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COMMITTEE REPORT

Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts

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Abstract

Developments in technologic and analytical procedures applied to the study of brain electrical activity have intensified interest in this modality as a means of examining brain function. The impact of these new developments on traditional methods of acquiring and analyzing electroencephalographic activity requires evaluation. Ultimately, the integration of the old with the new must result in an accepted standardized methodology to be used in these investigations. In this paper, basic procedures and recent developments involved in the recording and analysis of brain electrical activity are discussed and recommendations are made, with emphasis on psychophysiological applications of these procedures.

Descriptors: EEG recordings, Artifacts, Sleep, Pediatrics, Quantified EEG, Statistical analyses

More than 60 years ago, Hans Berger reported the first recordings of electrical activity from the human brain (Berger, 1929), and our fascination with this organ and its electrical activity continues to intensify. We persist in our attempts to decipher the code of electrical activity produced by the brain and continue to use this information to guide our understanding of behavioral state characteristics and aspects of cognitive functioning. The nature of the limitations of this understanding have remained much the same as they were in Berger's time, that is, advances mainly parallel development of instrumentation, the accumulated knowledge base, and current conceptual orientation. The purpose of this paper is to provide an update regarding the present status of these influences as they relate to the application of current technology and procedural recommendations for the recording and analysis of the human electroencephalogram (EEG) in nonclinical populations. Only spontaneously occurring background EEG activity will be considered in this paper; evoked activity will be the topic of another guidelines paper in this series.

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Electrode Types and Application

Interest in human EEG activity has focused primarily on the 0–30-Hz frequency range,[1] and a variety of electrode types and application procedures (Broughton, Hanley, Quanbury, & Roy, 1976) have been developed to accommodate specific investigational and situational requirements necessary to study these activities. For recording slow potentials, nonpolarizable electrodes, preferably Ag/AgCl, are required, whereas Ag/AgCl and gold or silver cup electrodes are suitable for recording higher frequency EEG activity. Needle electrodes, once commonly used for clinical EEG recordings, have never been the electrodes of choice for nonclinical studies. For some situations, such as multiple recording sites or when recording infants, fitted caps in which electrodes are imbedded are used. However, caps can

[1]Although the primary focus of most of the research activity has been restricted to this frequency range, some investigators (e.g., Spydell & Sheer, 1982) have studied frequency activity in the gamma range (36–44 Hz and sometimes higher). Because this frequency range substantially overlaps with muscle activity, very careful controls are required to keep muscle activity from confounding activity of true neurogenic origin.

become easily misaligned, and special effort must be made to assure precision of electrode position.

Quality of recording is dependent upon several factors, one of which is the integrity of the electrode–electrolyte–skin interface. To reduce electrical resistance at the point of contact of the electrode-electrolyte with the skin, it is necessary, prior to the attachment of electrodes, to clean recording sites with a diluted alcohol solution and slightly abrade the surface to reduce impedance to less than 5,000 ohms. When cortical slow potentials are to be recorded, contamination of recordings by skin potentials may be avoided by scratching the skin surface with a sterile needle (Picton & Hillyard, 1972).

Other than the situation where electrodes are held in place by a cap or clip (e.g., attached to the ear lobes), one of three techniques of attachment is commonly used: (a) a thick conductive electrode paste holds the electrode in place; (b) a patch of gauze soaked in collodion covers the electrode (gold or silver cup) and secures it to the scalp; or (c) a collodion-impregnated patch with an opening cut over the recording site may be secured to the scalp and an electrode attached to this patch with an adhesive collar. When collodion is used, it is normally dried by a jet of compressed air. For recordings from sites free from hair, electrodes may be secured with adhesive collars or tape.

Under conditions in which direct coupled slow potential recordings are to be made, electrodes that will be referenced to one another should be stored in a manner that will reduce offset potentials and maximize stability of the electrodes (Tassinary, Geen, Cacioppo, & Edelberg, 1990).

Derivations

Correct interpretation of EEG recordings depends upon accurate localization of recording sites. The accepted standardized system for electrode placement is the International 10-20 System (Jasper, 1958). Positioning of electrodes should conform to this system, with any deviations clearly specified. Determination of electrode position should always be made using a measuring tape and not by estimation. The head is rarely symmetric, and special care must be taken when laterality or other topographic issues are of importance (Myslobodsky, Coppola, Bar-Ziv, & Weinberger, 1990). When it becomes necessary to use scalp locations other than the traditional 10-20 sites, the additional sites should be located at points halfway between the standard sites whenever possible. These halfway sites can be named in a standard manner consistent with the 10-20 system. The coronal rows can be labeled with letters of the rows immediately anterior and posterior to each halfway row, for example, row CP lies halfway between row C and row P. The coronal row between Fp and F can be labeled AF instead of the three character label FpF. Likewise, the anterior–posterior rows can be labeled with numbers that lie between the numbers employed in most rows, for example, C1 lies halfway between CZ (the Z stands for Zero or Zenith) and C3. The obvious exceptions to these rules lie in the temporal regions at sites T3–T8. When using the halfway nomenclature, the traditional T nomenclature can be used for those well-defined points and as the substitute of C and P nomenclature for the interposed halfway points. Formal definitions for this system have been proposed (American Electroencephalographic Society, 1991) (Figure 1). Regardless of the system used, location of electrodes must always be unambiguously described.

Grounding

To minimize leakage currents that may flow through the subjects via the recording system and to decrease artifact, subjects are connected to a ground on the EEG amplifier system. This ground connection is best made through an electrode placed near other EEG recording sites—a midforehead placement is common. The method of subject grounding and the placement of the grounding electrode should be specified.

Reference Placement

Because the basis for recording electrophysiological activity is the potential difference between two electrodes, the selection of both recording sites is of equal importance. For bipolar recordings in which the EEG activity reflects the potential differences between two active sites, both sites will usually be selected on the basis of the particular relevant investigational interest. However, in the case of referential recordings in which the activity at a single active site is of primary interest, the selection of the reference electrode presents a complex problem. This placement is an important methodological consideration because different reference locations basically offer a different window of geometry through which to view the underlying brain activity of interest (Henriques & Davidson, 1990, 1991). Ideally, the reference placement should be electrophysiologically silent, but there really is no such thing as a truly inactive reference site. Both cephalic and noncephalic reference placements will contribute to the recorded activity, with varying amounts of EEG activity present at cephalic sites and an increased probability of electrocardiographic (EKG) and muscle activity being detected at noncephalic sites. Many suggestions have been made regarding the optimal location of reference electrodes.

In addition to the influence on EEG of biologic activity present at the reference site, it is also important to consider the distance between the active EEG electrode and reference electrode sites. Sites that are close together increasingly cancel out activity that occurs identically at both sites. This is especially so for slow activity, which tends to have broad fields. A reference electrode situated distant from the active electrode will tend to pick up more artifacts from many different sources. Although there is no perfect solution for these various reference electrode position-related problems, recognition of the situation is important, and the potential impact of the reference site on results should be discussed in the research report (Nuwer, 1988).

Some investigators have used average-reference and reference-free recordings to circumvent this problem (Hjorth, 1980, 1986; Lehmann, 1987). An intended advantage of reference-free transformations is accentuated local sources and minimized spurious interelectrode correlations. There are several procedures in use for this type of analysis. One method has been termed current source density analysis and is derived from the second derivative of the interpolated voltage surface (Perrin, Bertrand, & Pernier, 1987). Another procedure is the radial current flow method (Hjorth, 1980). To compute current flow radial to the surface at the index electrode site, the voltage gradients directed at that site from all other sites are computed by dividing the voltage difference between each other site and the index site by the surface distance between them. These transforms are performed on data in the time domain before any frequency analyses are done. The surface Laplacian is a transform to current source density, and this property acts as a spatial filter (Nunez, Pilgreen, Westdorp, Law, & Nelson, 1991). However, the Laplacian transform requires many electrodes because it essentially

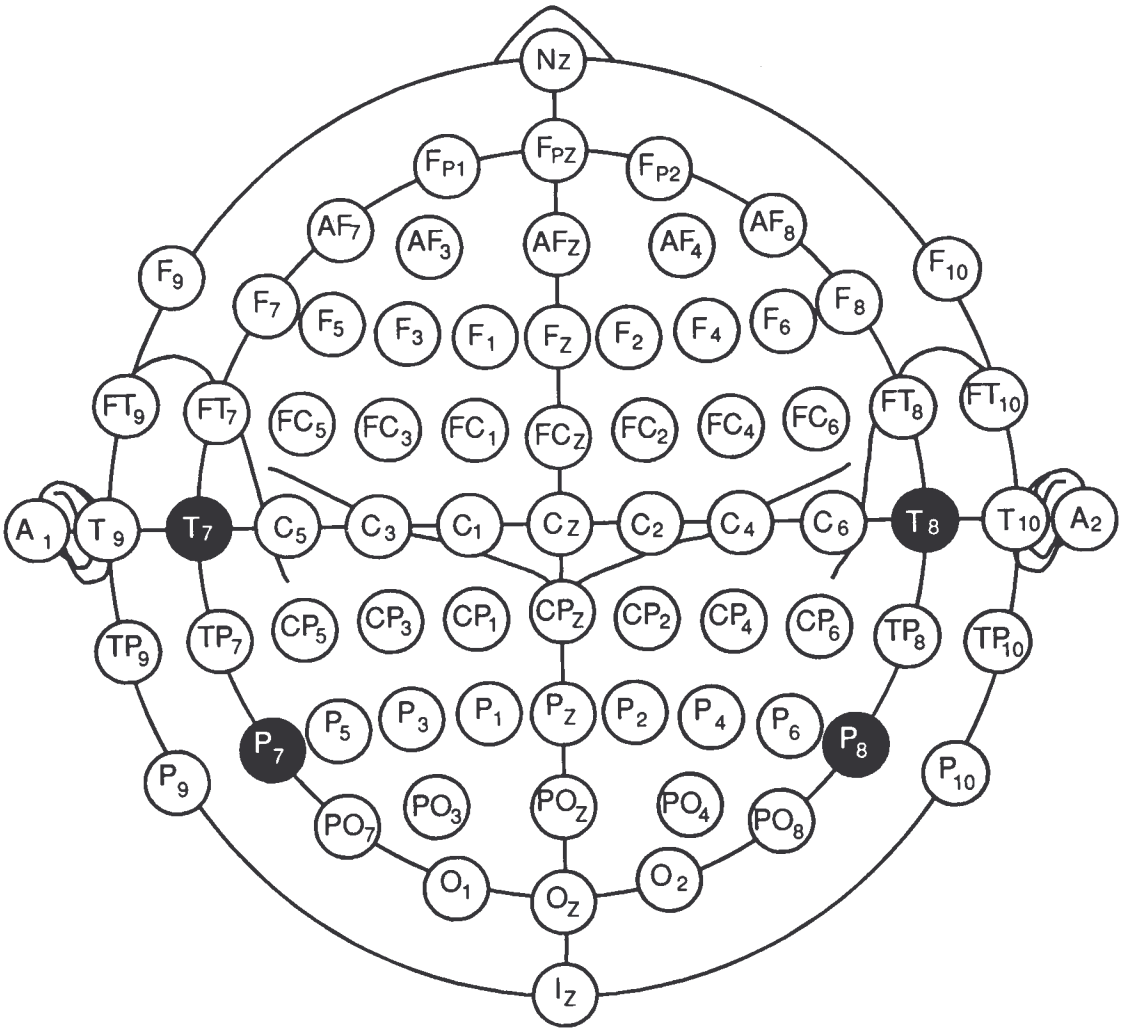

Figure 1. Adjustments to the 10-20 system and the resulting modified combinatorial nomenclature. The modifications are designated by black background circles. From "Guidelines for Standard Electrode Position Nomenclature" by the American Electroencephalographic Society, 1991, *Journal of Clinical Neurophysiology*, *8*, pp. 200–201. Copyright 1991 by the American Electroencephalographic Society. Reprinted by permission.

takes the difference between a target electrode and the several electrodes that surround it. If the goal of the investigation is to sample EEG activity from the entire head, then at least 32 channels are required. However, even these solutions have their difficulties. Any activity present in a substantial number of channels will show up quite prominently in the average-reference recordings. Use of the radial current flow method, as proposed by Hjorth (1980), can also be problematic, especially for electrodes near the lateral boundaries of the field of electrode sites.

In many conventional EEG studies, a contralateral or occasionally unilateral earlobe or mastoid reference is employed. Another reference used especially in quantitative EEG studies involves linking electrodes placed on the earlobes (designated A_1 and A_2) or mastoids (M_1 and M_2) (Gilbert, Robinson, Hamberlin, & Spielberger, 1989; Jesiukaitis & Hakerem, 1988). However, equalizing ear reference impedance is not easily done, and the effect of unequal impedances in a linked-reference configuration would be to artificially inflate the amplitude of the leads on the side of the reference electrode of highest resistance (Garneski & Steelman, 1958). Even if equalization can be achieved at the onset of a recording session, these values may change over the course of that session. A number of strategies have been developed to deal with the problem of changes in impedance in a linked-reference configuration. One common strategy is to place a resistor in series with each electrode prior to electrically linking the leads. This strategy requires a priori knowledge of the range over which impedances may change during the course of the study and the selection of a resistor of sufficient value that the tendency toward imbalance is of no consequence. A resistor of inappropriately high resistance, in combination with other factors (e.g., the length of the electrode lead), may introduce noise into the EEG signal. Nevertheless, the range of impedance changes can be closely estimated, and one can choose a set of resistors to compensate for the imbalance.

A second strategy is to place a variable resistor in series with each active electrode, constantly monitor electrode impedances, and balance the impedances or changes in impedance over the

course of the experiment. This strategy has the advantages of empirically correcting any imbalances and not assuming a particular change or range of changes. It may also reduce noise produced by high-value resistors, as used in the first strategy. Obvious disadvantages are the time required for this monitoring/adjustment and the possibility that these activities may interfere with a particular experimental protocol.

A third strategy is one in which a separate preamplifier channel is dedicated to each reference electrode and the outputs of the two amplifiers are electrically linked. With this method, a resistor is placed in series with the output of each amplifier and the two channels are linked prior to input into the A/D channel. Current preamplifiers typically have high input impedances, with impedance outputs that are low and generally well matched. Because the output impedance of the preamplifier is constant and very low, the resistor placed in series on the output side does not introduce noise into the signal. The size of this output resistor should be 10-fold greater than the maximum output impedance of the amplifier. For example, for a constant maximum output impedance of 300 ohms, a 3K ohms resistor would be selected. The input impedance of the A/D device must be large in relation to the 3K resistor, for example, at least 300K ohms. One important requirement for the described system is that the preamplifiers used for each reference channel must have identical gains. This is determined by calibrating the preamplifiers for signals of known voltage and frequency with the resistors in place. This configuration ensures that imbalances in reference electrode impedance do not affect the measurement of the EEG activity on either side of the head. There is little chance that extraneous noise is introduced by resistors in series with the electrode leads themselves, and there is no need to constantly monitor impedances during the course of the experiment. A potential disadvantage of this strategy is that it necessitates dedicating two amplifier channels per derivation. The separate amplifier outputs of each reference channel can be input into separate A/D channels, with the advantage that multiple reference configurations may be derived in software, including average-reference sites, average reference, and Laplacian solution, including the reference sites. A series of recent studies has indicated that once the electrode impedances of the two ears are well matched, there is no systematic difference between physically linking ear reference electrodes and computer averaging two separate ear channels in terms of effects on baseline measures of asymmetry (Andino et al, 1990; Lutzenberger & Elbert, 1991; Senulis & Davidson, 1989). Under these conditions, where impedances can be matched and the ear electrodes physically linked, recordings may be conducted using only one channel. Unfortunately, it is difficult to independently evaluate the validity of different referencing solutions. What is needed is to compare data from different solutions to a "gold standard" of regional brain activation, such as regional glucose metabolism derived using positron emission tomography. Such investigations in which the EEG recordings are taken simultaneously with glucose uptake procedures are currently underway (Davidson, personal communication, 1992), and the results of such studies may help clarify the relationship between various referencing solutions and regional brain activation.

Although the recording arrangement ultimately chosen is dictated by the specific investigational demands of the study, there are conditions in which specific recommendations have been made to standardize EEG recording parameters. Examples of these conditions include EEG mapping, sleep recordings, and developmental studies in infants.

Calibration, Filtering, and Digitization

Calibration of the amplification system is essential to provide a reference potential of known voltage against which measurement of the voltage of the EEG potentials is made and to establish the equivalence of amplification across amplifiers. Calibration prior to data acquisition is obligatory, and repeated calibration during extended data gathering sessions and/or at the end of recording sessions is recommended. Generally, polygraphs have built-in calibration pulse generators, but independent, stable calibration sources providing sinusoidal signals of known amplitude are also recommended (Dumermuth, Ferber, Herrmann, Henricks, & Künkel, 1987). At times, special calibration procedures may be considered; for example, when doing spectral analysis, calibration may be done with white noise instead of pulse or sine-wave signals. In any case, a high-quality calibration signal is required, and the method of calibration must be specified.

Amplifier settings and properties, such as filter settings, the use of any special line frequency rejection filters, and indications of amplifier gain, should be documented. Properties of amplifiers should be indicated, including drift, linearity of amplification in both the signal amplitude and frequency range, and, particularly when low amplitude signals are being processed, the noise level of the amplifier as determined by short-circuiting amplifier input. Another amplifier-related property that should be characterized is the extent to which cross-talk between channels is restricted. This consideration is of general importance and can be of particular significance when relationships between channels are fundamental to the investigation, for example, in studies of EEG coherence or laterality. Cross-talk rejection should be specified in decibels with a recommended rejection level of at least 60 dB (Dumermuth et al., 1987).

Interfacing the output of EEG amplifiers with analog data storage or analog–digital conversion equipment can be done using IRIG specifications. However, because EEG equipment now has a wider dynamic amplitude range providing a $\pm$10-volt range at the output connector, use of the IRIG $\pm$1.4-volt maximum amplitude norm may result in clipping in some circumstances. Therefore, the use of interface equipment with the $\pm$10-volt input range is recommended. For digital interfacing, the IEEE standard interface for programmable instrumentation (IEEE 488-1975, GPIB, HPIB 488) is recommended.

The extent to which the analog signal is accurately reflected by digital representation depends on the sampling rate. The rule used to regulate this relationship is provided by the Nyquist theorem, which requires that the data sampling rate be at least twice the highest frequency present in the signal. Frequency components higher than twice the sampling rate must be removed from the EEG before digitizing to avoid the problem of aliasing, that is, the production of "spurious low frequency components which cannot be distinguished from those of the true signal" (Dumermuth et al., 1987, p. 214). Aliasing can be prevented either by sampling at rates high enough (i.e., more than four- to fivefold greater than the filter cutoff frequency) to ensure that the spectral band width far exceeds any component in the data or by analog filtering (Oken & Chiappa, 1986).

New technology often creates new complications and concerns in the processing of data, and one such concern related to processing of EEG data has been recently addressed in papers by Miller (1990) and Lutzenberger and Elbert (1991). These authors evaluated the operation of A/D boards used in personal computers, noting that most A/D boards that operate in DMA mode do not sample all channels at exactly the same moment and time. The interval between time points at which the voltage of a subsequent channel is measured corresponds to the sampling interval divided by the number of active channels. Thus, to use the example given by Lutzenberger and Elbert (1991), if there are five EEG channels, each sampled at 10 ms per point, the delay between any two adjacent channels is 2 ms and the delay between the first and last channel is 8 ms. As noted by Miller (1990), this may lead to a systematic difference in latencies between channels and may be a severe problem when channels are subtracted off line for rereferencing. A number of commercial EEG analysis systems have A/D boards that function in this fashion. The solution is to perform some type of interpolation to latency correct the channels. However, a linear interpolation will not be accurate, particularly at higher frequencies, although the magnitude of residual error will be a function of the sampling rate. Nonlinear procedures of the sort described by Lutzenberger and Elbert (1991) may be required.

Normal Variants and EEG Artifacts

The raw EEG must be visually analyzed carefully for normal typical waveforms, their variants, and artifactual segments for deletion prior to further data elaboration, and considerable expertise is needed to properly identify many of these characteristics (Nuwer, 1988). In descriptions of the waking record typically consisting of alpha rhythm maximal in parieto-occipital regions, theta or beta activities maximum centrally, and theta or alpha frequency in the temporal regions, accepted terminology must be employed. In particular, investigators often indiscriminately confuse such terms as rhythm and activity (all alpha activities are not the alpha rhythm). The many terms employed in characterizing the EEG have been fully defined elsewhere (International Federation of Societies for Electroencephalography and Clinical Neuropsychology [IFSECN], 1974; Niedermeyer, 1987), and the careful investigator will use such terminology or, if at variance, will define the terms as employed.

The EEG contains a number of normal waveform variants, common among which are the mu rhythm in central regions, psychomotor variants in the temporal regions, and a variety of different shapes and harmonics of the posterior dominant alpha frequency activity. Intersubject variability is substantial and can be a serious confounding factor in EEG research. Research studies must carefully define the ways in which these potentially serious problems are resolved. Typical approaches to reduce the severity of this problem include the use of subjects as their own controls and the use of a sufficiently large number of different subjects. Careful examination of the raw EEG will allow the experienced investigator to identify these normal variants.

The EEG of normal individuals may contain other features that are unusual but of no known clinical or psychological importance, such as the presence of 6-Hz spike-wave complexes, 14 and 6 spikes, and a variety of others. Such variants must be excluded from further analysis. Methods of artifact rejection and the nature of criteria for artifact identification should be unambiguously indicated.

Extended recordings of EEG in the awake state almost always contain brief periods of drowsiness. Many subjects will become drowsy quite easily and fall asleep if left alone in a quiet recording room. Drowsiness can therefore be a substantial confounding factor in EEG recordings, particularly when recordings are taken under relaxed waking conditions. This problem can even occur during vigilance tasks when the subject becomes bored or has overlearned the task. Drowsiness can be identified through the examination of the raw EEG record and can be indexed by signs of EEG slowing in conjunction with anterior diffusion, slight slowing and then decrease in abundance of alpha activity, or the presence of vertex sharp waves. Slow eye movement artifacts, mainly horizontal, that are present during drowsiness will be evident in the anterior temporal (interior frontal) leads and can be more directly monitored by electrooculographic (EOG) leads.

Almost all EEG recordings will contain artifacts. Some can be identified visually and subsequently deleted from further analysis. The monitoring of known sources of artifacts (such as eye movements, EKG, skin potential, and muscle activity) is very helpful and is essential for the detection of artifacts of a biological nature. Although some artifacts can be identified by automated artifact rejection mechanisms, even under the best of conditions these procedures will commonly miss a substantial portion of such artifacts. Careful screening of all of the raw EEG is mandatory for all analysis systems.

A most persistent source of artifact, particularly in electrophysiological studies of cognitive and affective processes, is muscle activity. Unfortunately, simple filtering will not eliminate this form of artifact. The major reason filtering is not effective is that the frequency spectrum of electromyographic activity is very broad, with the lower end intruding on the traditional EEG frequencies, even down into the alpha band (e.g., Cacioppo, Tassinary, & Fridlund, 1990). Thus, an investigator interested in examining power in the alpha (8–13 Hz) and beta (13–20 Hz) bands cannot have a simple low-pass filter set at 40 Hz and expect to exclude electromyographic (EMG) activity. There will be activity below 40 Hz that is myogenic.

In some situations, muscle activity may be minimized by having the subject actively relax the involved muscles or by forced contraction followed by relaxation of these muscles. These procedures may be used in conjunction with visual editing of the data to exclude all portions of the record that contain visible muscle artifact. For certain types of experiments during which muscle activity is minimal and/or very large quantities of data are recorded, this strategy would be acceptable. However, for studies where an investigator might be interested in extracting brain activity coincident with facial expression, for example, this procedure would be exceedingly costly because a large percentage of the data would be excluded. To deal with this situation, Davidson (1988) developed procedures for statistically partialling out muscle activity from the EEG. In principle, the method is based upon frequency domain procedures that have been developed to remove EOG artifact (e.g., Woestenburg, Verbaten, & Slangen, 1983). This method samples the EEG at a sufficiently high rate to derive a measure of power in a high-frequency band that is exclusively myogenic, for example, 2 ms per point, with a Nyquist frequency of 250 Hz. Low-pass anti-aliasing filters are set at 200 Hz to obtain a measure of power in the 90–150-Hz

band, which is defined as an EMG band. Power in this band is then used to residualize the EEG in the traditional EEG frequencies. A regression-based approach is used separately for each channel and for each defined epoch of EEG. Residuals are then computed that represent power in the EEG frequencies following removal of the variance shared with power in the EMG band. This approach dramatically improves the data yield from records with extensive muscle activity.

In general, various artifacts, normal waveform variants, and effects of drowsiness occur frequently during most EEG recordings taken during relaxed wakefulness. These problems are serious and must be dealt with prospectively in any EEG research study.

Sleep

EEG polygraphic variations during extended periods of sleep and the minimal electrographic requirements for sleep–wake state analysis, have been well defined (Rechtschaffen & Kales, 1968). The sleep–wake analyses employ recordings of EEG activity, eye movements, and the EMG of axial (usually mental or submental) muscles. Eye movements help characterize sleep onset and rapid eye movement (REM) sleep, and EMG activity helps identify arousals during non-REM sleep and identify REM sleep through the presence of background atonia and brief "twitch" potentials. Comprehensive coverage of EEG polygraphic recording methodology is available elsewhere (Broughton, 1987; Broughton et al., 1989; Guilleminault, 1982).

The widely followed Rechtschaffen–Kales (1968) manual recommends the use of a single central EEG lead referred to the contralateral ear or mastoid for sleep–wakefulness classification. In the absence of a large array of electrode placements, it was considered necessary to specify a single EEG derivation that would normally adequately register critical types of EEG activity necessary for sleep stage classification. With some exceptions, such as alpha activity (which is more prominent in occipital areas) and K-complex distribution (Kubicki, Herrmann, & Holler, 1985), the central (C3 or C4) derivations satisfy these requirements. To maximize the detection of alpha activity, some investigators (e.g., Broughton, 1987) have recommended that both central and occipital placements be used. Generally, even in recordings done only for staging purposes, it is useful to add bilateral central, occipital, and reference electrodes so that in the event an electrode becomes nonfunctional during the night, an alternate can be selected without having to enter the room and awaken the subject for electrode replacement (Broughton, 1987). As with recordings during wakefulness, the use of more extensive arrays of electrodes should always conform to the 10-20 international placement system.

Although sleep study recordings are much longer than most EEG recordings, the types of electrodes and attachment of these electrodes for sleep recordings generally conform to those used during more brief waking recordings. For example, nonpolarizable preferably Ag/AgCl, as well as gold or silver cup electrodes, are typically used. Electrodes with holes through which electrolyte paste (a slow-drying type) may be added are useful for particularly prolonged recordings. Attachment of electrodes to sites covered with hair is usually made using the collodion-soaked gauze technique. For prolonged sleep recordings of infants, in whom the skin is extremely delicate, suction electrodes are much less traumatic and are often used. Needle electrodes would be impractical, indeed potentially dangerous, in long-term sleep studies and should never be used for sleep recordings (Broughton, 1987). Because subjects may be quite active and execute complex movements even during sleep, it is helpful for electrode wires to be long enough to permit full movement in bed. These wires may be collected together at the back of the head in the form of a single cable, rather than left loose to entangle the subject.

Recording Equipment and Room

Although sleep may occur during traditional EEG recordings in which subjects and recording equipment are in the same room, for research purposes the recording equipment and monitoring person should always be in a room separate from the subject, whether the study is one of sleep or waking EEG activity. For sleep studies, the subject's room should be as homelike as possible, sound attenuated, and air conditioned and have lighting rheostatically controlled from the equipment room. An intercommunication system is essential, as is the ability to view the sleeping subject either through a window or via a video monitor. The preparation for polysomnography, that is, the recording of multiple channels of information during sleep, generally requires at least $\frac{1}{2}$ hr for electrode application and familiarization of subjects with the environment. Sleep studies in pediatric populations have found that such subjects adapt more readily to the laboratory when accompanied by a parent who may either sleep in the recording room area or in a neighboring room.

Special Recording Techniques

There are three special data gathering techniques, long-cable recordings, ambulatory monitoring, and telemetry, that, although not peculiar to sleep studies, have often been employed in such studies. Long-cable recordings have been used to record sleepwalking episodes (Jacobson, Kales, Lehmann, & Zweig, 1965). The cables can be quite lightweight and, with appropriate grounded shielding, produce quality recordings. The development of modern ambulatory monitoring and telemetry, however, has rendered this approach essentially obsolete.

Ambulatory EEG monitoring utilizes systems usually consisting of a small amplifier–recorder worn on the belt and provides recording capability under free-moving conditions for extended periods of time. Recording may be FM by cassette with a slow tape drive or, following A/D conversion, by digital memory. The systems are powered by batteries or rechargeable battery packs. In addition to the possibility of being able to record essentially around the clock, other advantages of such systems include the reduced technologist time required, the ability to easily obtain recordings in the normal home environment, the lack of subject restraint by more conventional plug-in electrodes, and convenience to the subjects as reflected in more rapid adaptation to the recording conditions. The main disadvantages of such systems are that they currently are limited to only eight channels of recorded information, documentation of behavior is generally absent, technical problems may become evident only on tape replay, the equipment is somewhat delicate, and cassette tape speed may be sufficiently inconsistent that quantified EEG analysis (e.g., spectral analysis) cannot accurately be accomplished. Despite these difficulties, ambulatory monitoring can provide satisfactory recording for many psychophysiological studies. Laboratories using ambulatory monitoring for the study of sleep have reported less than 5% of the recordings as inadequate (Broughton, 1989). Steps can be taken to optimize the likelihood of quality recordings with these systems, including using

only fresh batteries of known shelf life, ensuring very secure electrode placements, adding a calibration signal to the apparatus preamplifiers prior to recording, and playing back a short portion of data after a few minutes of recording to verify recording quality. Interpretation of results from such recordings can be enhanced by addition of a diary of daily events and an event marker to be used by the subject to note unusual occurrences.

Telemetry systems have been widely available for a number of years and have most of the advantages of ambulatory monitoring, including full, unrestrained movement of the subject (Duffy, Iyer, & Surwillo, 1989; Ebersole, 1987; Kamp & Lopes da Silva, 1987). The radio transmitters for these systems are worn either on the head or on a belt pack. Moreover, these systems often permit the recording of 16 or more channels of information simultaneously and usually have receiving fields of about 92 m (100 yards). Generally, a technologist must remain with the subject, but telemetry may be combined with video recording of the subject using a split screen technique, which is extremely useful for psychophysiological studies of behavior during wakefulness or sleep.

Pediatric Studies

In addition to being plagued by difficulty in maintaining task-oriented motivation and behavior, psychophysiological studies in pediatric populations also face a common and predictable lack of cooperation from restless subjects during the application of electrodes. To overcome this problem, the experimenter should be seated in front of the subject and should try to distract the subject while electrodes are being attached. The presence of a parent may be helpful in some instances. Generally, once the electrodes are in place and arranged so they cannot be easily reached, these young subjects will often forget about them during the course of the recording session.

One method for easy application of the 10-20 electrode system to infants or toddlers is the use of a lycra stretch cap which has sewn into it small plastic holders containing electrodes. The cap is manufactured in four different sizes within both the infant (1 week–1 year) and toddler (1–3 years) age ranges. With accurate measurement of the subject's head circumference, it is possible to choose the correct size cap for these recordings. The cap fits snugly on the infant's head and can be held in place with a small chest band and a stretch head band. Application of a small amount of abrasive/conductive gel usually results in impedances below 10K ohms. A light intensity rub through the hole of the electrode on the cap can reduce impedances to less than 5K ohms. For situations in which a large array of electrodes is not required, the application of suction cup electrodes, the use of electrodes with adhesive collars, or even the application of cup electrodes using collodion can be used. However, because of the sensitivity of the skin in these young subjects, collodion is not highly recommended. For these methods of electrode attachment that do not utilize a cap, the child's head can be wrapped in a gauze elastic bandage to prevent pulling at leads once they are in place.

EEG Mapping

Advances in the technology underlying the recording and analysis of EEG activity have resulted in an increasing emphasis on multichannel EEG recording. This procedure provides a display of the constantly varying spatial distributions of brain electrical activity measured from the scalp but does not provide any additional information with respect to where EEG potential fields originate.

The nomenclature developed to describe this approach has been confusing and often misleading (International Pharmaco-EEG Group [IPEG], 1989). Today, the most generally accepted terms are *brain mapping* and *EEG topography*. Displays of topographic maps of EEG features have been popularized in part because of the ease of production of these graphically attractive displays. Color-coded displays are now published in journals, drawing readers' attention to significant features while providing an esthetic quality to the results. However, the use of topographic maps and color displays has serious drawbacks, and these problems can be separated into several broad categories.

EEG topographic maps are often very misleading in their localization features (Kahn, Weiner, Brenner, & Coppola, 1988; Nuwer, 1988). Many scientists and clinicians are used to looking at computerized tomography (CT) or magnetic resonance image (MRI) scans of anatomic data, which provide precise locations for anatomic features. The visual similarity between EEG topographic maps and the other imaging scans suggests a similarity in anatomic localization across these techniques that is not completely correct. One important factor affecting EEG topographic maps is the reference electrode (Coppola, 1990; MacGillivray & Sawyers, 1988). EEG amplitude and composition may be significantly affected by the position of this electrode, and this aspect is especially important for topographic maps in which the reference electrode site is often accompanied by an area of particularly low voltage. In EEG analyses using a linked-ear reference, the lowest amplitude of the topographic map display is near each of the ear electrode sites. This amplitude variation causes a scalloping of the topographic map, with low amplitudes near the ears and relatively high amplitudes near the vertex of the scalp, which in turn can displace the apparent localization of focal EEG activity, tending to move it away from the area of the reference electrode. In the case of linked-ear references therefore, areas of interest are inappropriately displaced too medially. When analyzing left–right differences, the opposite can be seen, with areas of EEG activity being displaced inappropriately too laterally. A similar phenomenon can occur with any other reference site. Unfortunately, the placement of the reference over the chest or other noncephalic regions can result in more pronounced artifacts. The effect of the reference site in the analysis of any particular topographic display must be carefully evaluated. The use of a reference-free solution might facilitate the interpretation of EEG maps and render maps created across different laboratories more comparable.

The use of color coding can also lead to inappropriate conclusions. Vivid color differences can draw the reader's attention but may represent only subtle differences in data. Readers and investigators must be sensitive to the misleading influences of color.

Another extremely important way in which EEG topographic maps differ from CT or MRI pictures relates to the degree of spatial resolution represented. EEG topographic maps have a degree of spatial resolution that corresponds to the number of sites of EEG electrodes placed on the scalp. Often there may be 20 electrodes, or even fewer, for the entire scalp. In dramatic comparison, CT or MRI scans have a resolution that corresponds to each pixel on the display, that is, the CT or MRI scan resolution of display is several orders of magnitude better than

that of an EEG topographic map. Generally, over 99% of the pixels on an EEG topographic map are an interpolation among the few real data points on the display. Interpolations are usually made among the nearest three or four electrode sites, although more complex interpolation paradigms are available and occasionally used. Even with these more complex paradigms, 99% of the data displayed remain interpolations.

Although the number of electrodes needed for topographic displays is restricted by technical and practical limitations of electrode montages on the human scalp, the larger the number of electrodes, the better the resolution of topographic features. However, large numbers of electrodes are difficult to apply and require a great deal of time from the investigator and both tolerance and time from the subject. Although a reasonable trade-off seems to be 20–30 electrodes, particularly extensive topographical displays have been examined by some investigators using more than 100 electrodes (Gevins & Illes, 1991). With very large multisite montages, mapping the data may be essential to observe systematic patterning. The most prudent course is for the investigator to use such maps for data display but not for inferential purposes. All statistics should be restricted to actual electrode-site data rather than interpolated values.

Considerable expertise is required to analyze the subtleties of any topographic map. A variety of tails, whorls, or spots can appear due to artifacts and the interpolation paradigm (Nuwer & Jordan, 1987). Only with considerable experience can features of importance be distinguished from features that are simply technical artifacts. The need for standardized procedures for quantitative analysis and interpretation of EEG maps is recognized, and a variety of approaches has been developed. Although sometimes related to a specific mapping technique, for example, significance probability mapping in association with brain electrical mapping (BEAM; Duffy, 1989), these approaches are generally not limited in application to a single technique. Information regarding the rationale, development, and application of such approaches can be found in the recent literature (Duffy, 1989; Kahn et al., 1988; Lehmann, 1988, 1989).

Quantitative Techniques

Traditional analyses of EEG activity have focused on the time domain, that is, have examined variations in voltage (amplitude) as a function of time. However, many features of the EEG may be better appreciated in the frequency domain. Digital computers have made it easier to extract and quantify this information in terms of waveform frequency, amplitude, and phase. Peak frequency and degree of rhythmicity can also be determined. Once EEG activity has been properly acquired and preliminary processing completed (digitization and prefiltering), an appropriate epoch length must be selected, that is, one that will maximize the amount of continuous artifact-free samples while allowing accurate representation of the lowest frequency of interest. For example, a 1-s segment of EEG can resolve 1 Hz, whereas a 10-s epoch can resolve 0.1 Hz—the longer the epoch, the better the resolution of the frequency content. For the Fast Fourier Transform (FFT), frequency resolution is equal to the reciprocal of the epoch length. With 2-s segments, frequency analysis can resolve 0.5-Hz bands, for example, resolve 9.0 Hz versus 9.5 Hz directly. Because use of longer epochs is generally recommended, epoch length as a limiting factor in frequency analyses is not usually an issue. Shorter epochs ($\approx$1 s) should only be used when EEG must be extracted during comparably brief epochs of behavior, for example, during spontaneous facial expressions (e.g., see Davidson, Ekman, Saron, Senulis, & Friesen, 1990).

In frequency analyses, the EEG is decomposed into its frequency components. These can be clustered together into broad bands such as 8–12-Hz alpha activity or the individual frequency components can be kept separate and treated as a continuous function over a broad range of frequencies, such as 1–30 Hz. In the most common technique, the EEG is clustered into broad bands reflecting those of traditional EEG analysis, such as alpha, or into fractions of these broad bands, such as alpha-1 and alpha-2 (low and high alpha). The EEG in each band is then quantified according to the root-mean-square average amplitude within that band or in terms of power (the square of the amplitude) within the band.

Studies of infant EEG cannot assume that the traditional frequency bands used with adults (e.g., 8–12-Hz alpha) will apply. Two approaches to deal with this issue have been used (cf. Bell & Fox, in press), and both involve computing 1-Hz bins during the FFT procedure and plotting individual spectra for subjects. In the first procedure, EEG analyses take place for whole band power, that is, for a wide frequency band that includes all frequencies in which there is evidence of power. For infants and toddlers (below the age of 4), the broad frequency band includes power between 1 and 12 Hz. Other than myogenic frequencies, there is little power above 12 Hz in the infant EEG. A second approach also involves inspection of individual spectra and determination of the frequency band that centers around the peak in the spectrum. This procedure is more difficult because there may be considerable variability in the peak spectral frequency for infants at a certain age. In general, longitudinal data indicate that the peak frequency changes with age, with an increase in frequency with age (Bell & Fox, in press). Studies of infant EEG should therefore specify the method by which the frequency bands of interest are identified.

Once the EEG is quantified, a variety of transformations can be made. Measures of either *relative power* or *absolute power* can be derived. Relative power is the amount of EEG activity in a frequency band divided by the amount in all bands. In contrast, absolute power is the amount of EEG in one band without relationship to other bands. Because interpretation of variations in a frequency band is limited when using relative power, absolute power measures are recommended. If relative power measures are used, they should be presented in conjunction with absolute power so that the precise contributions to changes in relative power are understood.

Among factors contributing to the variance in power at any given site is skull thickness (Tomarken, Davidson, Wheeler, & Kinney, 1992). Because there are wide-ranging individual differences in skull thickness, the contribution of this factor to variance in EEG power measures may influence or obscure other relationships under study. Procedures have been developed to deal with this problem, for example, Laplacian transformation or regression-based procedures (Wheeler, Davidson, & Tomarken, 1993). However, to be effective these approaches require a relatively large array of electrodes.

Ratios between specific bands are often employed in frequency analyses. Ratios can also be used to transform data into a more Gaussian distribution. The most popular transformation for relative power is $\log(x/\sin 1 - x)$ and, for absolute power, $\log(x)$. These two transformations are helpful when further analysis will be undertaken using parametric statistics. David-

son, Chapman, Chapman, and Henriques (1990) reported that log transformation results in consistently better distributional properties than do other transforms for every frequency band and especially for the alpha band. Ratios can also be formed from the frequency content at different sites, such as for left–right differences. Because ratios can be formed in many different ways, it is especially important that their derivation be carefully specified. For example, there are at least six common ways in which left–right (L–R) hemispheric differences are expressed: L/R; L − R; (L − R)/L; (L − R)/R; (L − R)/(L + R); (L − R)/0.5(L + R). Of these, (L − R)/(L + R) has the most straightforward interpretation in terms of asymmetry index and is closer to a normal distribution. Similar multiple variations can be applied to other types of ratios that are formed. Details regarding the specific procedures used to obtain values must be specified; it is not enough to state, for example, that the left–right difference was calculated (Nuwer, 1988).

In addition to specifying the details of the specific metric used, investigators must also provide data on the individual hemispheres to ascertain which hemisphere is contributing to the effect in question. In laterality studies, hemisphere should be included as a factor in an analysis of variance to examine which hemisphere shows significant changes among conditions or groups. Sometimes, very important theoretical issues are at stake with respect to which hemisphere changes more (e.g., Davidson & Tomarken, 1989), and individual hemisphere data are needed to make this determination.

Differences in power among EEG leads have been demonstrated with different procedures. For example, power ratios between low- and high-frequency bands are accurate estimators of changes in EEG activity in conjunction with metabolic changes (Nagata, 1988). Another method for describing interlead differences in power is termed *amplitude asymmetry*. This measure is based on the difference in power between two leads expressed either as a ratio or as the mathematical difference. Amplitude asymmetry determined for homologous left and right recording sites gives a measure of lateralized differences. However, because head shape is not generally symmetric, interpretation of EEG asymmetry may reflect structural and/or functional asymmetry (Myslobodsky, Coppola, & Weinberger, 1991).

In addition to frequency and amplitude, a measure of phase can be gleaned from FFT analyses. This measure reflects the relationship between frequencies of a complex waveform and the onset of the epoch. When onset of the epoch is arbitrary, this measure reflects only limited EEG information. However, in evoked-potential studies in which the onset of each response is locked to the stimulus onset, phase relationships are very important.

FFT analyses also afford measures to describe relationships among activities recorded at different electrode sites. Coherence and phase measurements can be used to investigate cortical interactions of EEG activity. Coherence is determined from the cross-spectrum analysis of two signals at different sites and reflects the degree of synchrony between frequency components of the two signals. Maximum synchrony is indexed by a coherence value of 1, and the absence of synchrony is indexed by a coherence value of 0. Thatcher and colleagues (Thatcher, Krause, & Hrybyk, 1986; Thatcher, Walker, & Giudice, 1987), for example, have proposed a model to examine within-hemisphere long- and short-distance coherence between electrodes, computing a ratio of the two. They claimed that EEG coherence reflects axonal connectivity between regions of cortex (see also Nunez, 1981). Researchers interested in the computational methods and formulas for examining between-site EEG coherence should consult Saltzberg, Burton, Burch, Fletcher, and Michaels (1986).

Another procedure used to examine cortical EEG interactions is the study of phase relationships. Phase relationships provide a measure of temporal differences between two signals for common frequency components. This measure is expressed in degrees; 0° indicates no time lag between signals, and 180° indicates signals of opposite polarity. Coherence between electrodes should only be interpreted if the phase lag is nonzero. If the phase lag between electrodes is zero, the coherence arises as a function of volume conduction. Skew is also important in the evaluation of coherence data. Skew in the A/D board will affect the phase lag between channels. Use of a common reference (e.g., vertex) inextricably confounds true coherence with power and phase at the recording and reference electrodes (Fein, Raz, Brown, & Merrin, 1988), and a spherical spline interpolation, as recommended by Perrin, Pernier, Bertrand, and Echallier (1989), results in artifactually high coherences (Biggins, Fein, Raz, & Amir, 1991).

As with other analyses, frequency analysis has limitations. Recognized difficulties with this type of analysis fall into several broad areas, including the choice of reference electrode, which influences the activity recorded at all channels.

Another problematic area in frequency analysis involves the amount of EEG analyzed. Because the EEG varies considerably from moment to moment, for attempting frequency analysis, data should be averaged across substantial amounts of time (e.g., 60 s) to minimize the unwanted effect of second-to-second variability. This averaging can be done by combining smaller epochs, for example, 2–4 s, to yield an averaged extended interval amount. Reproducibility of these data should be assured by showing that the data collected are similar, either for several separate extended averages or for several subsets of a single extended average. These data must be carefully screened for artifacts, normal variants, and changes in alertness. At times, the analysis of very short time intervals may be desirable, for example, to isolate phasic events or to correlate with discrete cognitive manipulations. Reducing the epoch length can reduce the frequency range of the power spectrum that can be validly examined, resulting in a compromise between time and frequency resolution.

Frequency analysis itself introduces new artifacts into the data analysis, in part because of the mathematical techniques used in this procedure. In the typical FFT, even an ideal sine wave may be smeared across several adjacent frequency points—a phenomenon that has been termed "leakage." Additional error may be introduced as the result of discontinuities that occur at the beginning and end of each EEG epoch. This error can be reduced by putting a taper-transformation at the beginning and the end of each epoch. A popular transformation is the cosine window, also known as the Hanning window, which tapers the beginning and end of each epoch down to 0 amplitude while allowing the middle of the epoch to remain at 100% of its original amplitude. The Hanning window can substantially reduce leakage but at the same time increases the amount of "smearing," that is, broadening of a peak on a plot of frequency activity. These problems of leakage and smearing are most noticeable when calibrating equipment with a pure sine signal. However, they also cause the same kind of effect with EEG data (see Dumermuth & Molinari, 1987, for an extensive discussion of windowing).

The methods section of any research report involving EEG analyses should include the details of how the frequency analysis was conducted, including the epoch length used, the number of epochs averaged together to produce the data set, whether a window transformation was employed, and standard features such as the types of analog filters. This section should also state the means used to screen artifacts, determine normal EEG variants, and detect drowsiness. Furthermore, formulas used in calculations should be specified, including those used for seemingly simple calculations such as left–right differences. When conditions or groups are being compared, the investigator must match the conditions or groups on the amount of artifact-free data available for analysis. If they are not matched, differences in the reliability of the measures among the groups or conditions may affect the mean differences. Investigators should be encouraged to provide data on the mean duration of artifact-free data by condition and/or group.

Statistical Analyses

Proper statistical comparisons depend both upon selection of the appropriate test(s) and meeting the assumptions underlying the statistical procedure used. However, for such analyses to be valid and meaningful, they also assume and require consistency and control in the application of methodological procedures, such as recording parameters, electrode placement, artifact rejection, and subject behavior. Still, even under the best of conditions, proper statistical analysis of quantified EEG data presents a formidable challenge to the investigator. Difficulties inherent in such analyses include the tremendous data sets generated, the large number of dependent variables relative to the generally small number of subjects, and the lack of independence of EEG activity recorded either at closely related times in the same subject or among electrode sites in the same or different subjects. To guard against violations of the assumption of normality, various transformations can be applied to the data.

Another difficulty related to both the selection of EEG data and the interpretation of analyses of such data concerns the within-subject consistency of EEG activity across testing sessions. A large number of variables may affect this measure, including age, time interval, and measure being used, in addition to other specific manipulations imposed by the investigator.

The preceding caveats regarding statistical analysis of quantified EEG activity are significantly enhanced when simultaneous multichannel recordings are considered. The complexity of the data sets in such studies can be appreciated by recognizing that virtually hundreds of variables can be generated when the combination of the numbers of EEG subject states, electrode sites, frequency bands, and epochs for analysis are considered. In terms of data quantity, a multichannel EEG recording sampled at 200 samples/s/channel over a 20-min period can produce several megabytes of data. This combination of overwhelming numbers of variables and data sets underscores the need for scrupulous attention to data acquisition, processing, and selection of statistical analyses (Abt, 1988). In this regard, the specification of hypotheses in advance of data collection and analysis is strongly recommended, and the importance of the replication of significant results becomes even more critical.

A variety of statistical procedures have been used to analyze quantified EEG data, including *t* tests, multivariate analyses, principal component analysis, composite variables in multivariate statistics, and the use of discriminate function analysis based on univariate or a multivariate subset of quantitative measures. The use of multiple *t* tests in these (or other) analyses is not recommended. Where applicable, the use of methods to adjust statistical alpha values in view of the number of tests (cf. Bonferroni, Greenhouse–Geisser) is essential. Where possible, condensing methods should be used to reduce the number of variables, but in these instances the rationale for the validity of such methods must be explicitly stated. If a particular EEG feature is being used as a trait index, the investigator should establish the psychometric properties of the metric. For example, the test–retest stability (assessed with the intraclass correlation) and internal consistency reliability (coefficient alpha) should be computed and presented (see Tomarken et al., 1992, for an example). Discussions of concerns and approaches to statistical analysis of quantified EEG data have been the subject of several recent publications (Abt, 1988; Duffy, 1988; Nuwer, 1988; Zappulla, 1991).

Health Concerns Associated With EEG Recording Procedures

The procedures required to obtain EEG recordings can create health concerns for both the investigator and the subject in two general areas, electrical safety and disease transmission. Regarding electrical safety, the current required to power the EEG machine could be a source of dangerous electrical shock. This hazard can be minimized or eliminated by the use of well-described procedures for properly grounding both equipment and subjects. Procedures for ensuring electrical safety in the recording environment can be found in operating manuals for EEG machines, as well as in several publications (e.g., Duffy et al., 1989; Morrison, 1967).

The potential for disease transmission associated with EEG recording procedures comes primarily from abrasion of the skin to reduce electrical impedance. Guidelines have been in place for minimizing the transmission of blood-borne infectious diseases in health-care settings, and awareness of the need to apply such guidelines to research laboratories has been underscored by the proliferation of the acquired immunodeficiency syndrome (AIDS). Guidelines detailing precautions to be taken to prevent disease transmission in health-care environments have been published (American Electroencephalographic Society, 1986; Centers for Disease Control, 1987, 1988; Duffy et al., 1989). In addition, a guidelines paper specifically focused on similar recommendations for research laboratories doing psychophysiological research in non-health-care settings has been recently published (Putnam, Johnson, & Roth, 1992). These guidelines stressed three areas where precautions must be taken to reduce the risk of disease transmission in such laboratories. Recommendations include (a) the use of sterile surgical gloves during electrode preparation, application, removal, and cleaning; (b) taking special care during the process of abrading the skin to keep the extent of abrasion to a necessary minimum and immediately disposing of or sterilizing any instruments used to abrade the skin; and (c) the use of recommended sterilants to disinfect electrodes and instruments.

Conclusions

The use of quantitative EEG recordings and measures to study behavioral state and cognitive functioning has been accelerated

by technological developments and has created an ever-growing data base. The sheer mass and complexity of data generated and the increasing reliance on computerized methods for data processing and analysis—often at the expense of adequate visual screening of data—places ever greater emphasis on the need for detailed and standardized methodologies for acquiring and processing such data. These same factors present new demands with respect to the statistical analyses used, because many of the assumptions and constraints for different statistical tests are violated by quantitative EEG data sets. Interfacing new developments in these areas of acquisition, processing, and statistical analysis of EEG information, both quantitative and descriptive, will continue to be a challenge and a process of gradual approximation for researchers who struggle to interpret EEG activity–behavior relationships.

REFERENCES

Abt, K. (1988). Descriptive data analysis (DDA) in quantitative EEG studies. In D. Samson-Dollfus, J. D. Guieu, J. Gotman, & P. Etevenon (Eds.), *Statistics and topography in quantitative EEG* (pp. 150–160). Paris: Elsevier.

American Electroencephalographic Society. (1986). Report of the committee on infectious diseases. *Journal of Clinical Neurophysiology, 3*, 38–42.

American Electroencephalographic Society. (1991). Guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 8*, 200–202.

Andino, F. L. G., Marqui, R. D. P., Sosa, P. A. V., Lirio, M. B., Machado, C., Diaz, G., Rodriguez, P. F., & Torrez, C. C. (1990). Brain electrical field measurements unaffected by linked earlobes reference. *Electroencephalography and Clinical Neurophysiology, 75*, 155–160.

Bell, M. A., & Fox, N. A. (in press). Brain development over the first year of life: Relations between EEG frequency and coherence and cognitive and affective behaviors. In G. Dawson & K. Fischer (Eds.), *Human behavior and the developing brain*. New York: Guilford.

Berger, H. (1929). Über das Elektrenkephalogramm des Menschen. *Archives Psychiatrie Nervenkrankheiten, 87*, 527–570.

Biggins, C. A., Fein, G., Raz, J., & Amir, A. (1991). Artifactually high coherences result from using spherical spline computation of scalp current density. *Electroencephalography and Clinical Neurophysiology, 79*, 413–419.

Broughton, R. J. (1987). Polysomnography principles and applications in sleep and arousal disorders. In E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroencephalography: Basic principles, clinical applications and related fields* (2nd ed., pp. 687–724). Baltimore, MD: Urban & Schwarzenberg.

Broughton, R. J. (1989). Ambulant home monitoring of sleep and its disorders. In M. Kryger, T. Roth, & W. Dement (Eds.), *Principles & practices of sleep medicine* (pp. 696–701). Philadelphia: Saunders.

Broughton, R. J., Billiard, M., Frost, J. S., Hishikawa, Y., Cirignotta, F., & Krieger, J. (1989). Monitoring sleep and sleep disorders. In R. Ellingson (Ed.), *Recommendations for the practice of clinical neurophysiology* (2nd ed., pp. 696–701). Amsterdam: Elsevier.

Broughton, R. J., Hanley, J., Quanbury, A., & Roy, O. (1976). Electrodes. In A. Remond (Ed.), & R. J. Broughton (Vol. Ed.), *Handbook of electroencephalography and clinical neurophysiology: Vol. 3, Part 4. Acquisition of bioelectric data: Collection and amplification* (pp. 67–75). Amsterdam: Elsevier.

Cacioppo, J. T., Tassinary, L. G., & Fridlund, A. J. (1990). The skeletomotor system. In J. T. Cacioppo & L. G. Tassinary (Eds.), *Principles of psychophysiology* (pp. 325–384). Cambridge, England: Cambridge University Press.

Centers for Disease Control. (1987). Recommendations for prevention of HIV transmission in health-care settings. *Morbidity and Mortality Weekly Report, 36*(2S), 1s–18s.

Centers for Disease Control. (1988). Update: Universal precautions for prevention of transmission of human immunodeficiency virus, hepatitis B virus, and other bloodborne pathogens in health-care settings. *Morbidity and Mortality Weekly Report, 37*, 377–388.

Coppola, R. (1990). Topographic mapping of multilead data. In J. W. Rohrbaugh, R. Johnson, & R. Parasuraman (Eds.), *Event-related brain potentials* (pp. 37–43). Oxford, England: Oxford University Press.

Davidson, R. J. (1988). EEG measures of cerebral asymmetry: Conceptual and methodological issues. *International Journal of Neuroscience, 39*, 71–89.

Davidson, R. J., Chapman, J. P., Chapman, L. P., & Henriques, J. B. (1990). Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive tasks. *Psychophysiology, 27*, 528–543.

Davidson, R. J., Ekman, P., Saron, C., Senulis, J., & Friesen, W. V. (1990). Approach/withdrawal and cerebral asymmetry: Emotional expression and brain physiology, I. *Journal of Personality and Social Psychology, 58*, 330–341.

Davidson, R. J., & Tomarken, A. J. (1989). Laterality and emotion: An electrophysiological approach. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. 3, pp. 419–441). Amsterdam: Elsevier.

Duffy, F. H. (1988). Clinical decision making in quantified electroencephalographic analysis. In D. Samson-Dollfus, J. D. Guieu, J. Gotman, & P. Etevenon (Eds.), *Statistics and topography in quantitative EEG* (pp. 9–26). Paris: Elsevier.

Duffy, F. H. (1989). Topographic mapping of brain electrical activity: Clinical applications and issues. In K. Maurer (Ed.), *Topographic brain mapping of EEG and evoked potentials* (pp. 19–52). New York: Springer-Verlag.

Duffy, F. H., Iyer, V. G., & Surwillo, W. W. (1989). *Clinical electroencephalography and topographic brain mapping: Technology and practice*. New York: Springer-Verlag.

Dumermuth, G., Ferber, G., Herrmann, W. M., Henricks, H., & Künkel, H. (1987). Recommendations for standardization of data acquisition and signal analysis in pharmaco-electroencephalography. *Neuropsychobiology, 17*, 213–218.

Dumermuth, G., & Molinari, L. (1987). Spectral analysis of EEG background activity. In A. S. Gevins & A. Rénaud (Eds.), *Handbook of electroencephalography and clinical neurophysiology* (pp. 85–130). Amsterdam: Elsevier.

Ebersole, J. S. (1987). Ambulatory EEG: Telemetered and cassette-recorded. In R. J. Gumnit (Ed.), *Intensive neurodiagnostic monitoring* (pp. 139–155). New York: Raven Press.

Fein, G., Raz, J., Brown, F. F., & Merrin, E. L. (1988). Common reference coherence data are confounded by power and phase effects. *Electroencephalography and Clinical Neurophysiology, 69*, 581–584.

Garneski, T. M., & Steelman, H. F. (1958). Equalizing ear reference resistance in monopolar recording to eliminate artifactual temporal lobe asymmetry. *Electroencephalography and Clinical Neurophysiology, 10*, 736–737.

Gevins, A. S., & Illes, J. (1991). Neurocognitive networks of the human brain. In R. A. Zappulla, F. F. LeFever, J. Jaeger, & R. Bilder (Eds.), *Windows on the brain: Neuropsychology's technological frontiers. Annals of the New York Academy of Sciences, 620*, 22–24.

Gilbert, D. G., Robinson, J. H., Hamberlin, C. L., & Spielberger, C. D. (1989). Effects of smoking/nicotine on anxiety, heart rate, and lateralization of EEG during a stressful movie. *Psychophysiology, 26*, 317–320.

Guilleminault, C. (1982). *Sleeping and waking disorders: Indications and techniques*. London: Addison-Wesley.

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.

Henriques, J. B., & Davidson, R. J. (1991). Left frontal hypoactivation in depression. *Journal of Abnormal Psychology, 100*, 535–545.

Hjorth, B. (1980). Source derivation simplifies topographical EEG interpretation. *American Journal of EEG Technology, 208*, 121–132.

Hjorth, B. (1986). Physiological aspects of EEG data as a basis for topographic mapping. In F. H. Duffy (Ed.), *Topographic mapping of brain electrical activity* (pp. 175–193). Boston: Butterworths.

International Federation of Societies for Electroencephalography & Clinical Neuropsychology. (1974). A glossary of terms commonly used

by clinical electroencephalographers. *Electroencephalography and Clinical Neurophysiology, 37*, 538–548.

International Pharmaco-EEG Group. (1989). Recommendations for EEG and evoked potential mapping. *Neuropsychobiology, 22*, 170–176.

Jacobson, A., Kales, A., Lehmann, D., & Zweig, J. R. (1965). Somnambulism: All-night electroencephalographic studies. *Science, 148*, 975–977.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371–375.

Jesiukaitis, P., & Hakerem, G. (1988). The effect of prestimulus alpha activity on the P300. *Psychophysiology, 25*, 157–165.

Kahn, E. M., Weiner, R. D., Brenner, R. P., & Coppola, R. (1988). Topographic maps of brain electrical activity—Pitfalls and precautions. *Biological Psychiatry, 23*, 628–636.

Kamp, A., & Lopes da Silva, F. (1987). Special techniques of recording and transmission. In E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroencephalography: Basic principles, clinical applications and related fields* (2nd ed., pp. 619–633). Baltimore, MD: Urban & Schwarzenberg.

Kubicki, S. T., Herrmann, W. M., & Holler, L. (1985). Critical comments on the rules by Rechtschaffen and Kales concerning the visual evaluation of EEG sleep records. In S. T. Kubicki & W. M. Herrmann (Eds.), *Methods of sleep research* (pp. 19–35). New York: Gustav Fischer.

Lehmann, D. (1987). Principles of spatial analysis. In A. G. Gevins & A. Rémond (Eds.), *Handbook of electroencephalography and clinical neurophysiology* (Vol. 1, pp. 309–354). Amsterdam: Elsevier.

Lehmann, D. (1988). Spontaneous EEG momentary maps and FFT power maps. In D. Samson-Dollfus, J. D. Guieu, J. Gotman, & P. Etevenon (Eds.), *Statistics and topography in quantitative EEG* (pp. 27–48). Paris: Elsevier.

Lehmann, D. (1989). From mapping to the analysis and interpretation of EEG/EP maps. In K. Maurer (Ed.), *Topographic brain mapping of EEG and evoked potentials* (pp. 19–52). New York: Springer-Verlag.

Lutzenberger, W., & Elbert, T. (1991). The linked-reference issue in EEG and ERP recording. *International Journal of Psychophysiology, 5*, 273–276.

MacGillivray, B. B., & Sawyers, F. J. P. (1988). A comparison of common reference, average and source derivations in mapping. In D. Samson-Dollfus, J. D. Guieu, J. Gotman, & P. Etevenon (Eds.), *Statistics and topography in quantitative EEG* (pp. 72–87). Paris: Elsevier.

Miller, G. A. (1990). DMA-mode timing question for A/D converters. *Psychophysiology, 27*, 358–359.

Morrison, R. (1967). *Grounding and shielding techniques in instrumentation*. New York: Wiley.

Myslobodsky, M. S., Coppola, R., Bar-Ziv, J., & Weinberger, D. R. (1990). Adequacy of the international 10-20 electrode system for computed neurophysiologic topography. *Journal of Clinical Neurophysiology, 7*, 507–518.

Myslobodsky, M. S., Coppola, R., & Weinberger, D. R. (1991). EEG laterality in the era of structural brain imaging. *Brain Topography, 3*, 381–390.

Nagata, R. (1988). Topographic EEG in brain ischemia—Correlation with blood flow and metabolism. *Brain Topography, 1*, 97–106.

Niedermeyer, E. (1987). The normal EEG of the waking adult. In E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroencephalography: Basic principles, clinical applications and related fields* (2nd ed., pp. 97–117). Baltimore, MD: Urban & Schwarzenberg.

Nunez, P. L. (1981). *Electrical fields of the brain*. New York: Oxford University Press.

Nunez, P. L., Pilgreen, K. R., Westdorp, A. F., Law, S. K., & Nelson, A. V. (1991). A visual study of surface potential and Laplacians due to distributed neocortical sources. *Brain Topography, 4*, 151–168.

Nuwer, M. R. (1988). Quantitative EEG: I. Techniques and problems of frequency analysis and topographic mapping. *Journal of Clinical Neurophysiology, 5*, 1–43.

Nuwer, M. R., & Jordan, S. E. (1987). The centrifugal effect and other spatial artifacts of topographic EEG mapping. *Journal of Clinical Neurophysiology, 4*, 321–326.

Oken, B. S., & Chiappa, K. H. (1986). Statistical issues concerning computerized analysis of brain wave topography. *Annals of Neurology, 19*, 493–494.

Perrin, F., Bertrand, O., & Pernier, J. (1987). Scalp current density mapping: Value and estimation from potential data. *Biomedical Engineering, 34*, 283–288.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology, 72*, 184–187.

Picton, T. W., & Hillyard, S. A. (1972). Cephalic skin potentials in electroencephalography. *Electroencephalography and Clinical Neurophysiology, 33*, 419–424.

Putnam, L. E., Johnson, R., & Roth, W. T. (1992). Guidelines for reducing the risk of disease transmission in the psychophysiology laboratory. *Psychophysiology, 29*, 127–141.

Rechtschaffen, A., & Kales, A (1968). *A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects* (National Institutes of Health Publication No. 4). Washington, DC: U.S. Government Printing Office.

Saltzberg, B., Burton, D. B., Burch, N. R., Fletcher, J., & Michaels, R. (1986). Electrophysiological measures of regional neural interactive coupling. Linear and non-linear dependence relationships among multiple channel electroencephalographic recordings. *International Journal of Bio-Medical Computing, 18*, 77–78.

Senulis, J. A., & Davidson, R. J. (1989). The effects of linking the ears on the hemispheric asymmetry of EEG. *Psychophysiology, 26*, S54.

Spydell, J. D., & Speer, D. E. (1982). Effect of problem solving on right and left hemisphere 40 Hertz EEG activity. *Psychophysiology, 19*, 420–425.

Tassinary, L. G., Geen, T. R., Cacioppo, J. T., & Edelberg, R. (1990). Issues in biometrics: Offset potentials and the electrical stability of Ag/AgCl electrodes. *Psychophysiology, 27*, 236–242.

Thatcher, R. W., Krause, P. J., & Hrybyk, M. (1986). Cortico-cortical associations and EEG coherence: A two compartmental model. *Electroencephalography and Clinical Neurophysiology, 64*, 123–143.

Thatcher, R. W., Walker, R. A., & Giudice, S. (1987). Human cerebral hemispheres develop at different rates and ages. *Science, 236*, 1110–1112.

Tomarken, A. J., Davidson, R. J., Wheeler, R. E., & Kinney, L. (1992). Psychometric properties of resting anterior EEG asymmetry: Temporal stability and internal consistency. *Psychophysiology, 29*, 576–592.

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.

Woestenburg, J. C., Verbaten, M. N., & Slangen, L. L. (1983). The removal of the eye movement artifact from the EEG by regression analysis in the frequency domain. *Biological Psychology, 16*, 127–147.

Zappulla, R. A. (1991). Fundamentals and applications of quantified electrophysiology. In R. A. Zappulla, F. F. LeFever, J. Jaeger, & R. Bilder (Eds.), *Windows on the brain: Neuropsychology's technological frontiers. Annals of The New York Academy of Sciences, 620*, 1–21.

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