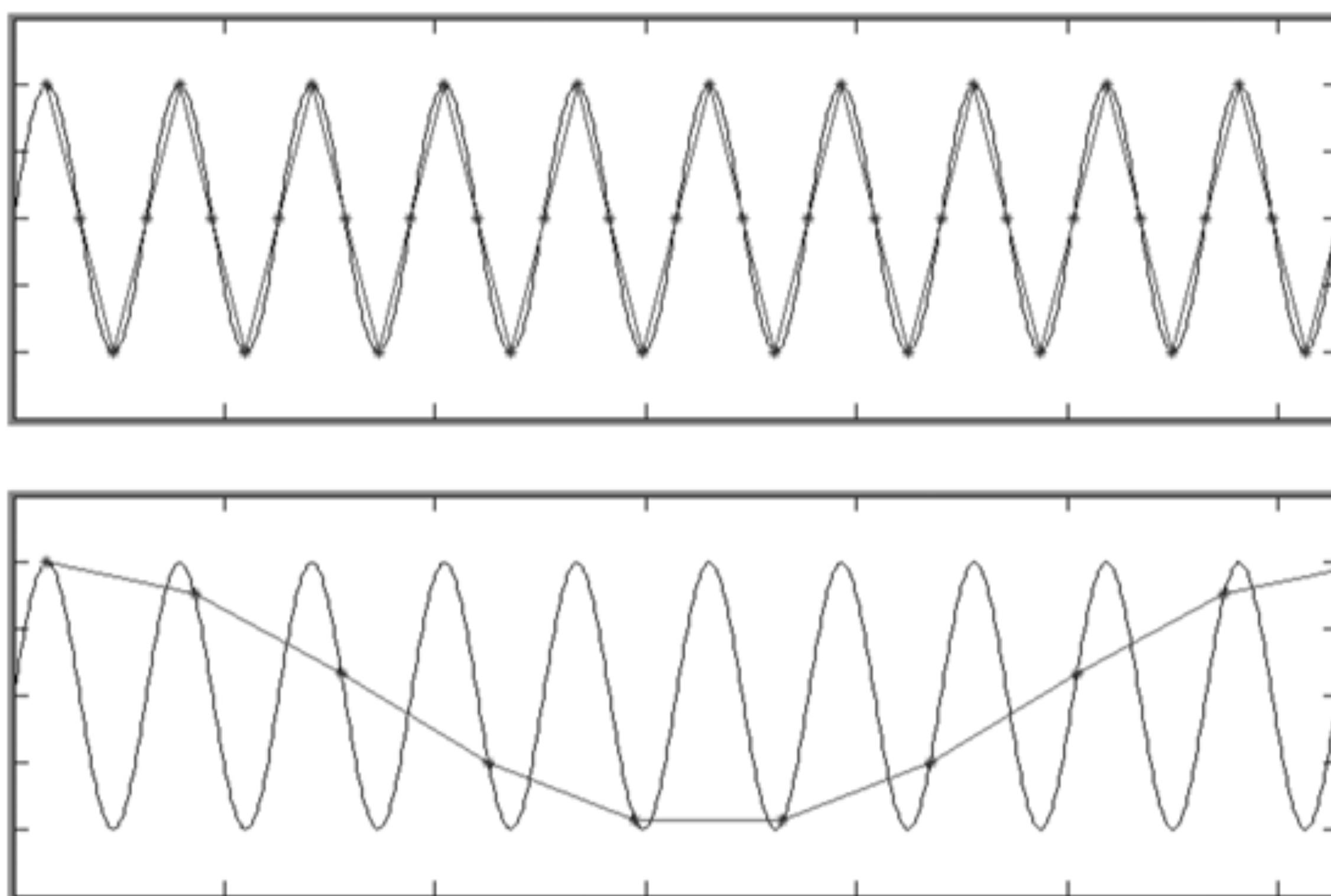


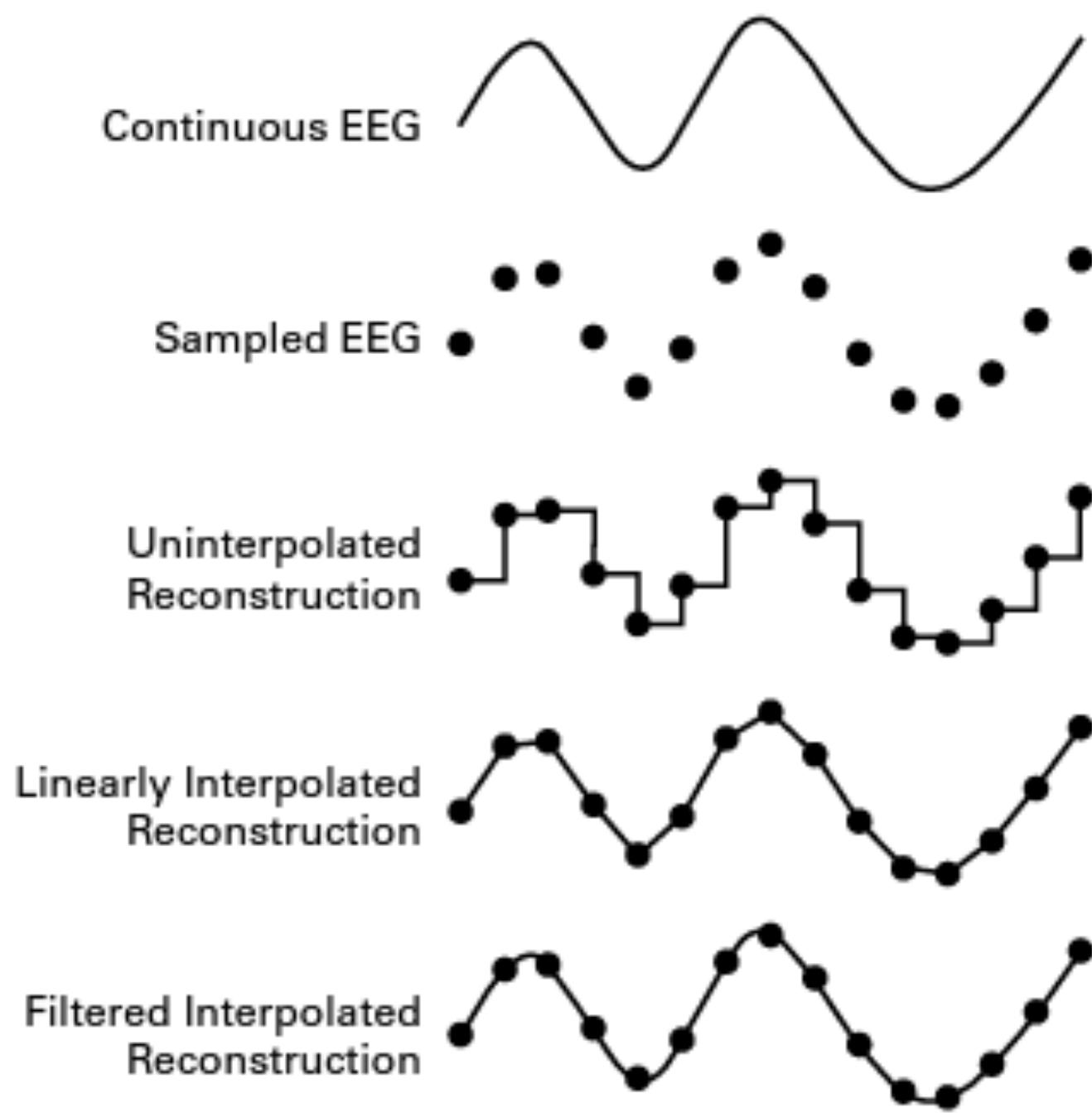
Figure 5.7

Example of aliasing. The black line is the original sine-wave signal, and the gray line simply connects the sampled values together. When the sampling is fast enough (top), the frequency of the samples reflects the frequency of the original signal. When the sampling is too slow (bottom), the sampled data appear to be at a much lower frequency.

In addition, if you sample at lower rates, you will induce artifactual low frequencies in the digitized data (this is called *aliasing*).

Aliasing is illustrated in figure 5.7. The top panel shows a sine wave that is sampled four times for each cycle, and you can see that it captures the frequency of the sine wave quite well. The bottom panel shows the same sine wave, but sampled a little less than once per cycle. When the samples are connected into a waveform, they form a very slow oscillation. Thus, when you sample too slowly, your high frequencies will be transformed into low frequencies.

Figure 5.8 provides a closer look at the idea that sampling allows you to capture all of the information in a continuous signal. When you sample, you are missing little bits of the signal between the samples, so you might think you are losing information. In fact, if you try to reconstruct the signal without any interpolation, you will get a waveform that is quite a bit different from the original signal. However, if you interpolate by simply drawing lines between each sample, you will obtain a fairly close approximation of the original signal. To obtain an exact reconstruction, you would need to use a more sophisticated interpolation method (which is beyond the scope of this book). With the appropriate interpolation method, you can reconstruct the original signal essentially perfectly (within the limits of the physical system). Thus, you will

**Figure 5.8**

Interpolation to reconstruct the continuous EEG from the samples. When appropriate interpolation is used, the reconstruction is essentially perfect. Linear interpolation is imperfect, but good enough for most purposes (assuming that the data were originally digitized at a sufficiently high sampling rate).

not lose any information by sampling (as long as you sample more than twice as fast as the highest frequency in the signal), but you will need to use intelligent interpolation if you ever want to reconstruct the original continuous signal.

To sample at a high enough rate, you need to know the frequency content of the signal that you are recording. If you are interested in ERPs that mainly contain power below 30 Hz, you might think you could just record at any rate higher than 60 Hz. However, the EEG will contain frequencies higher than 30 Hz, even if you're not interested in them, and the Nyquist theorem says that we need to sample more than twice as fast as *any* frequency that is in the signal. You can't really know in advance what frequencies might be present, so the standard approach is to use a hardware filter that eliminates all activity above a certain frequency and then sample more than twice as fast as this cutoff frequency.

Filtering will be discussed in more detail in chapter 7, but I will say a few more words here so that you know how to filter out the high frequencies prior to digitization. A filter that suppresses high frequencies and passes low frequencies is called a *low-pass filter*. Often, the filters that are used prior to digitization are called *anti-aliasing filters*, but they are really just low-pass filters.

In the vast majority of experiments that examine cognitive or affective processes, there is very little information of interest in the EEG above approximately 100 Hz. For such experiments,

you can set your low-pass filter cutoff at 100 Hz and sample at 400 Hz or higher. You will want to sample three to five times faster than the cutoff frequency of the filter because some activity above the cutoff frequency will be present in the filter's output (see chapter 7 for details). If you are not interested in high-frequency activity such as gamma oscillations, you could filter at 50 Hz and sample at 200 Hz or higher. If you are interested in very early sensory responses (e.g., <20 ms), you will want to filter and sample at a higher frequency (just look at published papers in your area of interest to see what frequencies other people use). Note that many systems automatically set the low-pass cutoff on the basis of your selected sampling rate (which is a good idea, because it avoids accidental errors).

For almost all cognitive and affective neuroscience experiments, I recommend a sampling rate between 200 and 1200 Hz. If you are near the low end of this range, you will use much less disk space, and all of your data analyses will run faster. Speed can be a significant issue, with some kinds of analyses taking hours or days (especially if you are using a computer with limited RAM). The main advantage of a higher sampling rate (assuming you are looking at typical cognitive or affective ERPs) is that you will have more precision in your latency measurements. But this greater precision may provide no practical advantage. For most analyses, the noise in the data is sufficiently great that a rounding error of ± 2 ms (which is the error that you will get with a sampling rate of 250 Hz) is inconsequential. One exception to this arises when you use the jackknife analysis approach (described in chapter 10), which dramatically reduces noise in the measurement process, making small rounding errors meaningful. If you use this approach, you may want a higher sampling rate. However, you don't need a higher sampling rate with this approach if your data analysis system uses intelligent interpolation during latency measurement or if you can resample the data at a higher sampling rate prior to latency measurement (using interpolation during the resampling). I find that a sampling rate of approximately 250 Hz is ideal for most cognitive and affective neuroscience experiments.

Amplifier Gain and Calibration

The signal from each active electrode passes through a separate amplifier before being digitized (so that the range of EEG values is appropriate for the ADC). In the old days, a 16-channel EEG amplifier was a fairly large device, covered with switches for setting the gain and filters for each channel. In most modern systems, the electrodes are attached to a small box that contains both the amplifiers and the ADC, and all the settings are controlled by an attached computer rather than by physical switches. Each channel is typically set to the same gain (amplification factor) and filter settings, although some systems allow different settings for different channels. Some systems do not give you any control over the gain and filter settings; they have a fixed gain and automatically vary the cutoff frequency of the anti-aliasing filter to match whatever sampling rate you specify. Although this gives you less flexibility, it avoids errors. When my lab used a system that allowed custom settings, we would sometimes find that someone had changed the settings without telling anyone, and these new settings were therefore used for a subset of subjects in ongoing experiments. I was happy to give up flexibility to avoid these kinds of mistakes

when we switched to our current system, which does not allow the user to directly modify the gain and filter settings.

Whether or not you directly set the gain on your amplifier channels, the actual gains will not be exactly what you specify, and they will not be exactly the same across channels (because analog devices like amplifiers are never perfect). It is therefore important to calibrate your system. The best way to do this is to pass a voltage of a known size through the system and measure the system's output. For example, if you create a series of 10- μ V voltage pulses and run them into your recording system, it may tell you that you have a signal of 9.8 μ V on one channel and 10.1 μ V on another channel. You can then generate a scaling factor for each channel (computed by dividing the actual value by the measured value), and multiply all of your data by this scaling factor. You can apply this multiplication process to the EEG data or to the averaged ERP waveforms; the result will be the same. The gains of the channels of an EEG amplifier may drift over time, so it is a good idea to calibrate the amplifiers for each subject.

Some EEG amplifiers are permanently calibrated, meaning that the manufacturer guarantees that the actual gain of each channel will be within some small range of the specified gain. For example, if you set the gain to be 1000, the manufacturer guarantees that the actual gain will be within X% of this value (e.g., within 5%). In these systems, it's not always obvious to the casual user that the EEG is being amplified before being digitized, because the output of the system is in units of microvolts. However, whatever system you are using, the signal is being amplified in some manner, and imperfect calibration of the amplifiers will have some effect on your data.

The effects of imperfect calibration may be minuscule or enormous, depending on how great the imperfections are and what you are doing with your data. If you are just looking at individual channels, minor imperfections in calibration (e.g., $\pm 5\%$) are not important because the exact size of an ERP effect does not usually mean very much. For example, it is unlikely to change your conclusions if the average N400 amplitude in a given experiment appeared to be 4.2 μ V even though the true value was 4.0 μ V. However, if the gain varies from subject to subject, this will add variance to your data and decrease your statistical power. If your system is not permanently calibrated, you should calibrate it for each subject to avoid this kind of variance. You should also calibrate regularly if you are combining data recorded from multiple systems (even multiple instances of the same type of system).

Whether or not your system is permanently calibrated, small differences in gain from channel to channel can distort your scalp distributions. If, for example, some of the channels have an actual gain of 95% of the specified value and others have an actual gain of 105% of the specified value, this could lead to systematic errors in ERP source localization. If you ever want to do any kind of ERP localization, you should definitely calibrate your amplifiers, even if the manufacturer claims that they are permanently calibrated. In my lab, we don't do source localization of ERP data, and we have permanently calibrated amplifiers, so we don't worry much about calibration.

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