Psychophysiology

The Mind-Body Perspective

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Preface

The idea to write an introductory textbook in psychophysiology came to me about ten years ago. I was just taking up a new position at the University of Bergen in Norway, leaving my laboratory and friends in Uppsala, Sweden, where I had studied and worked up to that day. Psychophysiology is a rather new discipline in the mind-body sciences, and maybe because of its multidisciplinary emphasis only a few textbooks, and a larger number of advanced research volumes, have appeared. The book I had in mind to write might have remained just an idea if Stephen Kosslyn, general editor for the Perspectives in Cognitive Neuroscience series, hadn't asked me at a meeting if there wasn't a need for a book on psychophysiology that would introduce undergraduates and graduate students to the new field. This book, I hope, will fill that need.

The merging of cognitive science with neuroscience into cognitive neuroscience has added an important new branch to the brain-sciences tree, and psychophysiology belongs on that branch. But the physiology of cognition is only one part of the field covered by psychophysiology. Another is the physiology of emotional experience. I would like to call this aspect of psychophysiology "affective neuroscience," and I predict that it will be the next new area of brain science. In this book I explore the newest findings from the physiology of cognition *and* the physiology of emotion, from the perspective of both cognitive psychology

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The Electroencephalogram

The electroencephalogram (EEG) is a recording of the difference in electrical potential between various points on the surface of the scalp. The rhythmic pattern of an EEG wave is generated by cyclical changes in the membrane potentials of underlying nerve cells. These cyclical changes are probably caused by synchronizing impulses from a corticothalamic neurogenerator, which establishes corticothalamic "current loops" that produce synchronous neuronal activity in the cortex.

The potentials recorded in the EEG come from the cortex, and particularly the large pyramidal cells in layers IV and V of the cortex. A pyramidal cell might be considered a dipole whose axes are perpendicular to the surface of the cortex (Cooper, Osselton, and Shaw, 1974). In this model, a current dipole, which is an approximation of the currents caused by sources and sinks in many neurons, gives rise to a localized flow of current when the neurons and their axons depolarize.

Nunez (1981) has provided a somewhat different view on what an EEG represents. According to Nunez, the EEG records the interaction of cortical neurons by means of action potentials. The neurons of the cortex have a hierarchical columnar organization, with different types of neuronal cells at different cortical depths. There are six layers of cells in the cortex, designated layer I to layer VI from the cortical surface inward. Nunez postulated that neurons in one column of the

cortex interconnect with neurons in another through short-range intracortical fibers or through long-range association fibers (which link distant areas of the cortex, such as the anterior and the posterior parts). The recordings that Nunez calls *wave phenomena*—that is, standing waves—occur when action potentials travel along association fibers connecting cortical regions over some distance. This explains why EEG frequency is much more sensitive to changes in long-range (association) connections than to short-range (intracortical) connections.

When electrodes are placed on the scalp, the EEG will reflect the activity of large groups of neurons being synchronously depolarized. It is therefore important to keep in mind that the EEG is not particularly sensitive to focused activity in narrow regions of the cortex. This is further emphasized by the fact that the voltage signal picked up by the EEG electrodes has been conducted from the source through a conductive fluid medium, through the bony structure of the skull, and then through the scalp to the electrode.

This chapter will provide a framework for understanding EEG recordings and their applications in studies of activation, sleep, and hemispheric asymmetry, with a focus on the different waveforms in the normal EEG and quantitative techniques for describing EEG waves. Practical guidelines for recording the EEG signal are provided throughout the chapter. Chapter 12 discusses potential changes in the EEG in response to stimulus presentations, so called event-related potentials (ERPs).

Recording the EEG Signal

EEG patterns are wavelike, and their analysis is based on measurements of the frequency and amplitude of the waves. Visual inspection is the simplest way of characterizing the waveforms but, because different observers may have different opinions, it is not a scientifically reliable method. In clinical practice, though, visual inspection is standard procedure for identifying the distinctive patterns of serious disorders, such as an epileptic seizure.

For scientific purposes, the EEG signal is best described by decomposing it into sinusoidal waveform components, each with a certain frequency and amplitude. In a sinusoidal wave, the electrical potential (voltage) goes up and down around a resting baseline level in cycles.

(The example shown in Figure 11.1 illustrates two cycles.) One cycle is the change in voltage from resting baseline in a positive, then a negative, and then again a positive direction, until it returns to the baseline.

The peak-to-baseline amplitude is the magnitude of the deflection from baseline to maximum in one direction. The peak-to-peak ampli-

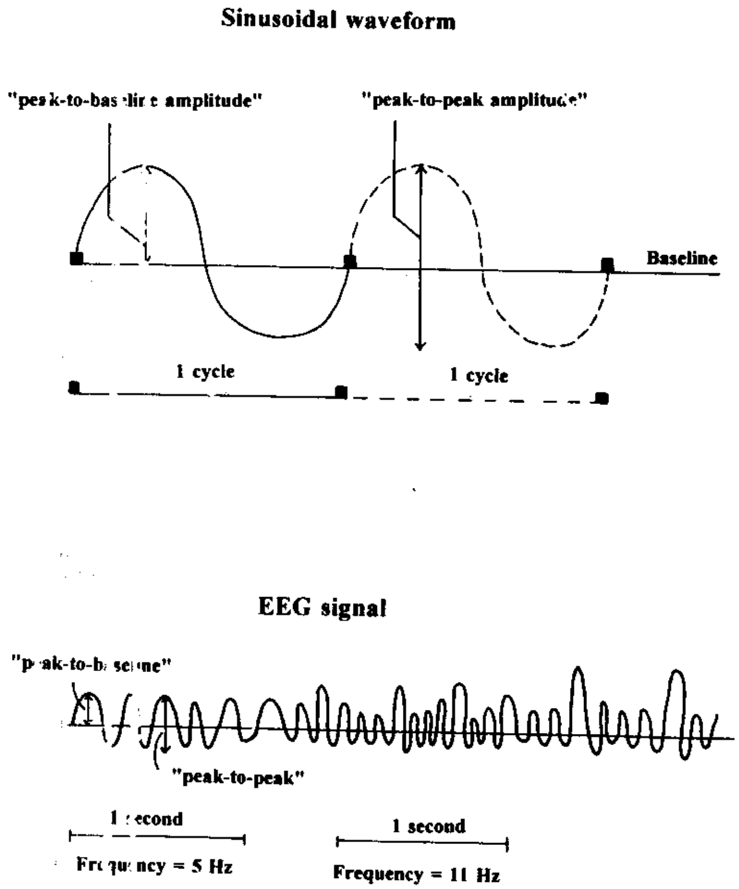


Figure 11.1. A sinusoidal wave with two cycles *(top)* and an EEG signal *(bottom)* with many cycles. Amplitude = displacement from baseline, frequency = cycles per second (in Hertz, Hz).

tude is the magnitude of the deflection between two peaks. The frequency of a sinusoidal signal is the number of cycles per second, measured in hertz (Hz) or kiloherz (1,000 Hz). A frequency of 5 Hz thus means five cycles in one second.

The EEG signal is picked up by tiny electrodes, usually placed on the scalp but sometimes implanted in the cortex or hippocampus. EEG electrodes are typically plated with gold or silver–silver chloride in order to prevent the buildup of electrode potentials during a recording session. The signal from the electrode is then amplified before it is written out on polygraph paper (as the standard EEG machines do) or stored on a computer for subsequent analysis (as modern research laboratories do). The EEG signal is in the microvolt range ($\mu V = 10^{-6}$ volt), much smaller than the ECG signal, which is in the millivolt range ($mV = 10^{-3}$ volt). Typical amplitudes are 30–50 μV for alpha waves and 10–20 μV for beta waves.

The International 10–20 System

The locations on the scalp for EEG electrodes have been standardized since 1958 (Jasper, 1958) in the so-called International 10–20 system. The system uses four reference points: the inion (the small bump at the back of the head), the nasion (the small cavity just at the base of the nose), and the left and right preauricular points (the tiny cavities above and behind each ear). The electrodes are placed on the scalp as shown in Figure 11.2, at points 10 and 20 percent of the distance of the lines from the nasion to inion and from the left to the right preauricular points.

As a general rule, the capital letter in each electrode location (F, T, P, O, C) refers to the cortical lobe—frontal, temporal, parietal, and occipital—or the central sulcus, respectively. Odd numbers refer to locations on the left side of the scalp, even numbers to locations on the right side. A full 10–20 montage involves nineteen EEG leads, which usually are supplemented with two recording leads of eye-movement recordings. Thus, a common full-scale EEG recording montage involves twenty-one recording channels, but many modern EEG and ERP laboratories use as many as 32, 64, or even 128 recording channels (e.g., Gevins and Bressler, 1988). A large number of recording channels is commonly used for functional analysis of brain electrical activity mapping (BEAM), which is described below.

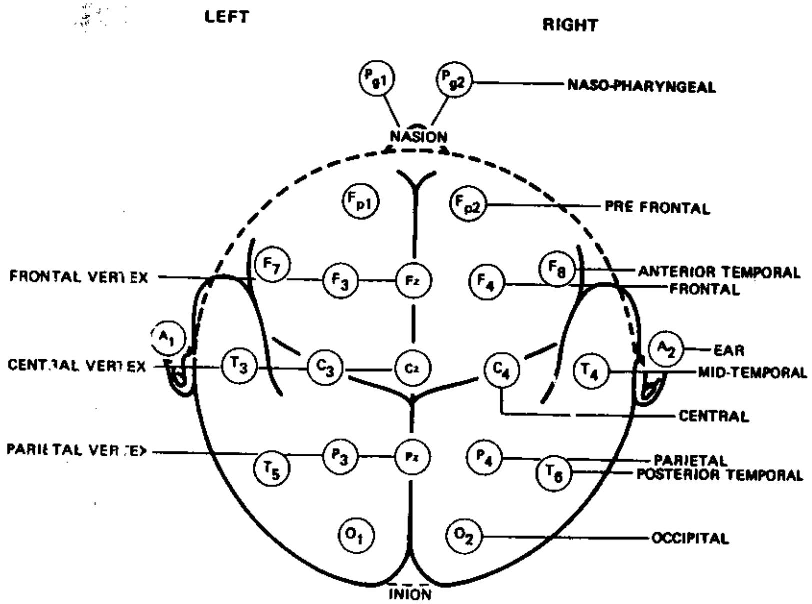


Figure 11.2. EEG electrode locations according to the International 10-20 System.

The EEG Laboratory

Figure 11.3 illustrates the layout of a standard EEG system, with preamplifiers, amplifiers, filters, FM tape recorder for data storage, and computer analysis. Note that only two leads, or channels, are being recorded, though most laboratories today use more than two leads. Many laboratories have also bypassed the FM tape recorder for storage of data in favor of off-line analysis. It is common now for the raw data to be stored directly on the hard disc on the computer or on various optical-disc storage devices.

Monopolar and Bipolar Recordings

A *montage* is a specific arrangement of electrodes. The nineteen electrodes in the 10–20 system may be connected together into various

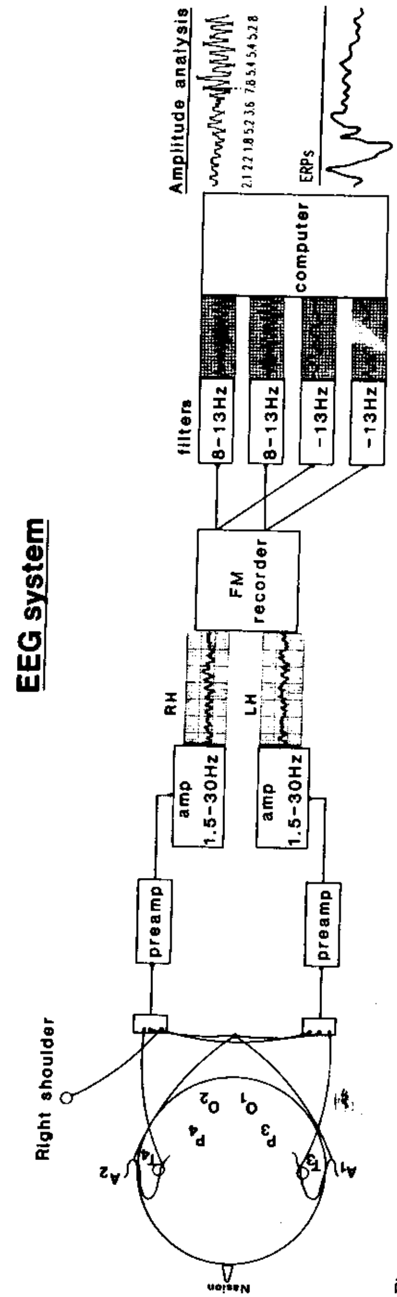


Figure 11.3. A typical EEG laboratory, with the subject to the left and examples of EEG recordings to the right. Only two electrode leads are shown here, but the principle is the same when more leads are added. RH = right hemisphere, LH = left hemisphere, amp = amplifier. The settings for the filters are only examples of possible settings.

montages, and standardized electrode montages are typically used in clinical EEG diagnostics.

Leads may be arranged to form monopolar or bipolar montages. In a bipolar montage, each recording channel is connected to two scalp electrodes, both of them being active. In a monopolar montage, also called the *common reference method*, one electrode is active and the other one (or two electrodes connected together—see below) acts as a reference electrode.

Typical arrangements for the reference electrode(s) are the "linked-ears" and the "linked-mastoids" arrangements. A linked-ears reference is made by connecting together two electrodes at points behind the ears (A_1 and A_2 in Figure 11.2) and using the connected electrodes as a common reference for the active electrode(s). A linked-mastoids reference is made by connecting together two electrodes placed on the mastoid muscle on the side of the neck and using this as the reference point. The reference electrode(s) should not be affected by the EEG signal from the scalp. Some authors have used the tip of the nose as the reference point, since it is further "away" from the brain. In addition to reference electrodes, a ground electrode, connected to earth, may also be used.

It is important to keep in mind that there is probably no area on the scalp, or the face, that is an absolute "zero" reference. All reference placements mentioned above will be affected by some neuronal activity. This is partly because of the problem of volume conduction, the fact that the electrical signal is conducted in a fluid-filled medium. (For more details, see the discussion in Chapter 12 on artifacts in electrical signals from the brain.) Selecting the reference electrodes is a complex problem, especially since there is no "absolute" reference point anywhere on the body surface. As will be discussed in more detail below, the use of a linked-ears arrangement as a reference in studies of EEG asymmetry may actually attenuate and abolish any effects of differences at homologous EEG sites across the hemispheres. Furthermore, noncephalic reference placements may pick up heart and muscle activity that could interfere with the EEG signal.

Filters

The EEG signal is usually filtered before being recorded in order to reduce "noise" and enhance the frequency components that are of interest. All standard EEG amplifiers have different filter functions built in. A typical instruction in psychophysiological research may be to filter out frequencies above 30 Hz and below 5 Hz, although the actual figures vary tremendously, depending on the research agenda and the available equipment. Today digital filters are included as part of the software in the EEG computers used to analyze the signal.

It should be remembered that setting the high- and low-frequency filters at a certain value does not mean that all frequencies within the accepted range are unaffected by the filter or that all other frequencies are ignored by the amplifier. Filters may differ in sharpness, which means that they attenuate the signal at certain frequencies lower and higher than the filter setting. How close to the filter setting the filter actually attenuates the EEG signal is determined by the sharpness of the filter.

Artifacts

The EEG signal may be affected by various types of *artifacts*, or interference. For example, the EEG may record 60 Hz interference from the main power line in the laboratory, or eye movements or heartbeats may change the signal recorded at the scalp. Alpha waves are particularly sensitive to whether the eyes are closed or open, and eye blinks may make EEG waves resemble event-related potentials.

A frequent artifact in EEG recordings is muscle activity (see Pivik, Broughton, Coppola, et al., 1993, for an excellent discussion of artifacts in EEG recordings), which is especially troublesome because the frequency spectrum of the electromyographic (EMG) signal is very broad, covering most of the EEG bands. Thus, filtering the EMG signal will in many instances not help the researcher, since doing so may filter out large aspects of the EEG signal as well. Alternatively, setting the low-pass filter at, say, 40 Hz in order to filter out frequencies above 40 Hz will not help, since EMG activity will also be recorded in the frequency range below 40 Hz. Muscle activity is especially problematic when the subject has to perform cognitive or emotional tasks during the recording, because subjects concentrating on these tasks will probably not be relaxed and immobile. Pivik et al. (1993) suggest methods for statistically separating muscle activity from EEG recordings.

The time constant of the low-pass filter may also affect the recorded signal, which requires the EEG psychophysiologist to have some understanding of basic electronics and electricity. The *time constant* (TC) is the time it takes for an AC signal to fall two-thirds of its initial amplitude. There is an inverse relationship between the lower cutoff frequency for the low-pass filter and the time constant, such that a cutoff frequency of 0.16 Hz corresponds to a time constant of 1.0 sec, a cutoff frequency of 0.027 Hz corresponds to a time constant of 6 sec. On some amplifiers the time constant is provided as a switch, while on others the low-pass frequency filter settings are provided. Conversion between time constants and cutoff frequency is given by the equation: $TC = 1/(2\pi F)$, where F is the lower cutoff frequency.

EEG Rhythms

EEG recordings will vary in frequency and amplitude when the individual being recorded is engaged in different cognitive or emotional activities. These differences have been noted since the introduction of the technology: Hans Berger, the Austrian psychiatrist who in 1929 suggested that "wavelike" electrical activity could be recorded from the human scalp, recognized that the "waves" tended to change in frequency and amplitude with the state of the organism—higher frequency and smaller amplitude in states of arousal, very large amplitudes and slow frequencies in sleep.

Berger furthermore observed that when the individual was at rest and relaxed, rhythmic wave sequences were generated at about 10 Hz, but when the individual became alert, this rhythm disappeared and was followed by a new, higher frequency varying somewhere between 15 and 50 Hz. Berger called the "relaxing" waves *alpha waves*, and the "alertness" waves *beta waves*. The occurrence of alpha and beta waves, respectively, in states of relaxing drowsiness and alertness is one of the major characteristics of the EEG. Figure 11.4 depicts the four most typical EEG waveforms: alpha, beta, theta, and delta.

The alpha rhythm. The alpha rhythm is a regular, but not always sinusoidal, waveform with a characteristic 8–12 Hz frequency of mid range amplitudes varying between 10 and 150 microvolts (μV). Alpha is most easily recorded from occipital-parietal regions and can be driven by opening and closing the eyes. Opening the eyes attenuates the alpha wave, and closing the eyes enhances alpha occurrence. The alpha rhythm is probably generated by multiple processes in the posterior part of the brain (Shagass, 1972). Cohn (1948) advanced the view that there were two source generators in each hemisphere and that a

change of dominance of the activity of one hemisphere relative to the other would give rise to movement of a single focus of EEG activity. It is further suggested that an alpha wave recorded from the scalp is the average signal of the activity of several generators deep in the brain tissue.

The alpha wave is also typically attenuated or blocked during arousal or cognitive activity. As previously mentioned, the blocking of alpha over one hemisphere when a subject is engaged in a particular cognitive activity has traditionally been used as an index of hemispheric differences in the performance of that particular task. The reason for this is that an absence of alpha waves from an area would indicate greater cortical activation in that area. However, conclusions about specific localizations of cortical activity based on the presence or absence of alpha activity in an EEG should be made with some caution, since the EEG does not have a particularly good spatial resolution.

The spontaneous alpha rhythm is typically recorded at occipital leads and is of similar amplitude over both hemispheres, although it may sometimes be of slightly higher amplitude in the right hemisphere. As can be seen in Figure 11.4, a characteristic feature of alpha is that it waxes and wanes over time.

The beta rhythm. The beta waveform is typically of higher frequency and smaller amplitude than the alpha (from 14 Hz and up, usually lower than 25 μV in amplitude). A simple rule of thumb regarding the relation between frequency and amplitude is that as the frequency increases, amplitude generally decreases, and vice versa.

Beta activity occurs over most parts of the scalp, often with frontal predominance, although posterior dominance may also occur. It is most often associated with increased activation and arousal. Since the alpha wave is absent when the individual is aroused and beta activity is recorded, this state is called *alpha desynchronization* or *alpha blocking*.

The theta rhythm. Theta waves are slow, high-amplitude waves with frequencies between 4 and 7 Hz. They have a variable distribution over the scalp, depending on the age and degree of alertness of the subject. The normally occurring theta has, though, a more posterior than anterior localization. Theta waves are considered to co-occur with vascular changes that accompany increasing age.

The delta rhythm. Delta waves are predominant during later sleep stages, when the subject is in deep sleep (see below), although this pattern of activity decreases with increasing age. The waves have vari-

Alpha (α)

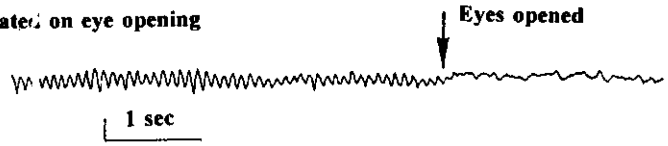
Frequency: 8 - 12 Hz

Amplitude: 50 - 150 µV

Location: Occipital/parietal regions

Attenuated on eye opening

P_z - O_1



Waxing and waning of alpha

P_z - O_1

Beta (β)

Frequency: 15 Hz and up

Amplitude: Up to 25 µV usually, but higher at times

Location: Typically frontal regions, but also posterior dominant

F_4 - F_2

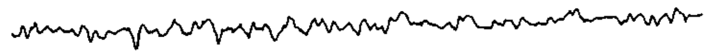
Figure 11.4. Four types of EEG waves. (Adapted from Craib and Perry, 1975, Beckman Instruments.)

Theta (Γ)

Frequency: 4-7 Hz

Amplitude: Variable

Location: Variable



T_z - C_z

Delta (δ)

Frequency: 3 Hz or slower

Amplitude: Variable

Location: Variable

C_z - P_z

able high amplitudes and very slow frequencies, from 3 Hz and slower. Delta waves are considered signs of brain abnormality if they occur frequently in the awake state. In general, slow waves below 8 Hz should be rare or absent in the EEG of a normal awake individual.

Analytic Techniques

The EEG signal can be analyzed by reference to the time or the frequency domain of the signal. Time-domain analyses are based on measures of the amplitude, such as correlational analyses, in which the amplitude of the signal is averaged over time, independent of signal frequency. Frequency-domain analyses are based on measurements of the frequency of the signal, as in power spectral analysis. Examples of each type of analysis are provided below.

Amplitude Analysis

A simple way of performing an amplitude analysis is to determine the mean amplitude. The investigator first determines a "scoring interval," perhaps 10 seconds after the presentation of a stimulus. The next step is to measure all peak-to-peak amplitudes within the scoring interval and convert the summed amplitudes to mean amplitude. Figure 11.5 illustrates an exercise in amplitude analysis across a 5-second scoring interval.

As an alternative, the investigator might first "rectify" the EEG signal. In a recording that has been rectified, all deflections of the signal point in only one direction. With the signal in this form, the investigator can then mathematically integrate and average the rectified amplitudes.

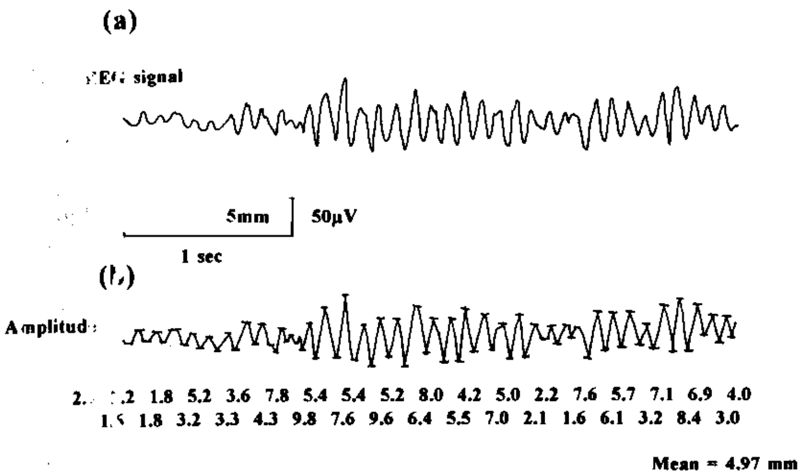


Figure 11.5. For EEG amplitude analysis, the peak-to-peak amplitudes of the waves in an EEG signal (as in *a*) are outlined and measured (as in *b*). The amplitudes are then summed and averaged across the scoring interval. (Adapted from Cooper, Osselton, and Shaw, 1974, with permission from Butterworth and Co., London, U.K.)

Correlational Analyses

Another type of amplitude analysis is correlational analysis. Correlational analyses are calculations of the degree of similarity between two EEG signals occurring at homologous sites on the scalp (see Cooper, Osselton, and Shaw, 1974). Theoretically, the degree of similarity between two signals may be expressed as a correlation coefficient. By multiplying two homologous signals together, the cross product of each pair is obtained, and the cross product is integrated and summed in order to obtain the covariance and correlation coefficient of the signal pair. Two signals may have a large covariance because they are similar in shape, but a large covariance can also be obtained because of large amplitudes in the individual signals. This problem is usually avoided by normalizing the covariance function by dividing the covariance by the square root of the product of the variance of the two signals. The normalized covariance is the correlation coefficient. Correlational methods, as stand-alone methods, are less frequently in use today than previously, after the introduction of power spectral analyses (described below).

Cross-correlation techniques are used to analyze signals that have similar patterns but that are recorded from different locations on the scalp. For example, alpha frequencies that occur over parietal brain areas may be delayed by 30–50 msec after the corresponding alpha waves at more anterior, frontal leads. Although this delay can be expressed as both phase and time differences, time differences are less complex mathematically. Cross-correlations provide information about similar activity recorded at the two leads and the time delay between the signals, so common patterns of activity are emphasized while dissimilar activity is suppressed (Gevins, 1987). An example of cross-correlation is a comparison of the EEG signals from two homologous (similar) sites on the left and right hemisphere, which might detect lateral asymmetries in EEG function across the two cortices of the brain. If two signals are similar in shape and frequency but have different time lags at different locations on the scalp, this pattern may indicate independence of underlying neuronal generators for this particular wave frequency.

Auto-correlation analysis is a comparison of the EEG signal with a time-shifted version of itself. The time delay can be as short as 5–10 msec. Auto-correlation techniques are primarily used to detect periodicity in the EEG signal. An example is the "waxing and waning" of the alpha frequency across time in a single EEG channel. The occurrence of alpha bursts at regular time intervals may be detected by auto-correlation. See Figure 11.6 for an example of an auto-correlation graph.

The mathematical principles behind cross- and auto-correlations are similar, but the auto-correlation technique compares epochs of the same signal while the cross-correlation technique compares epochs from two different signals.

Power Spectral Analysis

Frequency analyses are far more common than amplitude analyses, and Fast Fourier Transform (FFT) is one of the most common techniques. The FFT technique determines the *power spectrum* of an EEG signal, sometimes called a *frequency spectrum,* by separating the signal into its specific sinusoidal and cosine waveforms, a procedure called *spectral analysis.* The mathematical operations involved in FFT analysis are beyond the scope of this book. The resultant frequencies are graphed on an *x-y* plot, called a *power spectrum plot,* as relative amplitude for each frequency component.

For research purposes, the EEG signal may be filtered to get rid of unwanted frequencies (like interference from 60 Hz energy sources) before being subjected to a power spectral analysis, or Fourier analysis, to separate the relative contribution of the different frequencies in the signal. The result is plotted as the "power" or intensity for different frequencies by multiplying amplitudes by frequencies. Figure 11.6 shows a typical EEG signal recorded during rest in an adult individual and the resulting power spectrum. Note the maximum power in the frequency region 8–12 Hz, which corresponds to the alpha wave band usually recorded from occipital leads during rest.

Coherence Analysis

Coherence analysis is a technique in the frequency domain, although the method in itself is a correlational one. Coherence analysis involves

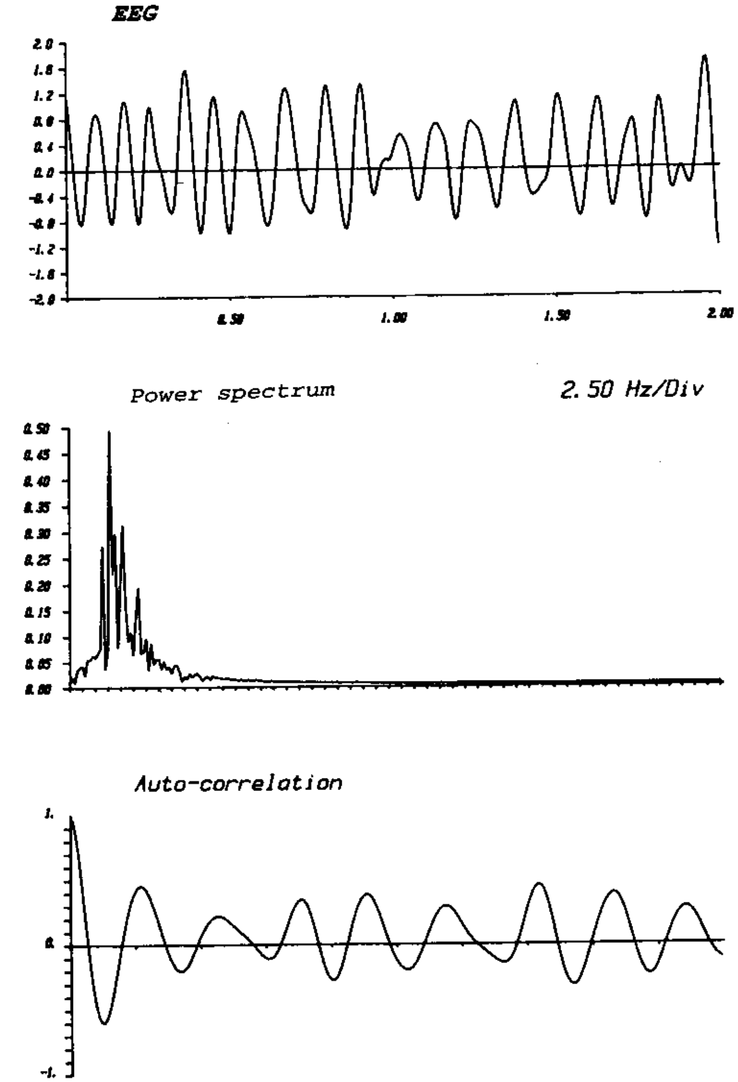


Figure 11.6. Frequency analysis of a raw EEG signal *(top)* by the power spectrum *(middle)* and auto-correlation *(bottom)* methods. (Courtesy of Lars Bäckström, Uppsala University, Sweden.)

the computation of Pearson's product-moment correlation coefficients between various EEG leads, which provides a measure of correlation at each frequency. Coherence is a measure of the relatedness between two EEG signals frequency by frequency. A high correlation coefficient thus indicates that two signals are similar in frequency, and that the activation patterns under these two electrodes are symmetrical. Coherence analyses are typically used in EEG studies of hemispheric asymmetry.

Topographical Mapping of EEG Activity

Brain electrical activity mapping, or *BEAM* (Duffy and McAnulty, 1985), is a new technique for analyzing EEG signals that has already yielded interesting results. It involves the simultaneous analysis of either EEG frequencies or ERP amplitudes at many electrode locations. Each electrode voltage, at any point in time, is given a digital value. The corresponding values at areas between the electrodes are "estimated" with various forms of mathematical interpolation, using data from the three or four nearest electrodes (see Itil, Mucci, and Eralp, 1991, for a comprehensive description of the BEAM technology). Other terms frequently used to denote BEAM technique are *brain mapping* and *EEG topography* (Pivik et al., 1993).

The result is a "map" of the scalp showing different values corresponding to the frequencies and amplitudes in the EEG or ERP signal. These values are then "color-coded" so that a color map of the cortex may be produced, with some colors (green or red) indicating areas of

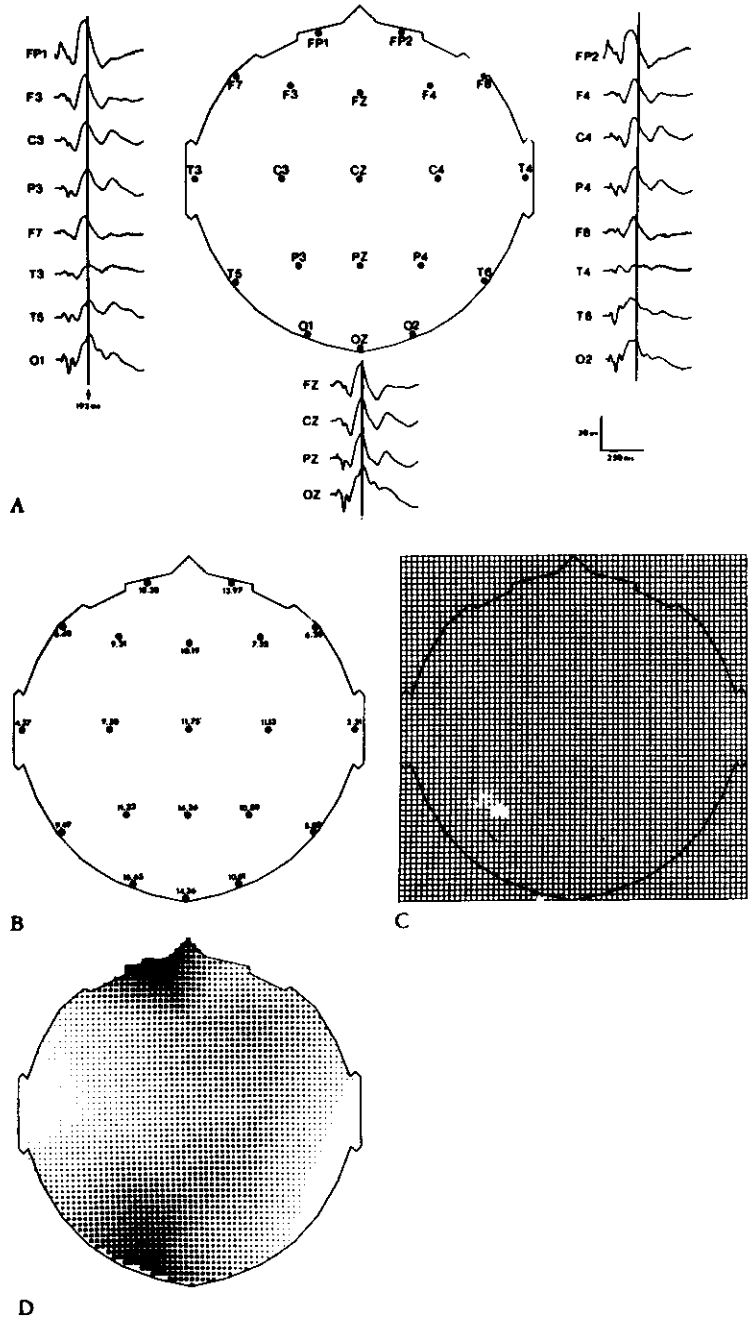


Figure 11.7. A topographic map of brain activity made from electrophysiological data. (Data for this map provided by ERP waves, which are derived from an EEG signal; see Chapter 12 for details.) Individual ERPs are recorded at the electrode locations indicated *(A)*. Mean voltage values are calculated for each location *(B)* for the interval beginning 192 msec after the stimulus (indicated by the vertical line in *A*). The head region is treated as a 64 × 64 matrix *(C)*, resulting in 4,096 different spatial domains (pixels). Each domain is assigned a voltage value by linear interpolation from the three nearest known points. Finally *(D)*, the raw voltage values are fitted to a discrete-level equal-interval intensity scale matched to the appropriate pixel, and the images are displayed in a gray scale (or can be converted to a color scale). (From Duffy and McAnulty, 1985, reprinted with permission from Little, Brown, and Company, Boston, MA.)

higher EEG frequencies, other colors (dark blue or white) indicating areas with lower frequencies. By relating the different frequencies in the EEG, or the amplitudes in the ERPs, to brain activity levels, the BEAM technique may thus map the spatial localization of cortical activity to a given stimulus at a given point in time.

BEAM maps can be upgraded at specific intervals, such as every 500 msec, to provide a series of brain maps over time. These may be presented in a display to show how EEG activity in certain areas of the brain may shift localization as a particular stimulus is processed or as a task is solved. The principle behind the BEAM technique is illustrated in Figure 11.7 (from Duffy and McAnulty, 1985).

Clinical BEAM Diagnosis

John, Prichep, Friedman, and Easton (1988) have developed a clinical diagnostic system that compares the BEAM profiles of normal control persons with the BEAM profiles obtained from individuals with different psychiatric disorders. They used computed values for the standard normal distribution (z scores) of the relative power in different EEG frequency bands (alpha, beta, theta, and delta), and each BEAM map represents the difference in relative EEG power after Fourier analysis between the diagnostic groups and the normal control group for each frequency band. The researchers noted a large decrease in activity among subjects with alcoholism and dementia relative to the control data.

BEAM in Psychopathology

The BEAM technique has been used to study the brain activity of individuals with various learning disabilities, including dyslexia (Duffy and McAnulty, 1985). The BEAM maps of children with learning disabilities, for example, show deviations of EEG features from the predicted normal range. Dyslexic children tend to have less variability in their BEAM topographic distributions. They also tend to have more alpha activity over the left hemisphere, a possible sign of reduced activity in the left (language-specialized) hemisphere. Furthermore, Buchsbaum, Hazlett, Sicotte, et al. (1985) found that administration of benzodiazepines to anxiety patients altered frontoparietal and occipital alpha distribution, in the direction of increased alertness. These findings reveal the usefulness of BEAM topographical mapping for investigating clinical disorders, in this case to identify cortical areas involved in anxiolytic drug action.

Although the BEAM technique is an interesting development of standard EEG technology, it should be remembered that it does not represent a new recording technique—it is simply a new way of plotting EEG and ERP data. Thus, a BEAM map is a more efficient way of displaying data produced by familiar recording technologies. An exception is the mapping technique for event-related covariances (ERPs) developed by Gevins (e.g., Gevins and Bressler, 1988), in which event-related potentials are mapped on the cortex from a large number of EEG channels. BEAM also has the advantage that it can show changes in EEG patterns across cortical sites with time, as noted above. This is a new and important addition to standard EEG and ERP analyses.

An important distinction must be made between BEAM maps and other models of brain activity; because BEAM maps resemble "pictures" of the brain, some researchers or clinicians may regard them as anatomically similar to MRI or PET scans, which are based on actual blood-flow changes (see Chapter 13 for a description of MRI and PET). For one thing, BEAM maps are usually created from data from a restricted number of EEG leads, and they have far less spatial resolution than, for example, an MRI scan. Furthermore, the use of similar color-coding principles in BEAM and PET maps may actually mislead the researcher to interpret effects in the BEAM image that are certainly not present.

The Electroencephalogram in Psychophysiology

The electroencephalogram is a record of a person's psychological state. As noted above, deviations from the normal EEG patterns for both frequency and amplitude may indicate pathology, most notably the occurrence of epileptic seizures. Some of the more typical and frequent EEG wave rhythms, for both normal and abnormal psychological states, are listed in Table 11.1.

EEG patterns are also useful for studying psychophysiological states and events. In classical psychophysiology, the EEG is most typically associated with studies of sleep stages (Dement and Kleitman, 1957), activation theory (Lindsley, 1960), and classical conditioning (Jasper and Shagass, 1941), although it has been used as a brain correlate of

Table 11.1. Description of EEG waveforms and corresponding scalp locations and psychological states.

Type of waves or rhythm	Frequency per second (range)	Amplitude or voltage (V)	Percent of time present	Regional or diffuse	Region of prominence or maximum	Condition when present	Normal or abnormal
Alpha	8–12	5–100	5–100	Diffuse	Occipital and parietal	Awake, relaxed, eyes closed	Normal
Beta	18–30	2–20	5–100	Diffuse	Precentral and frontal	Awake, no movement	Normal
Gamma	30–50	2–10	5–100	Diffuse	Precentral and frontal	Awake	Normal, sleep deprived
Delta	0.5–4 0.5–4	20–200 20–400	Variable Variable	Diffuse Both	Variable Variable	Asleep Awake	Normal Abnormal
Theta	5–7	5–100	Variable	Regional	Frontal and temporal	Awake, affective or stress stimuli	Normal (?) Abnormal
Kappa	8–12	5–40	Variable	Regional	Anterior and temporal	Awake, problem solving?	Normal
Lambda	Pos. or neg. spike or sharp waves	5–100	Variable	Regional	Parieto-occipital	Visual stimulus or eye opening	Normal (?)
K-complex	Pos. sharp waves and other slow pos. or neg. waves	20–50 50–100	Variable Variable	Diffuse Diffuse	Vertex Vertex	Awake, auditory stimulus Asleep, various stimuli	Normal (?) Normal
Sleep spindles	12–14	5–100	Variable	Regional	Precentral	Sleep onset	Normal

Source: From Lindsley (1960), with permission from Academic Press and the author.

almost every mental faculty, from personality (Henry, 1965) to intelligence (Kreezer, 1940). As early as 1944, however, Lindsley concluded that there was little empirical evidence to support the notion that EEG patterns could measure the intelligence of an individual.

In more recent psychophysiological research, EEG has been used to separate functions in the left and right hemispheres of the brain (Galin and Ornstein, 1972; Gevins, Schaffer, Doyle, et al., 1983), to characterize stable individual traits in positive and negative emotionality (Davidson, 1992), and to indicate hypnotic susceptibility (Morgan, MacDonald, and Hilgard, 1974), just to mention a few examples. EEG is frequently used in clinical neurological and psychiatric practice as an invaluable diagnostic tool for identifying functional disorders. For epileptic patients, for example, implanted EEG electrodes in the brain can give advance information that a seizure is about to start.

Activation Theory

Lindsley (1960) used associations between EEG waveforms and behavioral patterns, ranging from deep coma to strong emotional excitement, to describe a "behavioral continuum" going from lower to higher forms of awareness and consciousness. The EEG pattern served as a cortical correlate to the behavioral pattern, and it, too, was graded according to a "continuum" of activation and awareness.

The activation theory was quite influential during the 1960s and early 1970s, but it fell more or less into disrepute after studies by Lacey (e.g., 1967) suggested that different physiological measures changed in opposite directions from changes in behavioral activation. For example, as mentioned in Chapter 2, whereas an EEG moves through a gradual continuum of change from coma to rage, heart rate decreases in response to highly activating but nonaversive stimuli, but increases in response to aversive stimuli.

Hypnosis

The search for EEG concomitants of hypnosis and hypnotic susceptibility has traditionally been focused on two phenomena: the search for changes in brain activity during hypnosis, either as a state or as a trait phenomenon; and the search for shifts in hemispheric asymmetry during hypnosis, as mediating brain "markers" or "footprints" of hypnosis (MacLeod-Morgan and Lack, 1982; Morgan, MacDonald, and Hilgard, 1974). Although several promising findings have been reported, particularly that hypnosis may involve a general shift of hemispheric activation to the right hemisphere, a more critical analysis of the data reveals that neither search is unequivocally confirmed. It should be clear, though, that EEG effects of hypnosis are frequently observed and that they are probably a unique kind of "brain footprint" of the state of hypnosis.

It is problematic, however, that some studies report large differences in EEG activity between individuals with low and high susceptibility to hypnosis, and between hypnosis and the waking state, while other studies fail to find any differences at all. One disturbing fact may be that both slow and fast EEG frequencies are reported to covary with hypnosis. Since the alpha band (8–12 Hz) is a marker of a relaxed state and the beta band (>15 Hz) is a marker of an activated state, it is unsatisfactory that effects of hypnosis have been reported both in the alpha and beta ranges.

Another methodological problem is that only one or two EEG leads are used in many studies. Since many studies differ in their placement of the electrodes, differences in outcome between studies may thus be due to the different types of activity recorded at different cortical sites. For example, it has been shown that alpha power increases at occipital but not at central and frontal leads as subjects moved from waking to hypnosis. Thus, an experiment that records only from central or frontal areas will miss changes occurring at other electrode leads during hypnosis.

Hemispheric Asymmetry

Differences in EEG frequency over the left and right hemispheres of the brain have traditionally been taken as an indication of functional differences in processing ability between the hemispheres for various cognitive tasks. Briefly, reduced alpha power of one hemisphere, or parts of a hemisphere, relative to homologous sites over the other hemisphere is a sign of increased activity in that hemisphere. Since alpha power is related to resting state, a decrease or blocking of alpha over a certain region of a hemisphere during the performance of a specific task indicates that this region is more activated by this task than is the homologous region in the opposite hemisphere.

A problem with EEG frequency analyses of hemispheric asymmetry is that the spatial specificity of any EEG electrode is poor. The recorded frequency under one electrode on the scalp could, in principle, be generated at many local sites, possibly even from the other side of the corpus callosum. In other words, increased power over the cortex in one hemisphere may be generated by many local sources at different cortical sites. However, some studies have shown significantly reliable consistency of task-related asymmetries in the EEG over time. Ehrlichman and Wiener (1979), for example, demonstrated that the right to left differences in the alpha frequency band remained stable over two separate test occasions for four verbal and four spatial tasks.

A classic study of the EEG-frequency index of hemispheric asymmetry is the study by Galin and Ornstein (1972), who had subjects either write a letter from memory or solve Koh's Block Design (a spatial test from the WAIS intelligence test battery). To complete the Block Design, the subject must arrange a collection of different-colored cubes to match a two-dimentional sketch. In terms of hemispheric asymmetry theory, writing a letter is a language-related task that should activate the left hemisphere, and solving the Block Design test is a visuospatial task that should activate the right hemisphere. In line with the predictions, Galin and Ornstein found that posterior alpha wave was suppressed over the left hemisphere when the subject engaged in the letter-writing task, and it was suppressed over the right hemisphere when the subjects engaged in solving the Block Design test. In a critical examination of EEG studies of alpha asymmetries, Gevins, Zeitlin, Doyle, et al. (1979) made the important argument that noncognitive factors—stimulus characteristics, limb and eye movements, and the subject's ability and effort—may have affected the EEG patterns and contributed to the observed asymmetries. For example, writing a letter from memory involves unilateral hand movements in addition to cognitive processing. Hand movements may affect the EEG on the side contralateral to the writing hand, but this effect would be unrelated to the cognitive effort involved in verbal behavior.

In two experiments using tasks similar to those used by Galin and Ornstein (1972) and others who had observed alpha asymmetries, Gevins et al. (1979) tried to separate cognitive from noncognitive factors. In their second experiment, no motion of the limbs was required and stimulus characteristics were better controlled. After having analyzed the results of their studies, Gevins et al. (1979) concluded that "it is likely that the EEG patterns that discriminated between the tasks of experiment 1 were due to intertask differences in efferent activities, stimulus characteristics, or performance-related factors, rather than to cognitive differences. These experiments offer no support for the idea that lateralized EEG differences in different tasks reflect cognitive processes, as has previously been suggested" (p. 667).

Despite the critique of Gevins et al. (1979), several more recent papers have used EEG recordings to investigate the functional specialization in the brain for verbal and spatial tasks so often observed in other response modalities (see, e.g., Chapter 2). Papanicolau, Loring, Deutsch et al. (1986) concluded that left-hemisphere beta enhancement, rather than alpha suppression, is associated with unilateral activation of the left hemisphere during the performance of linguistic tasks. Thus, this study suggests that the beta frequency may be more sensitive than alpha blocking as an index of lateralized hemispheric function in the execution of cognitive tasks. However, following up on these findings, Davidson, Chapman, Chapman, et al. (1990a) again found evidence for a genuine alpha-suppression effect in posterior EEG leads during a word-finding (verbal, left-hemisphere) and dot-localization (spatial, right-hemisphere) task. Their recordings showed greater power suppression in the hemisphere putatively most engaged in task processing—that is, reduction of alpha waves over brain areas putatively engaged in processing of a specific task.

An important feature of the study by Davidson et al. (1990a) is that these authors were careful to match their verbal and spatial tasks psychometrically. They also chose tasks for which they had reliable performance data along with the EEG data, in order to relate differences in EEG asymmetries to differences in performance asymmetries. Furthermore, they showed that using the linked-ears arrangement for the EEG leads may produce an attenuation of existing asymmetries, for the leads may act as a shunt across the head and result in reduced asymmetries being detected between homologous EEG sites on the left and right hemispheres. In order to solve this problem, Davidson et al. (1990a) used a computer-derived equivalent to the linked-ears reference locations that did not involve physical linking of the two ears during the recording. In some recent studies from Davidson's laboratory (personal communication), it is obvious that physically linking the ears does not attenuate the magnitude of the asymmetry, but other problems may arise with linked-ears reference leads. The most important one for studies of laterality is an asymmetry in electrode impedance of the two ear electrodes. Since the ear leads are linked together prior to their input to the EEG amplifier, any disparity in impedance between the two ears will have an effect on the effective location of the reference, which in turn can affect the recorded asymmetry over the hemispheres. Another critical point to remember, particularly with regard to the use of the beta band to study asymmetries, is that these frequencies are dramatically affected by muscle activity, and this interference has not always been carefully controlled in studies of beta asymmetries.

To sum up: more recent findings have shown robust differences in posterior alpha asymmetries produced by well-matched verbal and spatial tasks, and particularly if care is taken to control for irrelevant factors, such as task and subject demands and limb movements.

EEG asymmetry analysis was also used in a study of hemisphere differences in sleep and dreaming (Ehrlichman, Antrobus, and Wiener, 1985). This study addressed the popular claim that sleep and particularly dreaming is mediated by a shift to right-hemisphere activation as processing for the "rationality" performed by the left hemisphere during waking decreases. In contrast to popular claims, Ehrlichman et al. (1985) found no evidence of a shift toward more right-sided activation during sleep, and particularly not during dreaming, than during the waking state.

Emotionality and Approach-Avoidance

In another series of studies, R. J. Davidson and his group (reviewed in Davidson, 1993) have investigated individual differences in resting EEG and emotional reactivity as subjects viewed filmclips depicting various positive and negative emotional scenes. Subjects with greater right-sided frontal activation (lower alpha power) were also the ones who rated filmclips designed to elicit fear and disgust more negatively. Thus, subjects with more right-sided activation in their EEGs also subjectively rated the filmclips as more negative and aversive. The opposite was found for subjects with greater left-sided EEG activation at rest. These subjects rated the filmclips designed to elicit happiness and amusement more positively than did the subjects with greater right-sided EEG activation.

From these studies, and others, Davidson has argued that anterior left and right: EEG asymmetry may predict affective behavior along an approach-withdrawal dimension: greater left-sided activation seems to be associated with approach behavior, greater right-sided activation with withdrawal behavior.

EEG Asymmetry and Psychopathology

Differences in left- and right-hemisphere EEG patterns have been identified in recordings from individuals in different psychopathological states, particularly schizophrenia. Merrin, Fein, Floyd, et al. (1986) found that reduced alpha power over the right hemisphere in premedicated schizophrenic patients, indicating overactivation of the left hemisphere, shifted toward normal alpha levels after treatment with neuroleptics

Davidson 1993) reviewed several studies from his laboratory showing how individual differences in anterior EEG asymmetry during resting may predict dispositional mood, affective reactivity, and psychopathology. In one study, subjects were screened for depression using the Beck Depression Inventory (BDI). Subjects with high scores on the BDI had less left frontal activation, according to a power spectral analysis of alpha EEG, than did subjects with low scores on the BDI.

In order to separate state effects from trait effects—that is, whether the decreased left frontal EEG power in depressed subjects is a marker of the state of depression or a marker of a trait that predisposes the subject to episodes of depression—Henriques and Davidson (1990) compared the EEGs of remitted depressive patients with those of healthy controls. All of the remitted depressives were functioning normally at the time of testing and showed no signs of depression, although each had a lifelong history of psychopathology. Interestingly, the remitted depressives showed the same decrease in left frontal EEG activation as the acutely depressed subjects screened with the BDI. Thus, Davidson (1993) concluded that an asymmetry in frontal EEG alpha power may be a state-independent marker of individual differences in vulnerability to depression.

Sleep and Dreaming

Although the ultimate function of sleep is not known, brain activity during sleep is clearly different from brain activity during waking. The frequency of the EEG signal is reduced and amplitude increased in sleep, leading to a kind of synchronization in the EEG. Sleep also seems to be related to energy conservation, for "whatever benefits sleep may accrue for tomorrow, one clear function is to conserve calories for today" (Hobson, 1990, p. 372).

Sleep is essential for health and life. Rechtschaffen, Bergman, Everson, et al. (1989) have shown that animals that are deprived of sleep will lose weight and, if kept awake for extended periods of time, will die even if they are adequately fed. Recent findings (Kreuger, Walter, Dinarelli, et al., 1985) have also revealed a link between sleep and immune system function: risk of infection increases after extensive sleep loss. This may explain why people often get colds or other common infections after a long journey, for example.

Sleep also has effects on cognitive functions, like learning, attention, and memory, although the empirical evidence has sometimes been inconsistent. Recent findings, though, indicate a decline in affect and cognitive performance after sleep loss (Mikulincer, Babkoff, Caspy, and Sing, 1989).

Hobson and McCarley (1977) proposed a neurophysiological theory of sleep and dreaming that entailed a demodulation of the adrenergic neurons in the brain during sleep and an increase of cholinergically driven activity. This "activation-synthesis" theory attempted to explain sleep in physiological terms, as the shutdown of the norepinephrine system during sleep, and particularly during those periods known as *REM sleep*.

That the EEG changes rather dramatically during sleep has been known since the 1930s, although it was in 1953 that Aserinsky and Kleitman first made the revolutionary discovery that rapid eye movements (REM) occurred regularly, with about 90-minute cycles, during a night's sleep. The eye movements, furthermore, seemed to occur when subjects were dreaming (Dement and Kleitman, 1957).

The REM periods were associated with EEG waves that resembled the wave pattern seen in the awake, resting state, and REM sleep during Stage 1 is therefore also called *paradoxical sleep*. In addition to changes in EEG patterns and REM cycles during sleep, loss of muscle tonus is also a typical characteristic of sleep.

A typical psychophysiological sleep laboratory is therefore equipped with apparatus for recording brain activity (EEG), eye movements (electrooculogram, EOG), and muscle tonus (elelctromyogram, EMG). Mamelak and Hobson (1989; see also Ajilore et al., 1995) have recently devised a simple, home-based recording system that the subject can wear in his own bed. The system (NightCap) consists of a piezoelectric sensing device that is taped to the eyelid and a movement detector attached to the forehead (see Figure 11.8). The piezoelectric sensor detects eye movements during the night and stores a record of these movements in a small computer memory under the pillow for later transfer to a host computer. In a similar way, the movement detector detects gross movements and stores that data on the computer memory too.

From EEG recordings, four stages of sleep have been identified during a good night's sleep (see Figure 11.9). A fifth stage is the REM stage mentioned above. Since REM epochs can occur during several of the other stages, however, one usually talks about four sleep stages and refers to the REM stage as a qualitatively different, or fifth, stage.

The awake state is characterized by a mixture of alpha and beta waves. When the individual closes his or her eyes and relaxes in order to sleep, alpha frequencies start to dominate. When the individual then actually falls asleep, the alpha waves are replaced by low-amplitude, high-frequency EEG waves mixed with slower waves (2–7 Hz).

When the subject falls deeper into sleep, there is a shift in the EEG pattern to slower frequencies with higher amplitudes *(theta waves)*. This is Stage 2 sleep, and it is characterized by the occurrence of K complexes and sleep spindles, large negative and positive deflections in the EEG together with bursts of high-frequency activity.

As the subject continues to sleep, there is a progressive change in the EEG, as *delta waves*, with larger amplitudes and slower frequencies, form. The EEG during Stage 3 sleep contains about 20–50 percent delta waves, and during Stage 4 sleep it contains more than 50 percent delta waves.

After a full cycle of sleep is completed, Stage 1 through Stage 4, a person shifts back and forth through the different stages of sleep. Typical REM episodes occur at intervals of about 90 minutes; non-REM (NREM) episodes occur during all four stages. Stages 2, 3, and 4 are sometimes also called *slow-wave sleep* because of the predominance of delta waves, particularly during Stages 3 and 4. Stages 3 and 4 are analogously sometimes also referred to as *delta sleep* or *deep sleep*.

Dreaming usually occurs during REM sleep, and an individual will have a much more vivid memory of a dream if awakened in REM than in NREM sleep and asked to recall the content of the dream. Crick

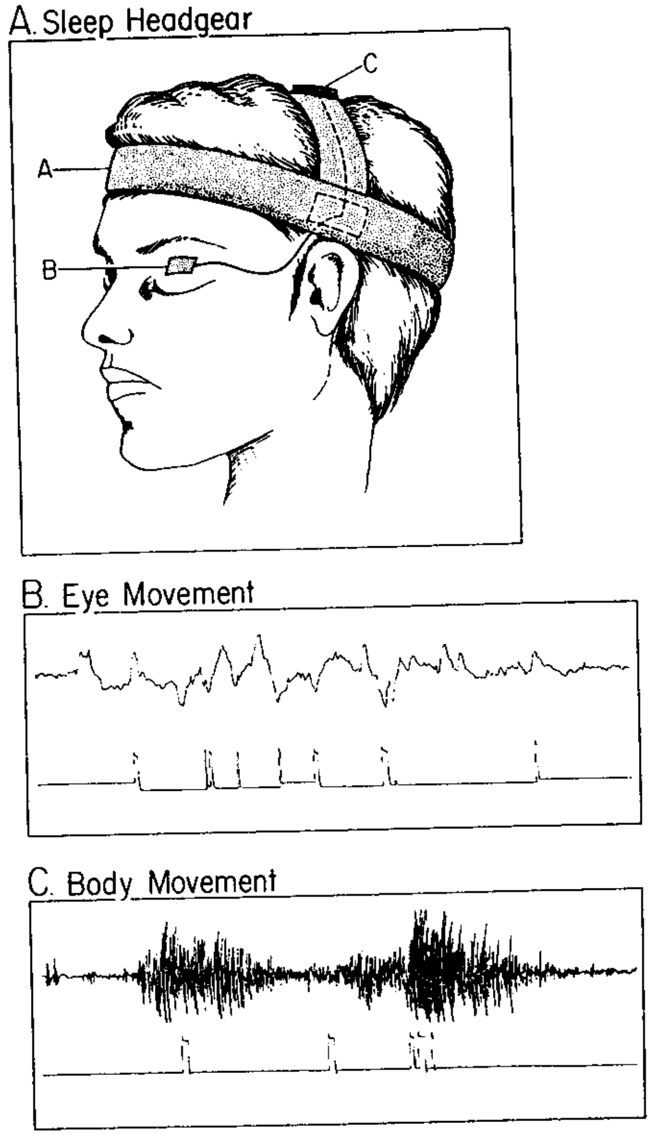


Figure 11.8. The "NightCap" headgear for recording eye and body movements during sleep. Sensing devices are fitted to the eyelid and the top of the head *(A)* to record eye movements *(B)* and gross body movements *(C)*. (From Mamelak and Hobson, 1989, reprinted with permission of the authors.)

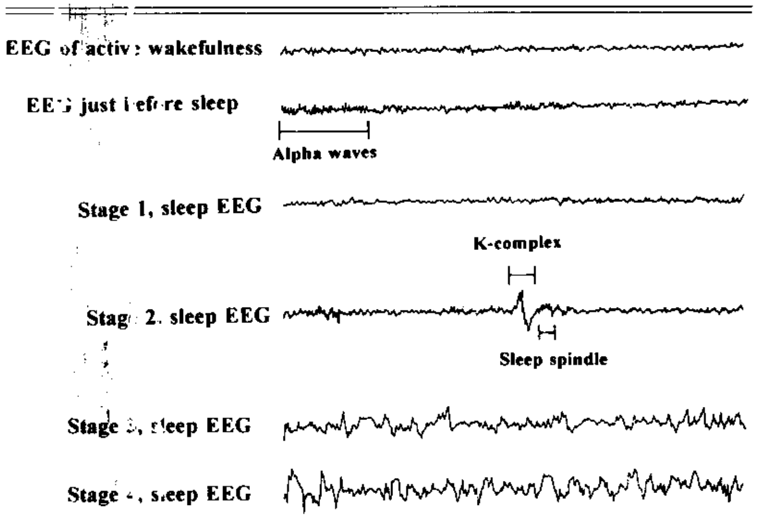


Figure 11.9. The stages of sleep as shown in the EEG signal. The waking state is characterized by alpha activity in the EEG and/or by a low-voltage, mixed-frequency EEG, frequent occurrences of beta activity. Stage 1 sleep: low-voltage, mixed frequency EEG with much 2–7 Hz activity. Stage 2 sleep: presence of sleep spindles (bursts of waves with 12–14 Hz) and/or K-complexes (bursts of high-voltage spikes) on a background of low-voltage, mixed-frequency EEG. Stage 3 sleep: 20–50 percent of epochs with high-amplitude delta waves (2 Hz or less). Stage 4 sleep: delta waves occurring in more than 50 percent of epochs.

and Mitchison (1983) have suggested that we dream because the brain needs to "forget," to get rid of neuronal connections that are no longer necessary—dreaming as a kind of "unlearning." Hobson (1990), on the other hand, suggested that dreaming is what happens when the noradrenergic system in the brain is "shut down" and there is just random neuronal input to the brain (see the discussion above of Hobson and McCarley, 1977). Thus, Hobson (1990) tries to explain dreaming in neurophysiological terms, in sharp contrast to Freud, who proposed that dreaming releases the anxieties and worries built up during the day.

Summary

In this chapter the principles of the electroencephalogram were described, and an overview was given of the use of EEG in psychophysiological research on activation theory, sleep and dreaming, hypnosis, emotionality, and hemispheric asymmetry. Particular emphasis was put on a review of the use of EEG to define different stages of sleep. Recording procedures, including electrode montages, filter settings, and controls for artifacts, were also described. Finally, some of the major analytical techniques for interpreting the EEG recording were discussed, including power spectral analysis and various correlational techniques. A separate section was devoted to the recently developed BEAM technique, a "brain mapping" technique based on the EEG signal (see Chapter 13 for mapping techniques based on other physical features of the brain).