input will usually have higher fidelity (but may have unknown timing properties). Figure 8.4 illustrates the output of the LCD at the location of a white square that was presented on a black background. The square was supposed to onset at 0 ms (the time of the event code) and offset at 350 ms (and this is exactly what would have happened if I had used a CRT monitor).

Figure 8.4A shows the entire time course of the LCD output; the onset and offset appear on expanded time scales in figures 8.4B and 8.4C, respectively. The figure illustrates three potential problems with LCDs. First, the LCD's output is slightly delayed: The onset of the luminance change does not begin until approximately 7 ms after the event code, and the luminance does not begin to decline until approximately 357 ms. I suspect that this is caused by the analog VGA connection; the analog signal must be converted back into a digital form by the LCD monitor. Second, the onset is not instantaneous, but instead builds up over a period of approximately 5 ms. This is probably fast enough for the majority of ERP experiments, but this particular LCD display was chosen for its rapid onset time, and other LCD displays ramp up over a substantially longer period. Third, the offset of the display is very gradual, requiring almost 100 ms to reach the baseline luminance value. This won't be a significant problem when stimuli are presented on a black background. However, if the stimuli are presented on a white background, the onset of a stimulus will be achieved by a decrease in luminance, and the luminance will change in the slow manner shown in figure 8.4C. This could be quite problematic for experiments in which precise timing is important.

LCDs do have a very significant advantage over CRTs: They don't pump a stream of electrons directly toward the subject's head. Consequently, LCDs should produce less electrical noise than CRTs, and a Faraday cage may not be necessary. LCDs may therefore become the best choice for most experiments once the technology reaches maturity. In the meantime, you may wish to try using LCD monitors, but you should carefully test the timing of an each display before using it (different models may have radically different temporal properties).

Appendix: Basic Principles of Electricity

This appendix describes some important aspects of electricity and magnetism that arise when considering the neural origins of ERPs and sources of noise that can arise in ERP recordings.

Electricity is simply the flow of charges through a conductive medium. In electrical circuits, it is usually electrons that actually flow. In the nervous system, much of the electricity is due to the movement of small ions across cell membranes. But the principles of electricity are the same in both of these situations.

Voltage, Current, and Resistance

The three most fundamental terms in electricity are *voltage*, *current*, and *resistance*. Voltage is essentially electrical pressure and is analogous water pressure. Voltage is also called electrical *potential*, because it reflects the potential for electrical current to flow from one place to another. This can be understood by analogy to the flow of water through pipes. Consider, for example, a tank of water at the top of a hill. There is a lot of potential for the water to flow to the bottom of the hill, but little potential for the water to float up to the top. Importantly, the potential for water to flow downhill is present even if no water is flowing at a given moment (e.g., because a valve is closed). Similarly, there is potential for electrical current to flow from one terminal of a car battery to the other even if no current is flowing. Voltage is usually labeled *E* for *electromotive force*.

Current is the number of charged particles (e.g., electrons) that flow past a given point in a specific amount of time. Current is measured in amperes, where 1 ampere is equal to 1 coulomb

(6.24×10^{18}) of charges moving past a single point in one second. Measuring electrical current is analogous to measuring the quantity of water that passes through a given segment of pipe in a fixed time period (e.g., 10 liters per minute). Current is usually labeled I for *intensity*.

Resistance is the ability of a substance to keep charged particles from passing (it's the inverse of *conductance*). Three main factors contribute to resistance: (1) the composition of the substance, (2) its length, and (3) its diameter. Due to their molecular properties, some substances conduct electricity better than others (e.g., copper is a better conductor than zinc). However, the ability of any substance to conduct electricity will be reduced if it is very thin. To use yet another hydraulic example, consider a water filtration system in which the water supply for a house passes through a large tank filled with carbon. If the carbon is tightly packed, water will not easily flow through the tank, but if the carbon is loosely packed, water will flow easily. This is analogous to the dependence of electrical resistance on the properties of the substance. Now imagine water passing through a hose. If the hose is very long and narrow, a great deal of pressure will be necessary to fill a bucket in a short amount of time; if the hose is short and wide, the bucket will fill quickly with only a moderate amount of water pressure. This is analogous to the dependence of electrical resistance on the length and diameter of the conductor. Resistance is measured in *Ohms* (Ω) and is usually labeled R.

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

Ohm's Law

These relationships are summarized by Ohm's law: $E = IR$ (voltage is equal to the product of the current and the resistance). This means that 1 volt of electromotive force is required to pass 1 ampere of current through a resistance of 1 ohm. This equation implies that if the voltage is increased, then this must be accompanied by an increase in current, an increase in resistance, or changes in both current and resistance. In particular, if the voltage increases and the resistance is constant, then the current must increase in proportion with the voltage. This makes sense, because an increase in the pressure (voltage) naturally leads to an increase in current. However, a somewhat less intuitive consequence of Ohm's law is that if the resistance increases and the current is held constant, then the voltage must increase in proportion to the resistance. This might seem counterintuitive, because you might expect that an increase in resistance would lead to a decrease in voltage, but it actually leads to an increase in voltage (assuming that current remains constant). However, this makes sense if you think about the hydraulic analogy: If you use a thinner hose but still have the same amount of water coming out the end, you must have increased the water pressure.

Another implication of Ohm's law is that it is possible to have a very large voltage without any significant current if the resistance is near infinity, which is very common (as in the case of the terminals of a car battery when they are not connected to anything). However, the only way to get a significant current without any significant voltage is to have a resistance that is near zero, which is very uncommon (it requires supercooling).

Impedance

There is one other term that I would like to mention in this context, namely *impedance*. Technically, the term *resistance* applies only when the current is constant over time (which is called direct current or DC), and *impedance* is the appropriate term to use when the current varies over time (alternating current or AC). Because ERPs vary over time, impedance is generally the most relevant concept. A different term is necessary because there are certain factors that contribute to impedance that do not contribute to DC resistance (specifically, inductance and capacitance). However, for most practical purposes, impedance is analogous to resistance, so you don't need to worry about the differences. Impedance is usually labeled Z, and most impedance meters measure the impedance using a small sine-wave voltage oscillating at around 10 Hz.

Electricity and Magnetism

Electricity and magnetism are fundamentally related to each other, and it is important to understand this relationship to understand how ERP recordings pick up electrical noise and how MEG/ERMF recordings are related to EEG/ERP recordings. Current flowing through a conductor generates a magnetic field that flows around the conductor. Moreover, if a magnetic field passes through a conductor, it induces an electrical current. Figure A.1 illustrates these

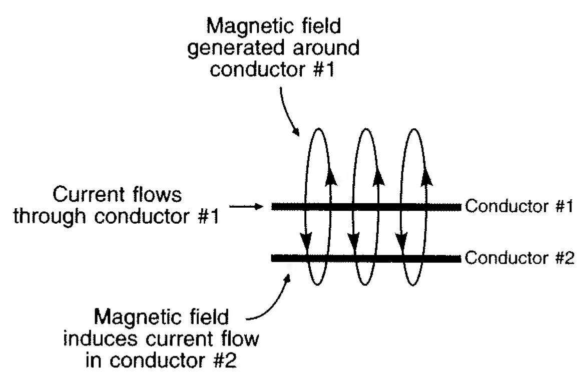

Figure A.1 Relationship between electricity and magnetism. A current is passed through conductor #1, and this generates a magnetic field that circles around conductor #1. As this magnetic field passes through conductor #2, it induces a small current in conductor #2.

two principles, showing what happens when a current passes through one of two nearby conductors. The flow of current through one of the conductors generates a magnetic field, which in turn induces current flow in the other conductor. This is how electrical noise in the environment can induce electrical activity in an ERP subject, in the electrodes, or in the wires leading from the electrodes to the amplifier.