

ELECTROENCEPHALOGRAPHIC METHODS IN PSYCHOLOGY

Eddie Harmon-Jones and David M. Amodio

PHYSIOLOGY UNDERLYING ELECTROENCEPHALOGRAPHY

Electroencephalography (EEG) refers to the recording of electrical brain activity from the human scalp. This method of measurement was discovered by Hans Berger in the late 1920s in experiments in which two sponges were soaked in saline and were then connected to a differential amplifier (Berger, 1929). EEG measurement techniques have advanced considerably since that time, and they now represent one of the most common methods for measuring brain function in studies of basic psychological and motor processes and in studies of psychological and motor dysfunction.

The observed EEG at the human scalp is the result of electrical voltages generated inside the brain. Electrical activity that is associated with neurons comes from action potentials and postsynaptic potentials. Action potentials are composed of a rapid series of electrochemical changes that run from the beginning of the axon at the cell body to the axon terminals where neurotransmitters are released. Postsynaptic potentials occur when the neurotransmitters bind to receptors on the membrane of the postsynaptic cell. This binding causes ion channels to open or close and it leads to a graded change in the electrical potential across the cell membrane. In contrast to EEG measurements, when electrical activity is measured by placing an electrode in the intercellular space, action potentials are more easily measured than postsynaptic potentials because it is

difficult to isolate a single neuron's postsynaptic potentials in extracellular space. Thus, the recording of individual neurons or single-unit recordings assesses action potentials but not postsynaptic potentials.

EEG is distinguished from electrocorticography (ECoG), in which electrodes are placed directly on the exposed surface of the cortex. Electrodes may be placed outside of the outer cranial membrane or dura mater (epidural) or under the dura mater (subdural). ECoG is typically performed in a medical operating room because a surgical incision into the skull is needed to implant the electrode grid onto the cortex. ECoG is often used to identify the origins of epileptic seizures in individuals whose epilepsy cannot be treated with nonsurgical methods. During such sessions, ECoG is also used for functional cortical mapping to ensure that important functions (e.g., language production) are not harmed during surgery. Once the regions that are responsible for epileptic seizures are identified, they are surgically removed from the cortex. During such surgeries, researchers have also been able to use ECoG to identify cortical regions that are involved in psychological and behavioral processes (e.g., Crone, Sinai, & Korzeniewska, 2006). ECoG signals are composed of synchronized postsynaptic potentials. These potentials occur primarily in cortical pyramidal cells. Because the potentials are recorded from the surface of the cortex, they must be conducted through several layers of the cerebral cortex,

The work presented herein was funded in part by a grant from the National Science Foundation (0921565), awarded to Eddie Harmon-Jones.

DOI: 10.1037/XXXXX.XXX

APA Handbook of Research Methods in Psychology: Vol. 1. Foundations, Planning, Measures, and Psychometrics, H. Cooper (Editor-in-Chief)
Copyright © 2012 by the American Psychological Association. All rights reserved.

cerebrospinal fluid, pia mater, and arachnoid mater before reaching subdural recording electrodes that are placed just below the dura mater (outer cranial membrane). Electrical signals must also be conducted through the skull with EEG; thus, the electrical potentials are severely reduced because of the low conductivity of bone. Consequently, the spatial resolution of ECoG is much higher than EEG.

Scalp-recorded EEG reflects the summation of postsynaptic potentials rather than action potentials because of the timing of action potentials and the physical arrangement of axons. That is, unless the neurons fire within microseconds of each other, action potentials in different axons will typically cancel each other out. If one neuron fires shortly after another one, then the current at a given location will flow into one axon at the same time that it flows out of another one; thus, they cancel each other and produce a much smaller signal at the electrode. Although the duration of an action potential is approximately 1 ms, the duration of postsynaptic potentials is much longer, often tens or hundreds of milliseconds. Postsynaptic potentials are also mostly confined to dendrites and cell bodies and occur instantaneously rather than traveling down the axon at a fixed rate. These factors allow postsynaptic potentials to summate rather than to cancel, which results in voltage changes that have larger amplitudes and can be recorded on the cortical surface or at the scalp. Hence, EEG signals are most likely the result of postsynaptic potentials, which have a slower time course and are more likely to be synchronous and summate than presynaptic potentials.

Scalp-recorded electrical activity is the result of the activity of populations of neurons. This activity can be recorded on the scalp surface because the tissue between the neurons and the scalp acts as a volume conductor. The activity generated by one neuron is small; thus, the activity that is recorded at the scalp is the integrated activity of numerous neurons that are active synchronously. Moreover, for activity to be recorded at the scalp, the electric fields that are generated by each neuron must be oriented in such a way that their effects cumulate. That is, the neurons must be arranged in an open as opposed to a closed field. In an open field, the neurons' dendrites are all oriented on one side of the structure,

whereas their axons all depart from the other side. Open fields are present where neurons are organized in layers, as in most of the cortex, parts of the thalamus, the cerebellum, and other structures.

The raw EEG signal is a complex waveform that can be analyzed in the temporal domain or frequency domain. Processing of the temporal aspect is typically done with event-related potential designs and analyses, and has been discussed by Bartholow and Amodio (2009). In this chapter, we focus on frequency analyses of EEG, in which frequency is specified in hertz or cycles per second.

EEG RECORDING

In contemporary psychological research, EEG is recorded from 32, 64, 128, or more electrodes that are often mounted in a stretch-lycra electrode cap. Caps are relatively easy to position on a participant's head, and they include electrodes positioned over the entire scalp surface. Electrodes are often made of tin or silver and silver chloride; the latter are nonpolarizable but are typically much more expensive. Most modern EEG amplifiers with high input impedance utilize very low electrode currents; thus, polarizable electrodes (tin) can often be used to record the typical range of electrical frequencies that are of interest in psychology experiments without distortion. However, for frequencies less than 0.1 Hz, nonpolarizable electrodes are recommended (see Polich & Lawson, 1985).

The electrode placements are typically based on the 10–20 system (Jasper, 1958), which was subsequently extended to a 10% electrode system (Chatrian, Lettich, & Nelson, 1988) and beyond. The naming convention for electrode positions is as follows. The first letter of the name of the electrode refers to the brain region over which the electrode sits. Thus, Fp refers to Frontal Pole, F refers to Frontal region, C to Central region, P to Parietal region, T to Temporal region, and O to Occipital region. Electrodes in between these regions are often designated by using two letters, such as FC for Frontal-Central. After the letter is a number, as in F3, or another letter, as in Z. Odd numbers are used to designate sites on the left side of the head and even numbers are used to designate sites on the

right side of the head. Numbers increase as distance from the middle of the head increases, so F7 is farther from the midline than F3. Z is used to designate the midline, which goes from the front to the back of the head. See Figure 26.1, which illustrates a modern multichannel system based on the 10–20 system. Caps often contain a ground electrode, which is connected to the iso-ground of the amplifier and assists in reducing electrical noise. Eye movements, recorded using an electro-oculogram (EOG), are also recorded to facilitate artifact scoring of the EEG. EOG can be recorded from the supra- and suborbit of the eyes, to assess vertical eye movements, and from the left and right outer canthus, to

assess horizontal eye movements. Additional electrodes are often placed on ear lobes so that off-line digitally derived references can be computed. See the section “Referencing” for a more complete discussion of reference electrodes.

Sites where electrodes will be placed must be abraded (i.e., exfoliated) and cleaned to reduce electrode impedances, typically under 5,000 ohms. Mild skin abrasion removes dead skin cells and oils that impede electrical conductance. Conductive gel is used as a medium between the scalp and electrodes. EEG, EOG, and other signals are then amplified with bio-amplifiers. For EEG frequency analyses, the raw signals are often bandpass filtered online

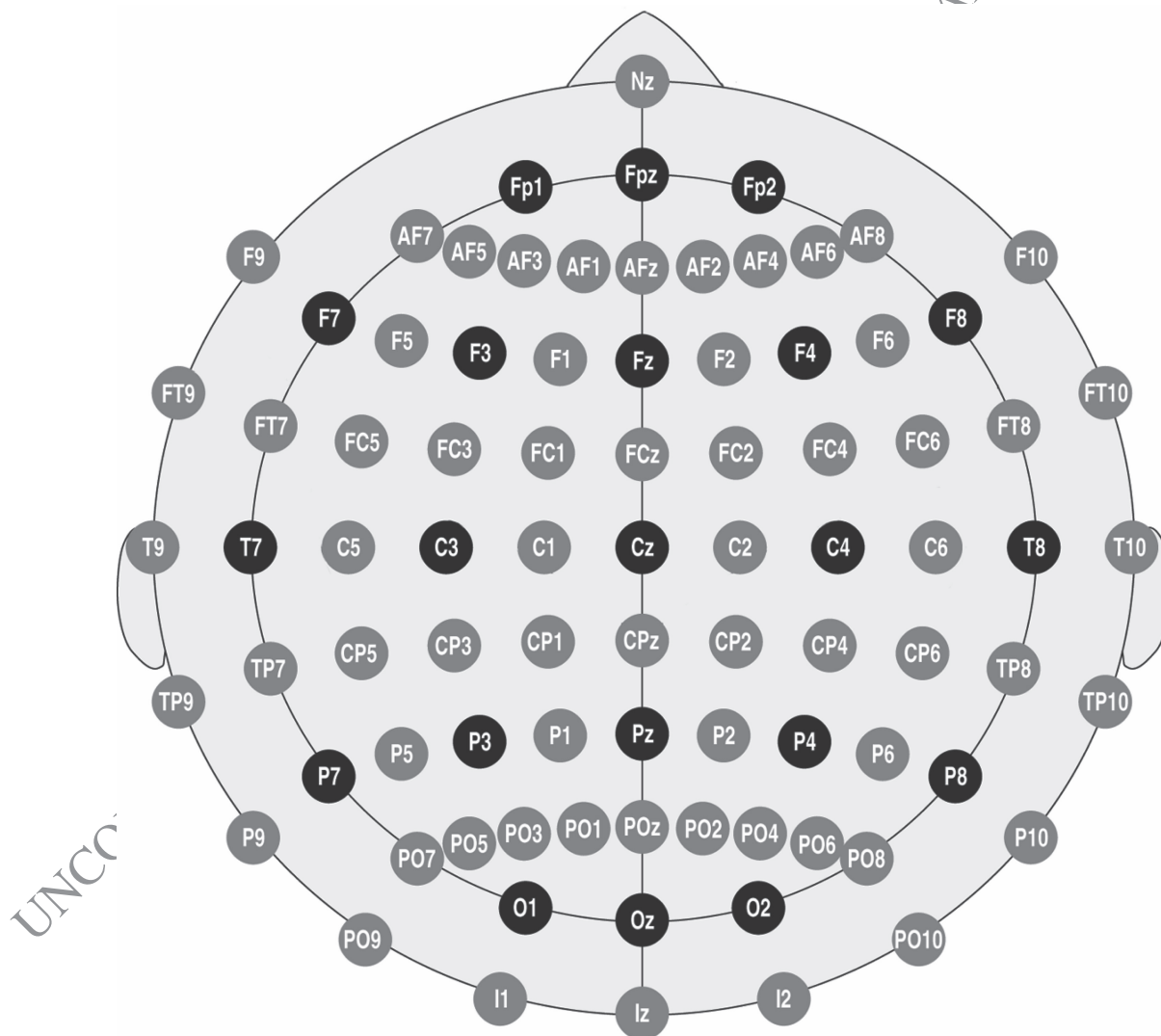


FIGURE 26.1. Electrode layout and labels commonly used in EEG recording. The figure shows the top of the head, with the triangle at the top representing the nose. The electrodes displayed in black are the original 10–20 electrodes.

(e.g., 0.1 to 100 Hz) because the frequencies of interest fall within a relatively narrow frequency band (e.g., between 1 and 40 Hz). Online 60 Hz notch filters (in the United States; 50 Hz in Europe) may also be used to further reduce electrical noise from alternating current (AC) sources, such as lamps and computers. From the amplifiers, the raw signals are digitized onto a computer at a sampling rate greater than twice the highest frequency of interest. For example, if one is only interested in frequencies below 40 Hz, then 80 samples per second are sufficient. This sampling rate is necessary because of the Nyquist theorem, which states that reliable reconstruction of a continuous signal from its samples is possible if the signal is of limited bands and if it is sampled at a rate that is at least twice the actual signal bandwidth. If this sampling condition is not met, then frequencies will overlap; that is, frequencies above half the sampling rate will be reconstructed as, and appear as, frequencies below half the sampling rate. This distortion is called aliasing because the reconstructed signal is said to be an alias of the original signal. Given the power and large storage capacity of modern computers, however, sampling rates well above the Nyquist frequency are typically used, allowing for high-fidelity digital representations of analog signals.

PREPARING THE PARTICIPANT

Before running each participant, we recommend that the equipment be calibrated by running a sine wave of known amplitude and frequency through the amplifier to ensure that it is working appropriately. Many commercial systems have calibration routines that can be used.

Most EEG protocols require the researcher to spend almost 1 hour preparing the participant for EEG data collection; thus, we offer a few comments regarding the behavior of the researcher. When talking with the participants, we avoid using words such as electricity, electrodes, needles, or anything that sounds painful. Instead, we say, "I am going to be putting a cap on your head to measure brain activity." We also train our experimenters to adopt the mind-set of a person who has done this *very routine procedure* many times. We work with them so that

they appear confident and do not cause the participant to worry about the procedure. For example, mistakes may be made during the attachment procedure, but we avoid announcing them to the participant because they can often be corrected easily. We also recommend that researchers avoid being too friendly, as this can drastically alter the mood of the participants. In general, researchers working with participants should be encouraged to adopt a professional mind-set (and to wear lab coats).

Once the equipment is calibrated and all of the materials that are needed for the attachment of the EEG electrodes are ready (e.g., adhesive collars, conductive gel), the participant is brought into the experiment room. With many EEG systems, electrical impedance of the scalp will need to be brought under 5,000 ohms. To assist in reducing impedance, we ask participants to brush their hair vigorously for about 5 min with a stiff-bristled brush, which aids in exfoliating the scalp. For example, we ask participants to, "Be sure to press the brush hard against your scalp as you brush. It helps with the attachment process. I will tell you when you can stop."

Once they are finished brushing their scalp, participants are told that we are going to use an exfoliant to clean some areas of their skin and use rubbing alcohol to remove the exfoliant. We clean their forehead, ear lobes, temples, and above and below the eyes with a mildly abrasive cleaning solution (e.g., Green Prep) and gauze pad. We follow the cleaning by wiping the areas with alcohol, which assists in removing the cleaning solution but also assists with further cleaning of the area.

As most labs now use EEG caps instead of single electrodes to collect EEG data, we will describe the capping procedure. We first use a metric tape to measure the length from the nasion (a point just below the eyebrows where there is an indentation at the top of the nose) to the inion (bump on skull over the occipital region at the back of head). Then, 10% of this total distance (cm) is calculated and measured up from the nasion. We mark this spot on the forehead with a wax pencil and explain this by saying, "I am going to make a mark on your forehead with a wax pencil. It will wipe right off." This mark will aid cap placement. Cap size is determined by measuring the distance around the participant's

head, crossing the marks on the forehead and theinion. Caps often come in small, medium, and large sizes. When using some types of caps (e.g., from ElectroCap, Eaton, OH), two adhesive, cushioned collars are placed on cap sites Fp1 and Fp2 (if the cap has high-profile plastic housing enclosures around the electrodes). These collars are then adhered to the forehead in line with the wax pencil marks and centered over the nose. These adhesive-cushioned collars are not usable with some types of caps. When collars are not used, the experimenter aligns the Fp1 and Fp2 electrodes with the wax pencil marking. The cap is then stretched toward the back of their head and down. Having the participants hold the cap in place on the forehead helps get the cap over the head. After the cap is straightened so that the midline electrodes align with the midline of the head, re-measure from the nasion to theinion and ensure that Cz is halfway between these sites. If it is not, adjust the cap so that it is. Cz is centered horizontally by measuring from the preauricular indentation in front of each ear (the indentation can be found by having participants open their mouths and the experimenter feeling for the indentation).

After attaching the cap's connectors to the pre-amplifier (e.g., the headbox), electrodes are often attached to each ear lobes because one of these sites is often used as a reference site and the other is recorded as a separate channel so that off-line rereferencing of the average of the ears can be performed (i.e., online averaging of ears is not recommended; see the section "Referencing"). The electrodes are attached by placing an adhesive collar on the flat side and sticking it on the ear; additional adhesive collars may be placed on top of the electrode to ensure that the electrode remains attached. Fill sensors with conductive gel but do not overfill; that is, avoid having gel run between two sensors or outside the adhesive collar because this will cause measurement problems or interfere with the adhesion of the collar. Next, abrade the ground electrode site with the blunt tip of a wooden cotton swab or the blunt tip of a large gauge needle, and apply gel with a syringe. We demonstrate to participants how we do this by making a motion with the syringe and blunt tip on their hands so that they know what to expect.

We then say, "I am going to put gel into each sensor." Impedances should be below 5,000 ohms. Some systems permit measuring EEG with higher impedances, but some researchers have questioned the reliability and validity of the data under certain recording conditions (Kappenman & Luck, in press). Finally, a chinstrap for the cap is positioned comfortably under the participant's chin to ensure that the cap stays in place.

Eye movements are often measured in EEG research so that procedures can later be taken to remove eye movements from the EEG or to correct the EEG from these movements (see the section "Eye movement artifacts"). The eyeball is polarized, with a dipole running from the cornea to the retina, and the relatively large voltage changes from eye movements are recorded from scalp electrodes (especially toward the front of the scalp near the eyes). These measurements are referred to as electro-oculograms (EOG). Electrodes are affixed to the face using double-sided adhesive collars. For measuring vertical eye movements (e.g., caused by eye blinks), one electrode is placed 10% of the inion-nasion distance above the pupil and another is placed 10% of the inion-nasion distance below the pupil. These two electrodes are referenced to each other rather than to the EEG reference electrode. For measuring horizontal eye movements, one electrode is placed on the right temple and another is placed on the left temple. These electrodes are also referenced to each other. Because the EOG signal is relatively large, impedances up to 10,000 ohms are acceptable, and thus less face abrasion may be needed.

In addition to ensuring that the EEG equipment is properly attached, it is equally important to ensure that the participant is in a state of mind that is desired for the research question. For instance, if the study concerns personality characteristics or individual differences, it is important that characteristics of the situation not be so intense as to overwhelm potential individual differences of interest. Along these lines, we avoid making participants self-conscious by covering the computer monitor until it is ready to be used, as a black-screened computer monitor can act as a mirror. Similarly, video cameras are best hidden to avoid the arousal of excessive self-consciousness.

Artifacts

Artifacts, whether of biological or nonbiological origin, are best dealt with by taking preventative measures. When they do occur, procedures exist to reduce their effects on EEG measurements.

Muscle artifact. Muscle artifact (electromyography; EMG) typically comprises electrical signals that cycle at higher frequencies than EEG. Most EEG signals of interest are less than 40 Hz, whereas EMG is typically greater than 40 Hz. Some EMG, however, may blend in with the EEG frequencies, so it is advisable to limit muscle artifacts by instructing the participants to limit their muscle movements. If muscle artifacts do appear in studies in which muscle movements should not occur, the artifacts can be removed during the data-processing stage. Often, this is done manually, through visual inspection and exclusion by someone trained in EEG scoring.

In some experiments, particularly those that evoke emotion, muscle artifacts cannot be avoided. That is, if an intense amount of fear is evoked, the facial muscles of the participant will move and create muscle artifact in the EEG, particularly in frontal and temporal regions. Removing these muscle movements is not advisable because the removal process would also exclude signals of interest related to emotion. One way to handle the EMG that may contaminate the EEG is to measure facial EMG directly and then use the facial EMG responses (in EMG frequency ranges, such as 50–250 Hz) in covariance analyses. This analysis would indicate whether any observed effects for EEG were related to EMG responses or whether statistical adjustment may be needed to reveal effects. Similarly, one can obtain EMG frequencies from the scalp electrode sites, rather than facial muscle sites, and use these EMG frequencies in covariance analyses (see Coan, Allen, & Harmon-Jones, 2001, for examples). These issues have been investigated extensively in recent research (e.g., McMenemy, Shackman, Maxmell, Greischar, & Davidson, 2009).

Eye movement artifacts. Eye movement artifacts are also best dealt with in advance of EEG recording. That is, training participants to limit eye movements during EEG recording is recommended. Researchers must not encourage participants to control their

blinking, because blinks and spontaneous eye movements are controlled by several brain systems in a highly automatic fashion (e.g., Brodal, 1992), and the instruction to suppress these systems may act as a secondary task, creating distraction and cognitive load (see Verleger, 1991, for a discussion).

Participants will inevitably blink, and these blinks will influence the EEG data, particularly in the frontal electrodes. Therefore, epochs containing blinks should be removed from the EEG or corrected via a computer algorithm (Gratton, Coles, & Donchin, 1983; Semlitsch, Anderer, Schuster, & Presslich, 1986). These algorithms often rely on regression techniques, but other techniques involving principal or independent component analyses have been recommended as well (e.g., Joyce, Gorodnitsky, & Kutas, 2004; Wallstrom, Kass, Miller, Cohn, & Fox, 2004). In the regression approaches to EOG correction, the actual EEG time-series is regressed on the EOG time-series, and the resulting residual time-series represents a new EEG from which the influence of the ocular activity is statistically removed. Then, eye-movement, artifact-corrected EEG data may be processed as would EEG data without EOG artifacts. This latter procedure has the advantage of not losing data; in contrast, the eye-movement rejection procedure can cause significant amounts of data loss. Some disadvantages of eye-movement artifact correction have been discussed (Hagemann & Naumann, 2001), but evidence suggests that it does not cause a distortion of frontal EEG asymmetry (Hagemann, 2004), a measure of interest in contemporary psychology that will be discussed in detail later.

Nonbiological artifacts. Nonbiological artifacts are those that typically involve external electrical noise coming from elevator motors, electric lights, computers, or almost anything running electricity nearby the subject. Again, prevention is the best defense against such artifacts. Although full electrical shielding is not usually necessarily with modern EEG amplifiers, it is important to remove or repair any poorly shielded electrical equipment. It is also helpful to limit the use of power outlets in the EEG recording chamber and to use direct current lamps if possible. High electrode impedances or a faulty

ground connection can also increase AC noise (e.g., 60 Hz). Electrodes need to be carefully washed after each use to prevent corrosion and to assist in prevention of artifacts. When electrical noise is present, it can be dealt with through filtering of the signal; that is, 60-Hz activity can be removed with an online filter or after the data are collected.

OFF-LINE DATA PROCESSING

Referencing

EEG signals are often re-referenced. The issue of referencing is the subject of some debate (Allen, Coan, & Nazarian, 2004; Davidson, Jackson, & Larson, 2000; Hagemann, 2004; Nunez & Srinivasan, 2006). All bioelectrical measurements reflect the difference in activity between at least two sites. In EEG research, one site is typically placed on the scalp, whereas the other site may be on the scalp or on a nonscalp area, such as an earlobe or nose tip. Researchers strive to obtain measures that reflect activity in particular brain regions; thus, they often search for a relatively inactive reference, such as the earlobe. There are no “inactive sites,” however; all sites near the scalp reflect some EEG because of volume conduction. To address this issue, some researchers suggest using an average reference composed of the average of activity at all recorded EEG sites. The average reference should approximate an inactive reference if a sufficiently large array of electrodes is placed in a spherical arrangement around the head. That is, activity generated from dipoles will be positive at one site and negative at a site 180 degrees opposite to this site; thus, the sum across sites should approach zero with a representative sample of the sphere. Electrodes are not placed under the head; thus, this assumption is rarely met. Moreover, use of smaller montages of electrodes causes more residual activity in the average reference.

Other researchers have recommended the use of linked earlobes as a reference because of the relatively low EEG activity in the earlobes and because linking the earlobes should theoretically center the reference on the head, making the determination of lateralized activity more accurate. Linking the ears into one reference electrode has been questioned

(Katznelson, 1981), however, because it can produce a low-resistance shunt between the two sides of the head, reducing any asymmetries that are observed at the scalp. Research, however, has suggested that physically linking the ears does not alter the observed EEG asymmetries (Andino et al., 1990). Some EEG researchers have suggested that the original idea was ill conceived because electrode impedances will be higher than the internal resistance within the head; thus, they do not provide a shunt that is lower in resistance than what is present inside the head (Davidson et al., 2000). Physically linking the ears is inappropriate for another reason. When the ears are linked before input into the amplifier, variations in the impedances of the left and right electrodes will change the spatial location of the reference and potentially alter the magnitude and direction of any observed differences in left versus right EEG activity (Davidson et al., 2000). This does not happen when creating an averaged ears reference off-line, after the data have been collected, because most contemporary amplifiers have very high input impedances (around 100 k Ω) and variations in electrode impedances of several thousand ohms will have a tiny effect on the observed voltage. To create an off-line linked or averaged ears reference, the collected EEG data need to be actively referenced online to one of the ears or some other location (e.g., Cz). Then, electrical signals from the other ear when the active reference is one ear, or both ears, in the case of a Cz reference, need to be collected. Off-line, the data are re-referenced to the average of the two ears.

Which reference should be used? From the perspective of psychological construct validity, use and comparison of different reference schemes in each study might be advisable (see Coan & Allen, 2003, for an example). A significant interaction involving reference factor would indicate that the EEG–psychological variable relation is moderated by the reference. If such research is conducted over several years, EEG researchers may establish good psychological construct validity of the particular EEG measure.

From the perspective of neurophysiological construct validity, selecting a particular reference in advance might be advisable, considering the

advantages and disadvantages of each method for the EEG measurement construct. For example, in research on asymmetrical frontal cortical activity and emotion and motivation, Hagemann (2004) recommended against using the average reference if only limited head coverage was used, as in the 10–20 system. He indicated that the average reference may cause increased anterior alpha activity; averaging of the whole head can inflate anterior alpha because anterior regions have much lower alpha power than posterior regions. Thus, the off-line average of earlobes may be more appropriate. Although this reference shows some alpha activity and, thus, is not inactive, it may yield greater signal-to-noise ratios for anterior sites that are better than the average (whole head) reference.

Obtaining the Frequencies of the EEG Signal

Several steps are involved in transforming EEG signals into indexes that are used in data analyses. First, a signal is collected in the time-domain and is

then converted to a frequency-domain representation, usually in the form of a power spectrum. The spectrum, which collapses data across time, summarizes which frequencies are present. See Figure 26.2 for an illustration. Spectral analysis involves examining the frequency composition of short windows of time (epochs), often 1 or 2 sec each. The spectra are averaged across many epochs. Epochs of 1 or 2 sec are used to meet an assumption underlying the Fourier transform, which is the method used to derive power spectra. The Fourier transform assumes a periodic signal, or one that repeats and does so at a uniformly spaced interval. Any periodic signal can be decomposed into a series of sine and cosine functions of various frequencies, with the function for each frequency beginning at its own particular phase. EEG signals are not exactly periodic because the repetition of features is not precisely spaced at uniform intervals. The use of short epochs allows one to analyze small segments of data that will have features that repeat in a highly similar fashion at other points in the waveform.

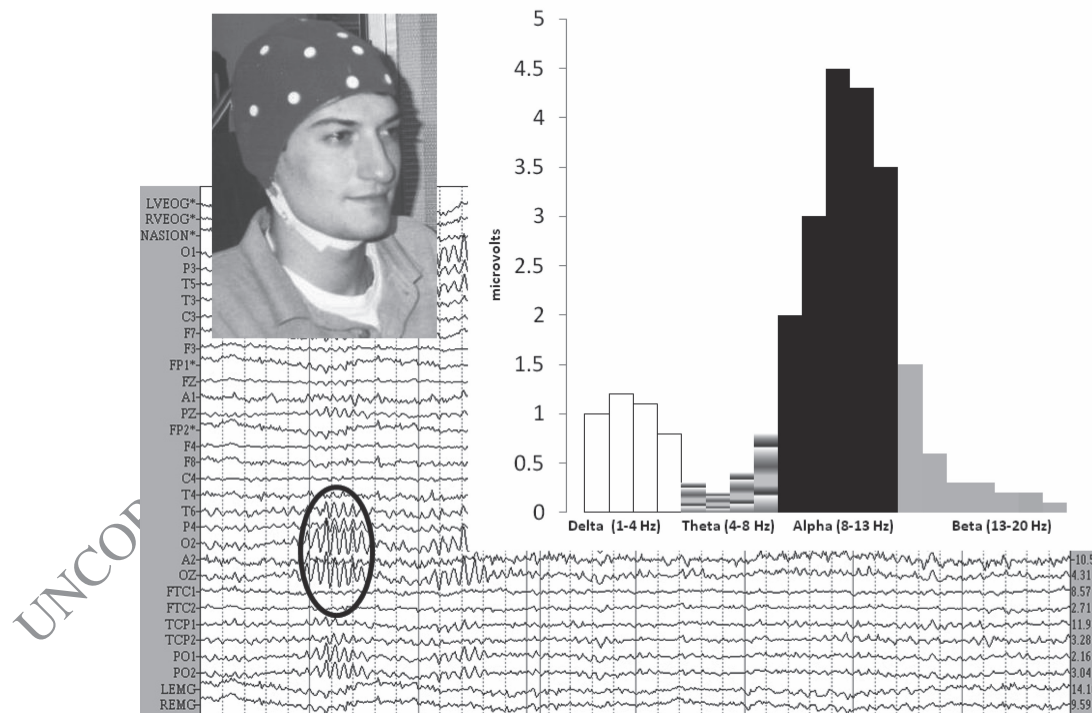


FIGURE 26.2. The background displays raw EEG, and the circled portion is an example of a prominent alpha burst obtained over occipital region when a subject’s eyes are closed. The picture in the upper right displays the results of an FFT at one electrode. The picture in the upper left displays David Amodio wearing an EEG cap.

In EEG research, epochs are often overlapped. This is done to prevent a problem that occurs with *windowing*, a necessary part of the EEG data processing. Windowing, as with a Hamming window, is used to avoid creating artifactual frequencies in the resultant power spectra. Windowing tapers the power of signals in an epoch toward the endpoints of the epoch, reducing the endpoints to near-zero values so that discontinuities will not occur if copies of the epochs are placed immediately before or after the epoch. This assists in meeting the Fourier assumption that the epoch repeats infinitely both forward and backward in time. Fourier methods introduce spurious frequencies if windowing is not used to prevent discontinuities in the signal. Windowing prevents discontinuity, but also prevents data near the ends of the epoch from being fully represented in the power spectrum. Overlapping epochs provides a solution to this problem because data minimally weighted at the end of one epoch will be weighted more heavily in subsequent epochs.

Most signal processing programs use a fast Fourier transform (FFT). The FFT requires that the epochs to be analyzed have data points that are a power of two (e.g., 128, 256, 512, or 1,048 data points). The FFT produces two spectra, a power spectrum and a phase spectrum. The power spectrum reflects the power in the signal at each frequency from direct current (DC) to the Nyquist frequency, with a spectral value every $1/T$ points, where T is the length of the epoch analyzed. The phase spectrum presents the phase of the waveform at each interval $1/T$. Often, analyses focus only on the power spectrum. The FFT of each epoch produces a power spectrum, and the average of the obtained power values is used in analyses. Further reduction is accomplished by summarizing data within conventionally defined frequency bands.

Frequency Bands of Interest

Past discussions of EEG frequency bands have suggested that there are five bands with relationships to psychological and behavioral outcomes. These bands are delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–20 Hz), and gamma ([μ mt] 20 Hz). Many of the psychological and behavioral correlates of these frequency bands that are mentioned in past

reviews were based on visual inspection of the frequency bands and not on mathematical derivations of the frequencies of interest, as is now commonly done with spectral analyses. Recent research with these more precise and accurate methods of measuring EEG frequencies has questioned some earlier conclusions, although much of the work is relatively recent and has not been incorporated into psychology as of yet. Moreover, the extent to which these bands are discrete from each other or differ as a function of scalp region has not been examined in a rigorous statistical fashion. Finally, research has suggested that the frequency bands below 20 Hz are highly and positively correlated (Davidson, J. P. Chapman, L. J. Chapman, & Henriques, 1990; Harmon-Jones & Allen, 1998). Consequently, we review research that has focused on alpha power, as it has attracted most of the attention of psychologists, perhaps in part because it accounts for a large percentage of the adult EEG.

RESEARCH EXAMPLES

Several psychological studies have examined differences in left and right frontal cortical activity in relationship to emotional and motivational processes (Coan & Allen, 2004; Harmon-Jones, Gable, & Peterson, 2010). In this research, alpha power has been used because alpha power appears to be inversely related to cortical activity using a variety of methods, such as positron emission tomography (Cook et al., 1998) and functional magnetic resonance imaging (fMRI; Goldman, Stern, Engel, & Cohen, 2002). Moreover, behavioral tasks that are presumed to activate one brain region have been shown to cause alpha power suppression in that region (e.g., Davidson et al., 1990).

Power within the alpha frequency range is obtained using the methods described in the previous section. Alpha power values are often log transformed for all sites to normalize the distributions. Then, in the research that is reviewed in the section “Research Examples,” asymmetry indexes [natural log right minus natural log left alpha power] are computed for all homologous sites, such as F3 and F4 or P3 and P4. Because alpha power is inversely related to cortical activity, higher scores on the

asymmetry indexes indicate greater relative left-hemispheric activity.

Frontal Alpha Power Asymmetry at the Trait Level

A large portion of the frontal EEG alpha-power asymmetry literature on individual differences has examined relations between personality and resting baseline asymmetry. In these studies, resting asymmetry is utilized as a stable index of an individual's dispositional style across situations. For example, resting EEG asymmetry appears to relate to social behavior. In one study, EEG data recorded from infants at 9 months old were used to predict social wariness at 4 years old (Henderson, Fox, & Rubin, 2001). Negative emotionality, as reported by the infants' mothers, predicted social wariness in infants who displayed relatively greater right frontal activity. This relationship was not found in infants who displayed relatively greater left-frontal activity (Henderson et al., 2001). Another study found that socially anxious preschool children exhibited increased right frontal activity compared with their peers (Fox et al., 1995).

The largest body of literature examining relations with resting EEG asymmetry stems from the research on emotion. Greater relative left and greater relative right frontal activity have been found to relate to individual differences in dispositional positive and negative affect, respectively (Tomarken, Davidson, Wheeler, & Doss, 1992). Individuals with stable relative left-frontal activity report greater positive affect to positive films, whereas individuals with stable relative right frontal activity report greater negative affect to negative films (Wheeler, Davidson, & Tomarken, 1993). The positive affect–left versus negative affect–right frontal asymmetry has been referred to as the *affective-valence* hypothesis of frontal asymmetry.

More recent research has suggested that affective valence does not explain the relation between emotive traits and asymmetrical frontal activity and that approach–withdrawal motivational direction may provide a more accurate explanation of this relation (Harmon-Jones, 2003). For example, Harmon-Jones and Allen (1997) compared resting frontal asymmetry to behavioral withdrawal–approach sensitivities,

as measured by the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) scales (Carver & White, 1994). They found that higher left-frontal cortical activity during a resting baseline period related to higher trait-approach motivation scores. Sutton and Davidson (1997) replicated this effect and found that asymmetrical frontal activity was more strongly related to approach–withdrawal motivation than positive and negative affectivity (as measured with the Positive and Negative Affect Schedule; Watson, Clark, & Tellegen, 1988). Consistent with findings linking left-frontal asymmetry to BAS, Master et al. (2009) recently observed an association between greater left-sided baseline activity and individual differences in emotional approach coping, another form of self-regulatory tendencies that are linked to approach motivation.

Other research examining relations between resting frontal asymmetry and psychopathology has also supported the role of motivational direction. Depression, for example, has been characterized by a general lack of approach motivation and decreased positive affect. Research has shown that higher scores on the Beck Depression Inventory (BDI; Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) relate to greater relative right-frontal cortical activity at resting baseline (Schaffer, Davidson, & Saron, 1983). Further studies support the relation, showing that depression relates to trait-level, increased right-frontal activity or reduced left-frontal activity (Allen, Iacono, Depue, & Arbisi, 1993; Henriques & Davidson, 1990, 1991). Other examples come from research on bipolar disorder. Increased relative right-frontal activity at resting baseline has been observed in bipolar depression (Allen et al., 1993), whereas increased relative left-frontal activity at resting baseline has been observed in mania (Kano, Nakamura, Matsuoka, Iida, & Nakajima, 1992).

The evidence that most strongly challenges the affective-valence hypothesis comes from research on anger. Most research examining relations between frontal asymmetry and emotion have confounded valence and motivational direction, for example, because most of the negative affects that have been examined are withdrawal oriented (e.g., fear, disgust). Anger, however, is an approach-oriented negative emotion (Carver & Harmon-Jones, 2009) that

appears to relate to relatively greater left-frontal, resting cortical activity rather than relatively greater right-frontal cortical activity (Harmon-Jones, 2004). For example, Harmon-Jones and Allen (1998) assessed dispositional anger using the Buss and Perry (1992) Aggression Questionnaire (1992) and then measured resting alpha power asymmetries over the whole head. Trait anger correlated positively with left-frontal activity and negatively with right-frontal activity (Harmon-Jones & Allen, 1998). These findings support the *motivational direction* model of frontal asymmetry, which proposes that approach motivation relates to relatively greater left- than right-frontal activity, whereas withdrawal motivation relates to relatively greater right- than left-frontal activity (Harmon-Jones, 2004).

Frontal Asymmetry and State Manipulations

Although resting baseline frontal asymmetries predict certain dispositional styles and psychopathologies, there have been failures to replicate some of the resting baseline asymmetry and affective trait relations (see Coan & Allen, 2004, for review). This may be because asymmetrical frontal cortical activity is also sensitive to state manipulations (e.g., Hagemann, Naumann, Becker, Maier, & Bartussek, 1998; Reid, Duke, & Allen, 1998). In fact, approximately half of the variance in baseline resting measurements is associated with state rather than trait variance (Hagemann, Naumann, Thayer, & Bartussek, 2002). Variance in resting EEG may even be caused by time of day and time of year, such that relative right-frontal activity is greatest during fall mornings (Peterson & Harmon-Jones, 2009). This latter finding fits with other work suggesting that (a) seasonal variations influence mood such that the fall is associated with more depression than other seasons and (b) circadian variations influence the release of the stress hormone, cortisol, such that mornings are associated with greater cortisol. These factors need to be considered in EEG asymmetry research.

Several studies have revealed asymmetric alpha power activations during the experience of emotive states. For instance, newborn infants evidenced greater relative left-hemispheric activation (suppression of

alpha power) in response to a sucrose solution placed on the tongue, whereas they evidenced greater relative right-hemispheric activation in response to a water solution, which elicited a disgust facial expression (Fox & Davidson, 1986).

Other experiments have examined the effect of manipulated facial expressions of emotion on asymmetric frontal alpha power. In one experiment, participants made expressions of disgust, fear, anger, joy, and sadness while EEG was recorded. Relatively less left- than right-frontal activity was found during facial expressions of withdrawal-oriented emotions (disgust, fear) compared with approach-oriented emotions (joy, anger; Coan et al., 2001).

Experiments on asymmetric alpha power have also examined more complex emotions such as guilt. Manipulated feelings of guilt, as a result of feedback informing low-prejudice participants that they had responded with racial bias, were found to cause a reduction in relative left-frontal cortical activity, and greater reductions were correlated with greater self-reported guilt but not with other negative emotions (Amodio, Devine, & Harmon-Jones, 2007).

To further compare the affective-valence (positive–negative) model with the motivational direction (approach–withdrawal) model of asymmetrical frontal cortical activity, experiments were conducted in which anger was manipulated. For example, Harmon-Jones and Sigelman (2001) manipulated state anger by leading participants to believe that another participant (ostensibly in the next room) had insulted them on the basis of an essay that they wrote on an important social issue. EEG activity recorded immediately following the insult revealed an increase in left-frontal activation compared with individuals in the no-insult condition (Harmon-Jones & Sigelman, 2001). This increase in left-frontal activation related to an increase in self-reported anger and aggressive behavior, which was not the case in the no-insult condition (Harmon-Jones & Sigelman, 2001). Subsequent studies have conceptually replicated these effects demonstrating that increases in state self-reported anger (and jealousy) relate to greater relative left-frontal activation after social rejection (Harmon-Jones, Peterson, & Harris, 2009; Peterson, Gravens, & Harmon-Jones,

in press). Additional research has found that manipulating sympathy before an angering event reduces the left-frontal activation that is caused by anger (Harmon-Jones, Vaughn-Scott, Mohr, Sigelman, & Harmon-Jones, 2004). Other research has revealed that it is specifically the approach-motivational character of anger that increases relative left-frontal activation (Harmon-Jones, Lueck, Fearn, & Harmon-Jones, 2006; Harmon-Jones, Sigelman, Bohlig, & Harmon-Jones, 2003).

Motivation often involves body movements and postures, so it may come as no surprise that body postures antithetical to approach motivation would reduce patterns of neural activity that are associated with approach motivation. When individuals were in a supine body posture and angered, they did not respond with an increase in relative left-frontal cortical activity that is typically observed during anger (Harmon-Jones & Peterson, 2009). These results may have important implications for research using neuroimaging methods that require individuals to be in a supine position during experiments.

In the above studies, anger and approach motivation were manipulated and EEG was assessed. To more firmly establish the causal role of relative left-frontal activity in aggressive motivation, a study was conducted in which asymmetrical frontal cortical activity was manipulated, and the effects of this manipulation on aggression was measured (Peterson, Shackman, & Harmon-Jones, 2008). In this experiment, participants made either left-hand or right-hand contractions for four periods of 45 sec. The contractions caused contralateral activation of the motor cortex and prefrontal cortex (i.e., right-hand contractions caused greater relative left activation and vice versa). Participants were then insulted by another ostensible participant. Following the insult, participants played a reaction-time game against the insulting participant. Participants were told that they would be able to administer a blast of white noise (of which the level and length was up to them) to the other participant if they responded faster to the stimulus than did the other participant. Individuals who made right-hand contractions were significantly more aggressive during the game than individuals who made left-hand contractions, and the degree of relative left-frontal activation

correlated with aggression in the right-hand contraction condition (Peterson et al., 2008).

The motivational direction model can also be compared with the affective-valence model by examining positive affects that differ in motivational intensity. Some positive affects are more strongly associated with approach motivation than others. According to the motivational direction model, positive affects that are higher in approach motivational intensity should evoke greater relative left-frontal activation than positive affects that are lower in approach motivational intensity. To test these ideas, participants were asked to recall and write about one of three things: (a) a neutral day; (b) a time when something positive happened to them that they did not cause, such as a surprise gift from a friend; or (c) a goal they were committed to achieving. The second condition was designed to manipulate positive affect that was low in approach motivation. The third condition was designed to manipulate positive affect that was higher in approach motivation. Past research suggested that this third condition increases positive affect (Harmon-Jones & Harmon-Jones, 2002; Taylor & Gollwitzer, 1995). Results from the experiment revealed greater self-reported positive affect in the two positive affect conditions relative to the neutral condition. More important, greater relative left-frontal cortical activity was found in the approach-oriented positive affect condition compared with the neutral condition and the low-approach positive affect condition (Harmon-Jones, Harmon-Jones, Fearn, Sigelman, & Johnson, 2008).

INDIVIDUAL DIFFERENCES PREDICT ASYMMETRY DURING STATE MANIPULATIONS

Research has also examined the role of individual differences in responses to state manipulations. For example, the BAS dysregulation theory posits that individuals with bipolar disorder are extremely sensitive to reward and failure cues, so that they show “an excessive increase in BAS activity in response to BAS activation-relevant events (e.g., reward incentives, goal striving) and an excessive decrease in BAS activity in response to BAS deactivation-relevant

events (e.g., definite failure)” (Nusslock, Abramson, Harmon-Jones, Alloy, & Hogan, 2007, p. 105). Given that the left-frontal cortical region is associated with approach motivation, it was predicted and confirmed that individuals with bipolar disorder would show increased left-frontal activation in response to goal-striving (Harmon-Jones, Abramson, et al., 2008).

Another study examined how hypomanic and depressive traits affected frontal asymmetry in response to an anger-inducing event (Harmon-Jones et al., 2002). Research on hypomania has suggested the involvement of increased BAS activity, whereas depression may be associated with decreased BAS activity. In support of these ideas, proneness toward hypomania related to an increase in left-frontal activation and proneness toward depression related to a decrease in left-frontal activation in response to an anger-inducing event (Harmon-Jones et al., 2002).

Research has also been conducted on normal populations. Gable and Harmon-Jones (2008) examined individual differences in response to appetitive stimuli. They found that self-reported time since last eating and liking for dessert related to greater relative left-frontal activation during viewing of desirable food pictures (Gable & Harmon-Jones, 2008; see also, Harmon-Jones & Gable, 2009).

The research on asymmetrical frontal cortical activity has shed light on a number of questions of interest to psychologists. Indeed, of the EEG frequency research to date within psychology, it is the most prevalent. Other EEG frequency research is of interest to psychologists, and we briefly review some of this exciting work in the next section.

Other Analyses of Interest

Relations among frequency bands. Recent research has suggested that the ratio between resting-state frontal theta and beta activity might shed light on important psychological processes. For example, increased theta–beta ratio has been observed in children with attention deficit hyperactivity disorder (ADHD; Barry, Clarke, & Johnstone, 2003). Other research has revealed that increased theta–beta ratios are associated with disadvantageous decision-making strategies on the Iowa gambling task (Schutter & van Honk, 2005). Scientists have suggested that slower frequency waves such as

delta and theta are associated with subcortical brain regions involved in affective processes (Knyazev & Slobodskaya, 2003), whereas faster frequency waves such as beta are associated with thalamo-cortical- and cortico-cortical-level activations that may be involved in cognitive control processes (Pfurtscheller & Lopes da Silva, 1999).

Event-related desynchronization. Event-related desynchronization (ERD) is a measurement of the time-locked average power associated with the desynchronization of alpha rhythms. It is measured using event-related potential designs, which are described in Bartholow and Amodio (2009). That is, across multiple experimental events, an average is taken within the same stimulus condition. The time window is usually 1 sec in length, and the amount of desynchronization is examined over 100-ms bins within the 1-sec window. We have examined alpha ERD in an experiment in which participants viewed photographs of attractive desserts or neutral items. Results indicated that relatively greater left-frontal activity, as measured by ERD, occurred during the first second of viewing of the photograph (Gable & Harmon-Jones, 2008). Moreover, this effect appeared to peak at 400 ms.

Coherence. Coherence measures the degree to which EEG signals (within a given frequency band) that are measured at two distinct scalp locations are linearly related to one another. High coherence implies that amplitudes at a given frequency are correlated across EEG samples. Moreover, there tends to be a constant phase angle (or time lag) between the two signals. Research has suggested that high EEG coherence occurs between scalp regions that are connected by known white matter tracts (Thatcher, Krause, & Hrybyk, 1986). For instance, during right-hand contractions, individuals with greater trait-approach motivational tendencies show greater EEG alpha power coherence between the left motor cortex and left-frontal region than do individuals with lower trait-approach motivational tendencies (Peterson & Harmon-Jones, 2008). Perhaps the appetitive processes associated with trait approach motivation and activation of the left-frontal cortical region require close connectivity with the motor cortex.

Similarly, phase synchrony in gamma band (30–80 Hz) EEG has been used to investigate

various cognitive phenomena, such as selective attention and working memory (e.g., Fell, Fernandez, Klaver, Elger, & Fries, 2003) and in understanding clinical problems such as schizophrenia (e.g., Lee, Williams, Breakspear, & Gordon, 2003).

Source localization. EEG frequency analyses do not provide direct information about the anatomical origins of the observed signals. With high-density EEG arrays, it is possible to conduct source localization techniques to estimate intracerebral electrical sources underlying EEG activity that is recorded at the scalp. These methods thus provide information regarding the neural generators of the observed signals. These techniques use mathematical models to represent the location, orientation, and strength of a hypothetical dipolar current source.

A number of source localization methods have been proposed. One that has generated much interest is LORETA (Pascual-Marqui et al., 1999). It computes current density (i.e., the amount of electrical current flowing through a solid) without assuming any active sources. The LORETA solution space (i.e., the locations in which sources can be found) is composed of 2,394 cubic elements (voxels, 7 by 7 by 7 mm) and is limited to cortical gray matter and hippocampi, as defined by a digitized MRI available from the Montreal Neurologic Institute (Montreal, Quebec, Canada).

LORETA solutions have been cross-modally validated with studies combining LORETA and fMRI (Mulert et al., 2004; Vitacco, Brandeis, Pascual-Marqui, & Martin, 2002), structural MRI (Worrell et al., 2000), positron emission tomography (PET; Pizzagalli et al., 2004), and intracranial recordings (Seeck et al., 1998). The core assumptions of LORETA, its mathematical implementation, and additional technical details, including relations between scalp-recorded EEG and LORETA data, are described in detail in Pascual-Marqui et al. (1999) and Pizzagalli et al. (2002, 2004).

ADVANTAGES AND DISADVANTAGES OF EEG METHODS

We hope that we have conveyed some advantages of using EEG methods in our brief review. In addition to these advantages, EEG methods are relatively

inexpensive compared with other neuroimaging methods. For instance, time on an fMRI scanner averages \$500 per hour (as of April 2010), and the scanner typically costs around \$5 million to set up. The hourly rate that is charged to researchers assists in covering the maintenance contracts and salaries of the support personnel. In contrast, most EEG researchers have their own equipment, which costs less than \$100,000. In this situation, no hourly fees are charged and maintenance contracts rarely exceed \$3,000 per year. EEG caps need to be replaced approximately once per year (depending on use), and they cost between \$300 and \$2,000, depending on the number and type of electrodes. There are also other regular expenses for conducting gel, adhesive collars, and sterilizing solution, but these costs are relatively minimal.

In relation to PET and fMRI, EEG provides better temporal resolution but poorer spatial resolution. EEG measures electrical activations instantaneously, at sub-millisecond resolution. However, EEG is less able to give precise information regarding the anatomical origin of the electrical signals. In contrast, PET and fMRI have better spatial resolution but poorer temporal resolution. Ultimately, both PET and fMRI rely on metabolism and blood flow to brain areas that have been recently involved in neuronal activity, although other changes affect fMRI such as oxygen consumption and blood volume changes. Because both PET and fMRI measure blood flow rather than neuronal activity, the activations are not in real time with neuronal activations but rather are blood responses to neuronal responses. Thus, there is a biological limit on the time resolution of the response, such that even in the best measurement systems, the peak blood flow response occurs 6–9 sec after stimulus onset (Reiman, Lane, Van Petten, & Bandettini, 2000). However, there are suggestions that experimental methods can be designed to detect stimulus condition differences as early as 2 sec (Bellgowan, Saad, & Bandettini, 2003). Finally, PET and EEG permit measurement of tonic (e.g., resting, baseline) activity as well as phasic (e.g., in response to a state manipulation) activity, whereas fMRI permits measurement of phasic but not tonic activity.

Spatial and temporal resolution comparisons are often made between EEG, fMRI, and PET, but rarely

do researchers consider that EEG and PET or fMRI may provide different information about neural activity. For instance, correlations between EEG alpha power and fMRI or PET measures are only of moderate magnitude, suggesting that the two measures are not assessing exactly the same signals or activations. Moreover, EEG measures are selective measures of current source activity, often corresponding to small subsets of total synaptic action in tissue volumes and largely independent of action potentials, as discussed. By contrast, hemodynamic and metabolic measures are believed to increase with action potential firing rates (Nunez & Silberstein, 2000). Consider, for example, cortical stellate cells. They occupy roughly spherical volumes and, as such, their associated synaptic sources provide a *closed field* structure. Thus, these stellate cells are electrically invisible to EEG sensors. Although stellate cells constitute only about 15% of the neural population of neocortex (Braitenberg & Schuz, 1991; Wilson, Ó Scailidhe, & Goldman-Rakic, 1994), they contribute disproportionately to cortical metabolic activity because of their higher firing frequencies of action potentials (Connors & Gutnick, 1990). Thus, they appear as large signals in fMRI and PET. On the other hand, strong EEG signals can appear while weak metabolic activity occurs. EEG can be large if only a few percent of neurons in each cortical column are “synchronously active,” provided a large-scale synchrony among different columns produces a large dipole in which individual columns tend to be phase locked in particular frequencies. Because, in this scenario, the majority of neurons in each intracolumn population are relatively inactive, minimal metabolic activity is produced. Consequential dissociations between electrical and metabolic measures have been found in studies of epilepsy (e.g., Olson, Chugani, Shewmon, Pielps, & Peacock, 1990). For example, in one study of children with lateralized epileptic spikes (measured with EEG), regional glucose metabolism that was measured with PET was not lateralized, suggesting that “metabolic changes associated with interictal spiking cannot be demonstrated with PET with 18F-fluorodeoxyglucose” (Van Bogaert, Wikler, Damhaut, Szliwowski, & Goldman, 1998, p. 123).

Methodologically, fMRI and EEG differ in an important way, particularly for research on motivational processes. Typically, fMRI studies require participants to lie flat on their backs while brain images are collected. In contrast, EEG studies often have participants in upright, sitting positions. Given the connection between body posture and motivation (Riskind & Gotay, 1982), we should expect that lying in a supine position may decrease approach motivation, as this position is often antithetical to approaching goals. In line with these ideas, EEG research has suggested that these body postures influence regional brain activity, with a supine posture leading to relatively less left-frontal cortical activation in response to approach motivation manipulations (Harmon-Jones & Peterson, 2009). Moreover, simply leaning forward causes greater relative left-frontal activity (as measured by EEG) than lying in a supine position (Price & Harmon-Jones, in press).

CONCLUSION

As we have described in this chapter, EEG measures of neural activity provide an important method for testing psychological theories and hypotheses. Among the most exciting new developments in EEG that are awaiting applications in psychological studies is the examination of distributed patterns of activation. Many psychological processes likely involve widely distributed networks of brain dynamics and most past work in EEG, fMRI, and PET has failed to examine the dynamics of brain activations as they unfold on the order of milliseconds. Given the exquisite temporal resolution of EEG, it will be the method of choice in addressing these questions. When brain operations are viewed as a “combination of quasi-local processes allowed by functional segregation and global processes facilitated by functional integration” (Nunez & Silberstein, 2000, p. 93), the importance of EEG methods in conjunction with other neurobiological methods at addressing important psychological questions will be obvious.

References

- Allen, J. J., Iacono, W. G., Depue, R. A., & Arbisi, P. (1993). Regional electroencephalographic asymmetries in bipolar seasonal affective disorder before and

- after exposure to bright light. *Biological Psychiatry*, 33, 642–646. doi:10.1016/0006-3223(93)90104-L
- Allen, J. J. B., Coan, J. A., & Nazarian, M. (2004). Issues and assumptions on the road from raw signals to metrics of frontal EEG asymmetry in emotion. *Biological Psychology*, 67, 183–218. doi:10.1016/j.biopsycho.2004.03.007
- Amodio, D. M., Devine, P. G., & Harmon-Jones, E. (2007). A dynamic model of guilt—Implications for motivation and self-regulation in the context of prejudice. *Psychological Science*, 18, 524–530. doi:10.1111/j.1467-9280.2007.01933.x
- Andino, S. L., Pascual Marqui, R. D., Valdes Sosa, P. A., Biscay Lirio, R., Machado, C., Diaz, G., . . . Castro Torrez, C. (1990). Brain electrical field measurements unaffected by linked earlobes reference. *Electroencephalography and Clinical Neurophysiology*, 75, 155–160. doi:10.1016/0013-4694(90)90169-K
- Barry, R. J., Clarke, A. R., & Johnstone, S. J. (2003). A review of electrophysiology in attention-deficit/hyperactivity disorder: I. Qualitative and quantitative electroencephalography. *Clinical Neurophysiology*, 114, 171–183. doi:10.1016/S1388-2457(02)00362-0
- Bartholow, B. D., & Amodio, D. M. (2009). Using event-related brain potentials in social psychological research: A brief review and tutorial. In E. Harmon-Jones and J. Beer (Eds.), *Methods in social neuroscience* (pp. 198–232). New York, NY: Guilford Press.
- Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An inventory for measuring depression. *Archives of General Psychiatry*, 4, 561–571.
- Bellgowan, P. S., Saad, Z. S., & Bandettini, P. A. (2003). Understanding neural system dynamics through task modulation and measurement of functional MRI amplitude, latency, and width. *Proceedings of the National Academy of Sciences of the United States of America*, 100, 1415–1419. doi:10.1073/pnas.0337747100
- Berger, H. (1929). Electroencephalogram in humans. *Archiv für Psychiatrie und Nervenkrankheiten*, 87, 527–570. doi:10.1007/BF01797193
- Braitenberg, V., & Schuz, A. (1991). *Anatomy of the cortex. Statistics and geometry*. New York, NY: Springer-Verlag.
- Brodal, P. (1992). *The central nervous system*. New York, NY: Oxford University Press.
- Buss, A. H., & Perry, M. (1992). The aggression questionnaire. *Journal of Personality and Social Psychology*, 63, 452–459. doi:10.1037/0022-3514.63.3.452
- Carver, C. S., & Harmon-Jones, E. (2009). Anger is an approach-related affect: Evidence and implications. *Psychological Bulletin*, 135, 183–204. doi:10.1037/a0013965
- Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. *Journal of Personality and Social Psychology*, 67, 319–333. doi:10.1037/0022-3514.67.2.319
- Chatrian, G. E., Lettich, E., & Nelson, P. L. (1988). Modified nomenclature for the 10-percent electrode system. *Journal of Clinical Neurophysiology*, 5, 183–186. doi:10.1097/00004691-198804000-00005
- Coan, J. A., & Allen, J. J. B. (2003). Frontal EEG asymmetry and the behavioral activation and inhibition systems. *Psychophysiology*, 40, 106–114. doi:10.1111/1469-8986.00011
- Coan, J. A., & Allen, J. J. B. (2004). Frontal EEG asymmetry as a moderator and mediator of emotion. *Biological Psychology*, 67, 7–50. doi:10.1016/j.biopsycho.2004.03.002
- Coan, J. A., Allen, J. J. B., & Harmon-Jones, E. (2001). Voluntary facial expression and hemispheric asymmetry over the frontal cortex. *Psychophysiology*, 38, 912–925. doi:10.1111/1469-8986.3860912
- Connors, B. W., & Gutnick, M. J. (1990). Intrinsic firing patterns of diverse neocortical neurons. *Trends in Neurosciences*, 13, 99–104. doi:10.1016/0166-2236(90)90185-D
- Cook, I. A., O'Hara, R., Uijtdehaage, S. H. J., Mandelkern, M., & Leuchter, A. F. (1998). Assessing the accuracy of topographic EEG mapping for determining local brain function. *Electroencephalography and Clinical Neurophysiology*, 107, 408–414. doi:10.1016/S0013-4694(98)00092-3
- Crone, N. E., Sinai, A., & Korzeniewska, A. (2006). High-frequency gamma oscillations and human brain mapping with electrocorticography. *Progress in Brain Research*, 159, 275–295. doi:10.1016/S0079-6123(06)59019-3
- Davidson, R. J., Chapman, J. P., Chapman, L. J., & Henriques, J. B. (1990). Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive tasks. *Psychophysiology*, 27, 528–543. doi:10.1111/j.1469-8986.1990.tb01970.x
- Davidson, R. J., Jackson, D. C., & Larson, C. L. (2000). Human electroencephalography. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (2nd ed., pp. 27–52). New York, NY: Cambridge University Press.
- Fell, J., Fernandez, G., Klaver, P., Elger, C. E., & Fries, P. (2003). Is synchronized neuronal gamma activity relevant for selective attention? *Brain Research Reviews*, 42, 265–272. doi:10.1016/S0165-0173(03)00178-4
- Fox, N. A., & Davidson, R. J. (1986). Taste-elicited changes in facial signs of emotion and the asymmetry of brain electrical activity in human newborns.

- Neuropsychologia*, 24, 417–422. doi:10.1016/0028-3932(86)90028-X
- Fox, N. A., Rubin, K. H., Calkins, S. D., Marshall, T. R., Coplain, R. J., Porges, S. W., . . . Stewart, S. (1995). Frontal activation asymmetry and social competence at four years of age. *Child Development*, 66, 1770–1784. doi:10.2307/1131909
- Gable, P., & Harmon-Jones, E. (2008). Relative left frontal activation to appetitive stimuli: Considering the role of individual differences. *Psychophysiology*, 45, 275–278. doi:10.1111/j.1469-8986.2007.00627.x
- Goldman, R. I., Stern, J. M., Engel, J., & Cohen, M. S. (2002). Simultaneous EEG and fMRI of the alpha rhythm. *Neuroreport*, 13, 2487–2492. doi:10.1097/00001756-200212200-00022
- Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, 55, 468–484. doi:10.1016/0013-4694(83)90135-9
- Hagemann, D. (2004). Individual differences in anterior EEG asymmetry: Methodological problems and solutions. *Biological Psychology*, 67, 157–182. doi:10.1016/j.biopsycho.2004.03.006
- Hagemann, D., & Naumann, E. (2001). The effects of ocular artifacts on (lateralized) broadband power in the EEG. *Clinical Neurophysiology*, 112, 215–231. doi:10.1016/S1388-2457(00)00541-1
- Hagemann, D., Naumann, E., Becker, G., Maier, S., & Bartussek, D. (1998). Frontal brain asymmetry and affective style: A conceptual replication. *Psychophysiology*, 35, 372–388. doi:10.1111/1469-8986.3540372
- Hagemann, D., Naumann, E., Thayer, J. F., & Bartussek, D. (2002). Does resting EEG asymmetry reflect a trait? An application of latent state-trait theory. *Journal of Personality and Social Psychology*, 82, 619–641. doi:10.1037/0022-3514.82.4.619
- Harmon-Jones, E. (2003). Clarifying the emotive functions of asymmetrical frontal cortical activity. *Psychophysiology*, 40, 838–848. doi:10.1111/1469-8986.00121
- Harmon-Jones, E. (2004). Contributions from research on anger and cognitive dissonance to understanding the motivational functions of asymmetrical frontal brain activity. *Biological Psychology*, 67, 51–76. doi:10.1016/j.biopsycho.2004.03.003
- Harmon-Jones, E., Abramson, L. Y., Nusslock, R., Sigelman, J. D., Urosevic, S., Turonie, L. D., . . . Fearn, M. (2008). Effect of bipolar disorder on left frontal cortical responses to goals differing in valence and task difficulty. *Biological Psychiatry*, 63, 693–698.
- Harmon-Jones, E., Abramson, L. Y., Sigelman, J., Bohlig, A., Hogan, M. E., & Harmon-Jones, C. (2002). Proneness to hypomania/mania symptoms or depression symptoms and asymmetrical cortical responses to an anger-evoking event. *Journal of Personality and Social Psychology*, 82, 610–618. doi:10.1037/0022-3514.82.4.610
- Harmon-Jones, E., & Allen, J. J. B. (1997). Behavioral activation sensitivity and resting frontal EEG asymmetry: Covariation of putative indicators related to risk for mood disorders. *Journal of Abnormal Psychology*, 106, 159–163. doi:10.1037/0021-843X.106.1.159
- Harmon-Jones, E., & Allen, J. J. B. (1998). Anger and frontal brain activity: EEG asymmetry consistent with approach motivation despite negative affective valence. *Journal of Personality and Social Psychology*, 74, 1310–1316. doi:10.1037/0022-3514.74.5.1310
- Harmon-Jones, E., & Gable, P. A. (2009). Neural activity underlying the effect of approach-motivated positive affect on narrowed attention. *Psychological Science*, 20, 406–409. doi:10.1111/j.1467-9280.2009.02302.x
- Harmon-Jones, E., Gable, P. A., & Peterson, C. K. (2010). The role of asymmetric frontal cortical activity in emotion-related phenomena: A review and update. *Biological Psychology*, 84, 451–462. doi:10.1016/j.biopsycho.2009.08.010
- Harmon-Jones, E., & Harmon-Jones, C. (2002). Testing the action-based model of cognitive dissonance: The effect of action-orientation on post-decisional attitudes. *Personality and Social Psychology Bulletin*, 28, 711–723. doi:10.1177/0146167202289001
- Harmon-Jones, E., Harmon-Jones, C., Fearn, M., Sigelman, J. D., & Johnson, P. (2008). Action orientation, relative left frontal cortical activation, and spreading of alternatives: A test of the action-based model of dissonance. *Journal of Personality and Social Psychology*, 94, 1–15. doi:10.1037/0022-3514.94.1.1
- Harmon-Jones, E., Lueck, L., Fearn, M., & Harmon-Jones, C. (2006). The effect of personal relevance and approach-related action expectation on relative left frontal cortical activity. *Psychological Science*, 17, 434–440. doi:10.1111/j.1467-9280.2006.01724.x
- Harmon-Jones, E., & Peterson, C. K. (2009). Supine body position reduces neural response to anger evocation. *Psychological Science*, 20, 1209–1210. doi:10.1111/j.1467-9280.2009.02416.x
- Harmon-Jones, E., Peterson, C. K., & Harris, C. R. (2009). Jealousy: Novel methods and neural correlates. *Emotion*, 9, 113–117. doi:10.1037/a0014117
- Harmon-Jones, E., & Sigelman, J. (2001). State anger and prefrontal brain activity: Evidence that insult-related relative left prefrontal activation is associated with experienced anger and aggression. *Journal of Personality and Social Psychology*, 80, 797–803. doi:10.1037/0022-3514.80.5.797

- Harmon-Jones, E., Sigelman, J. D., Bohlig, A., & Harmon-Jones, C. (2003). Anger, coping, and frontal cortical activity: The effect of coping potential on anger-induced left frontal activity. *Cognition and Emotion*, *17*, 1–24. doi:10.1080/02699930302278
- Harmon-Jones, E., Vaughn-Scott, K., Mohr, S., Sigelman, J., & Harmon-Jones, C. (2004). The effect of manipulated sympathy and anger on left and right frontal cortical activity. *Emotion*, *4*, 95–101. doi:10.1037/1528-3542.4.1.95
- Henderson, H. A., Fox, N. A., & Rubin, K. H. (2001). Temperamental contributions to social behavior: The moderating roles of frontal EEG asymmetry and gender. *Journal of the American Academy of Child and Adolescent Psychiatry*, *40*, 68–74. doi:10.1097/00004583-200101000-00018
- Henriques, J. B., & Davidson, R. J. (1990). Regional brain electrical asymmetries discriminate between previously depressed and healthy control subjects. *Journal of Abnormal Psychology*, *99*, 22–31. doi:10.1037/0021-843X.99.1.22
- Henriques, J. B., & Davidson, R. J. (1991). Left frontal hypoactivation in depression. *Journal of Abnormal Psychology*, *100*, 535–545. doi:10.1037/0021-843X.100.4.535
- Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *10*, 371–375.
- Joyce, C. A., Gorodnitsky, I. F., & Kutas, M. (2004). Automatic removal of eye movement and blink artifacts from EEG data using blind component separation. *Psychophysiology*, *41*, 313–325. doi:10.1111/j.1469-8986.2003.00141.x
- Kano, K., Nakamura, M., Matsuoka, T., Iida, H., & Nakajima, T. (1992). The topographical features of EEGs in patients with affective disorders. *Electroencephalography and Clinical Neurophysiology*, *83*, 124–129. doi:10.1016/0013-4694(92)90025-D
- Kappenman, E. S., & Luck, S. J. (in press). The effects of electrode impedance on data quality and statistical significance in ERP recordings. *Psychophysiology*.
- Katznelson, R. D. (1981). Increased accuracy of EEG scalp localization by measurement of current source density using a Laplacian derivation. *Electroencephalography and Clinical Neurophysiology*, *51*, 45.
- Knyazev, G. G., & Slobodskaya, H. R. (2003). Personality trait of behavioral inhibition is associated with oscillatory systems reciprocal relationships. *International Journal of Psychophysiology*, *48*, 247–261. doi:10.1016/S0167-8760(03)00072-2
- Lee, K. H., Williams, L. M., Breakspear, M., & Gordon, E. (2003). Synchronous Gamma activity: A review and contribution to an integrative neuroscience model of schizophrenia. *Brain Research Reviews*, *41*, 57–78. doi:10.1016/S0165-0173(02)00220-5
- Master, S. L., Amodio, D. M., Stanton, A. L., Yee, C. Y., Hilmert, C. J., & Taylor, S. E. (2009). Neurobiological correlates of coping through emotional approach. *Brain, Behavior, and Immunity*, *23*, 27–35. doi:10.1016/j.bbi.2008.04.007
- McMenamin, B. W., Shackman, A. J., Maxwell, J. S., Greischar, L. L., & Davidson, R. J. (2009). Validation of regression-based myogenic correction techniques for scalp and source-localized EEG. *Psychophysiology*, *46*, 578–592. doi:10.1111/j.1469-8986.2009.00787.x
- Mulert, C., Jager, L., Schmitt, R., Bussfeld, P., Pogarell, O., Moller, H. J., & Hegerl, U. (2004). Integration of fMRI and simultaneous EEG: Towards a comprehensive understanding of localization and time-course of brain activity in target detection. *NeuroImage*, *22*, 83–94. doi:10.1016/j.neuroimage.2003.10.051
- Nunez, P. L., & Silberstein, R. B. (2000). On the relationship of synaptic activity to macroscopic measurements: Does co-registration of EEG with fMRI make sense? *Brain Topography*, *13*, 79–96. doi:10.1023/A:1026683200895
- Nunez, P. L., & Srinivasan, R. (2006). *Electrical fields of the brain: The neurophysics of EEG* (2nd ed.). Oxford, England: Oxford University Press. doi:10.1093/acprof:oso/9780195050387.001.0001
- Nusslock, R., Abramson, L. Y., Harmon-Jones, E., Alloy, L. B., & Hogan, M. (2007). A goal-striving life event and the onset of hypomanic and depressive episodes and symptoms: Perspective from the behavioral approach system (BAS) dysregulation theory. *Journal of Abnormal Psychology*, *116*, 105–115. doi:10.1037/0021-843X.116.1.105
- Olson, D. M., Chugani, H. T., Shewmon, D. A., Plelps, M. E., & Peacock, W. J. (1990). Electroencephalographic confirmation of focal positron emission tomography abnormalities in children with epilepsy. *Epilepsia*, *31*, 731–739. doi:10.1111/j.1528-1157.1990.tb05514.x
- Pascual-Marqui, R. D., Lehmann, D., Koenig, T., Kochi, K., Merlo, M. C., Hell, D., & Koukkou, M. (1999). Low resolution brain electromagnetic tomography (LORETA) functional imaging in acute, neuroleptic-naive, first-episode, productive schizophrenia. *Psychiatry Research*, *90*, 169–179. doi:10.1016/S0925-4927(99)00013-X
- Peterson, C. K., Gravens, L., & Harmon-Jones, E. (in press). Asymmetric frontal cortical activity and negative affective responses to ostracism. *Social Cognitive and Affective Neuroscience*.
- Peterson, C. K., & Harmon-Jones, E. (2008). Proneness to hypomania predicts EEG coherence between left motor cortex and left prefrontal cortex. *Biological Psychology*, *78*, 216–219. doi:10.1016/j.biopsycho.2008.01.011
- Peterson, C. K., & Harmon-Jones, E. (2009). Circadian and seasonal variability of resting frontal EEG

- asymmetry. *Biological Psychology*, 80, 315–320. doi:10.1016/j.biopsycho.2008.11.002
- Peterson, C. K., Shackman, A. J., & Harmon-Jones, E. (2008). The role of asymmetrical frontal cortical activity in aggression. *Psychophysiology*, 45, 86–92.
- Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology*, 110, 1842–1857. doi:10.1016/S1388-2457(99)00141-8
- Pizzagalli, D. A., Nitschke, J. B., Oakes, T. R., Hendrick, A. M., Horras, K. A., Larson, C. L., . . . Davidson, R. J. (2002). Brain electrical tomography in depression: The importance of symptom severity, anxiety and melancholic features. *Biological Psychiatry*, 52, 73–85. doi:10.1016/S0006-3223(02)01313-6
- Pizzagalli, D. A., Oakes, T. R., Fox, A. S., Chung, M. K., Larson, C. L., Abercrombie, H. C., . . . Davidson, R. J. (2004). Functional but not structural subgenual prefrontal cortex abnormalities in melancholia. *Molecular Psychiatry*, 9, 325–405. doi:10.1038/sj.mp.4001469
- Polich, J., & Lawson, D. (1985). Event-related potential paradigms using tin electrodes. *The American Journal of EEG Technology*, 26, 187–192.
- Price, T. F., & Harmon-Jones, E. (in press). Approach motivational body postures lean toward left frontal brain activity. *Psychophysiology*.
- Reid, S. A., Duke, L. M., & Allen, J. J. B. (1998). Resting frontal electroencephalographic asymmetry in depression: Inconsistencies suggest the need to identify mediating factors. *Psychophysiology*, 35, 389–404. doi:10.1111/1469-8986.3540389
- Reiman, E. M., Lane, R. D., Van Petten, C., & Bandettini, P. A. (2000). Positron emission tomography and functional magnetic resonance imaging. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of Psychophysiology* (2nd ed., pp. 85–118). New York, NY: Cambridge University Press.
- Riskind, J. H., & Gotay, C. C. (1982). Physical posture: Could it have regulatory or feedback effects on motivation and emotion? *Motivation and Emotion*, 6, 273–298. doi:10.1007/BF00992249
- Schaffer, C. E., Davidson, R. J., & Saron, C. (1983). Frontal and parietal electroencephalogram asymmetry in depressed and nondepressed subjects. *Biological Psychiatry*, 18, 753–762.
- Schutter, D. J. L. G., & van Honk, J. (2005). Electrophysiological ratio markers for the balance between reward and punishment. *Cognitive Brain Research*, 24, 685–690. doi:10.1016/j.cogbrainres.2005.04.002
- Seeck, M., Lazeyras, F., Michela, C. M., Blanke, O., Gericke, C. A., Ivics, J., . . . Landis, T. (1998). Non-invasive epileptic focus localization using EEG-triggered functional MRI and electromagnetic tomography. *Electroencephalography and Clinical Neurophysiology*, 106, 508–512. doi:10.1016/S0013-4694(98)00017-0
- Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology*, 23, 695–703. doi:10.1111/j.1469-8986.1986.tb00696.x
- Sutton, S. K., & Davidson, R. J. (1997). Prefrontal brain asymmetry: A biological substrate of the behavioral approach and inhibition systems. *Psychological Science*, 8, 204–210. doi:10.1111/j.1467-9280.1997.tb00413.x
- Taylor, S. E., & Gollwitzer, P. M. (1995). Effects of mindset on positive illusions. *Journal of Personality and Social Psychology*, 69, 213–226. doi:10.1037/0022-3514.69.2.213
- Thatcher, R. W., Krause, P. J., & Hrybyk, M. (1986). Corticocortical associations and EEG coherence—A 2-compartmental model. *Electroencephalography and Clinical Neurophysiology*, 64, 123–143. doi:10.1016/0013-4694(86)90107-0
- Tomarken, A. J., Davidson, R. J., Wheeler, R. E., & Doss, R. C. (1992). Individual differences in anterior brain asymmetry and fundamental dimensions of emotion. *Journal of Personality and Social Psychology*, 62, 676–687. doi:10.1037/0022-3514.62.4.676
- Van Bogaert, P., Wikler, D., Damhaut, P., Szliwowski, H. B., & Goldman, S. (1998). Cerebral glucose metabolism and centrotemporal spikes. *Epilepsy Research*, 29, 123–127. doi:10.1016/S0920-1211(97)00072-7
- Verleger, R. (1991). The instruction to refrain from blinking affects auditory P3 and N1 amplitudes. *Electroencephalography and Clinical Neurophysiology*, 78, 240–251. doi:10.1016/0013-4694(91)90039-7
- Vitacco, D., Brandeis, D., Pascual-Marqui, R., & Martin, E. (2002). Correspondence of event-related potential tomography and functional magnetic resonance imaging during language processing. *Human Brain Mapping*, 17, 4–12. doi:10.1002/hbm.10038
- Wallstrom, G. L., Kass, R. E., Miller, A., Cohn, J. F., & Fox, N. A. (2004). Automatic correction of ocular artifacts in the EEG: A comparison of regression-based and component-based methods. *International Journal of Psychophysiology*, 53, 105–119. doi:10.1016/j.ijpsycho.2004.03.007
- Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, 54, 1063–1070. doi:10.1037/0022-3514.54.6.1063

- Wheeler, R. E., Davidson, R. J., & Tomarken, A. J. (1993). Frontal brain asymmetry and emotional reactivity: A biological substrate of affective style. *Psychophysiology*, *30*, 82–89. doi:10.1111/j.1469-8986.1993.tb03207.x
- Wilson, F. A., Ó Scalaidhe, S. P., & Goldman-Rakic, P. S. (1994). Functional synergism between putative gamma-aminobutyrate containing neurons and pyramidal neurons in prefrontal cortex. *Proceedings of the*

National Academy of Sciences of the United States of America, *91*, 4009–4013. doi:10.1073/pnas.91.9.4009

- Worrell, G. A., Lagerlund, T. D., Sharbrough, F. W., Brinkmann, B. H., Busacker, N. E., Cicora, K. M., & O'Brien, T. J. (2000). Localization of the epileptic focus by low-resolution electromagnetic tomography in patients with a lesion demonstrated by MRI. *Brain Topography*, *12*, 273–282. doi:10.1023/A:1023407521772

UNCORRECTED PROOFS © AMERICAN PSYCHOLOGICAL ASSOCIATION