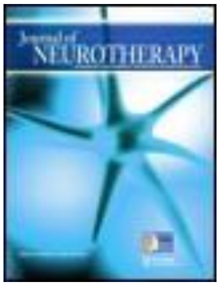

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Effects of Electrode Placement Upon EEG Biofeedback Training: The Monopolar-Bipolar Controversy

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TECHNICAL NOTE

Effects of Electrode Placement Upon EEG Biofeedback Training: The Monopolar-Bipolar Controversy

Lester G. Fehmi, PhD
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ABSTRACT. Roles of tradition, convenience, and noise or artifact rejection are discussed with regard to the referential versus bipolar electrode placement controversy in electroencephalography (EEG). Particular emphasis is placed on the relevance to neurofeedback. The crucial interactions between the differential amplifier, brain waves, and referential/bipolar placements are discussed. Through logical analysis and empirical observation, it is demonstrated how the very nature of the EEG differential amplifier must destroy those elements of brain activity which are common (synchronous) to the recording electrodes. Controlled experiments further illustrate the critical importance of electrode placements. Various methods, including preferred electrode placements, are presented to help resolve recording problems that frequently arise. It is concluded that there are serious implications for researchers, EEG clinicians, neurofeedback providers, and their clients in preferring one type of electrode placement technique over another. EEG recording information is affected by this choice. doi:10.1300/J184v11n02_04

KEYWORDS. Biofeedback, electroencephalography (EEG), brain waves, differential amplifier, electrode placements, referential, bipolar

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INTRODUCTION

The beginning of modern, noninvasive electroencephalograph (EEG) commenced with the publication, in 1929 of Hans Berger's seminal article depicting the recordings of electrical potentials from the human brain (Berger, 1929). A history of EEG recording is presented by Lindsley and Wicke (1974). Since the 1930s, the placement of the EEG electrodes has been an ongoing controversy, exacerbated particularly during the past few decades (Lindsley & Wicke, 1974; Goff, 1974; Reilly, 1987). The controversy is centered over whether referential (i.e., monopolar) electrode placement techniques are preferable to bipolar placement techniques. Monopolar (also termed common reference or unipolar) electrode placement refers to the condition in which one recording electrode (the reference electrode) is removed to a point where less, or none, of the activity of interest is reflected in the recording (e.g., one EEG electrode on the scalp and the reference electrode off the scalp). Bipolar electrode placement refers to the condition in which both recording electrodes are positioned so as to have approximately equal opportunity to reflect the activity of interest (e.g., both electrodes on the scalp). All EEG recording instrumentation currently utilizes the "differential" (double-ended, discriminating, balanced, push-pull) amplifier (Goff, 1974). The differential amplifier operates by taking the difference in potential of two measurements having a common ground. At a time when frequency filtering and other signal conditioning techniques were not as sophisticated as they are today, differential amplifiers were introduced so that unwanted transmitted signals and unwanted biological signals (together called noise or artifact) could be subtracted from the recording by the appropriate placement of electrodes.

Over the past few decades, bipolar EEG recordings have been widely utilized in neurofeedback and clinical electroencephalography. The purpose of the following discussion is to provide a context for understanding and considering the effects of electrode placement. The position is taken that much of the research conducted in the areas of neurofeedback using bipolar recording electrode placement techniques deserves to be reconsidered. In order to make clear why certain bipolar electrode placement procedures require re-evaluation and, in many (not all) applications deserve to be abandoned; a brief review of the measurement of electrical potentials is presented below.

MEASUREMENT OF ELECTRIC POTENTIALS

Introduction

In order to observe the electrical potential (in volts) between points A and G in physical space, a meter is connected between them. The standing or fluctuating potential difference, which exists between these points, causes current to flow through the amplifier of the recording device. As a result, it registers the voltage from moment to moment. One volt of potential difference is defined as that potential energy which is able to move one coulomb of electric charge (6.25×10^{18} electrons) past any point in the circuit in one second of time (one coulomb per second is defined as one ampere) when the resistance to current flow is one ohm. Measurements of "voltage" always refer to a relative difference in potential energy between two points being monitored. Thus, if the electric potential at each point, A and G, were fluctuating in phase (two waves are "in-phase" when peaks and then troughs of potential occur in both waves simultaneously, see Figure 1) with the other, and equal in amplitude with respect to a common distant inactive point, then the potential difference between point A relative to point G would be zero at any point in time. On the other hand with identically large amplitude fluctuations at A and G but each wave 180 degrees out-of-phase with the other, each wave measured with respect to an inactive reference point. (Two waves are 180 degrees out-of-phase when the peak of one wave occurs simultaneously with the trough of the other wave, i.e., one wave goes positive in sign while at the same time the other wave goes negative in sign at the same time as shown in Figure 2.) The potential difference measured at A relative to G would be twice the amplitude of either wave. With shifting phase, the potential between A and G would vary from zero (at exactly in-phase) to two times the peak amplitude (when 180 degrees

FIGURE 1. Two waves shown in-phase

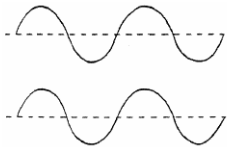
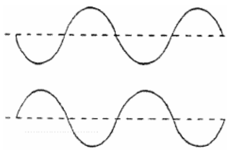


FIGURE 2. Two waves 180 degrees out of phase



out-of-phase) between points A and G. (References to distortion in amplitude measurements between two in-phase waves and between two 180 degrees out-of-phase waves shall be understood to include all the distortion which occurs as the phase changes from zero through 360 degrees between the two waves. In-phase and 180 degrees out-of-phase activity are highlighted in the present text because the result of subtraction of one wave from the other is readily visualized as either a straight line or double the actual, real amplitude, respectively.)

Using a single amplifier recording instrument, one has no way to determine whether amplitude changes measured between A and G are due to shifting phase or due to changing amplitudes of the individual potentials at A and G with respect to an inactive reference point.

THE REFERENCE POINT OR GROUND

One cannot say that an electrical potential exists at one point. A potential can exist at point A only relative to another point, a reference point B or ground G. The potential B or ground G measured is dependent upon the activity present at both points. All potential measurement, including the bioelectric potential s which are recorded in or on the body, represent the difference of the activity at two points measured (i.e., A minus G, or A − G). This relativity of bioelectric recording must be taken into consideration when interpreting EEG data and when forming subsequent conclusions. For example, the relativity of potential measurements requires that the placement of electrodes be chosen only after considering the impact of distortion in the recording of in-and 180 degrees out-of-phase activity upon the purpose of the experiment. Ideally, a ground or distant reference point would be a point in space which is electrically stable and which would contribute no fluctuations of electrical activity to measurement. However, there is no point on the body or in space which is electrically stable. In the recording of bio-potentials, the problem of choosing a reference or ground point, against which electrical potentials are compared, has led to various solutions (Lindsley & Wicke, 1974; Goff, 1974; Reilly, 1987). Each solution, however, is appropriate only for certain applications and contributes to its own characteristic interpretations of resultant bio-potential recordings. Therefore, exactly how the recorded potentials are affected by the choice of a reference point or ground deserves careful consideration in relation to the purposes of a given EEG experiment.

BIPOLAR RECORDING

Let us take, for example, the case where one monitors brain wave activity with bipolar placements using two points, A and B, on the scalp, during a period in which brain waves were fluctuating in-phase and equal in amplitude with respect to an inactive distant reference point G. As may be surmised from the previous discussion, a recording device connected between A and B would then not indicate any fluctuation in voltage. An oscilloscope would show a perfectly straight line; that is, a flat trace. This might be interpreted by the unsophisticated observer (one who is not aware that measurement is relative to a point of reference) as indicating an absence of brain wave activity at the recording sites. Indeed, a flat trace may either represent the presence of equal amplitude, in-phase brain wave activity, or it may indicate brain death–that case in which there is no brainwave activity at either of the recording sites. Under these circumstances, it is not possible to distinguish between these two extremely different electrophysiological events, when interpreting bipolar recordings without additional information. Similarly, 180 degrees out-of-phase fluctuations of brainwave activity at the two scalp recording sites A and B would yield an EEG trace whose amplitude is the sum of the two individual waves. This is because B activity has an opposite sign from A, and the difference involves subtracting a negative which results in their sum. (That is, from A subtracting a minus B [i.e., A− (−B) = A + B]. Thus, the amplitude of activity reflected by the trace is greater than is appropriate for an index of local brain wave activity at either of the two sites relative to an inactive ground.

REFERENTIAL RECORDING

Using the referential electrode placement method, one of the points of measurement is placed on the scalp and the other is placed at a distance from the scalp, ideally on a point reflecting no brain wave activity. In this example, there is no possibility of the occurrence of in-phase or 180 degrees out-of-phase brain activity at the recording sites relative to each other. Thus, there is no confusion of interpretation of the outcomes contributed by the occurrence of in-phase activity with the referential method of electrode placement. The occurrence of a flat trace (i.e., no amplitude fluctuations in the range of brain wave frequencies) would indicate only that no activity of the brain was measured at these referential electrode placements. In general, the accuracy of amplitude measurements is enhanced or preserved with referential placement, since the confusion engendered by the relativity of potential measurements as it interacts with phase relatedness is less of, or not an issue. Referential electrode placement would, thus, provide a more accurate and preferred method to determine EEG activity, under the conditions given in the example cited.

In order to be of maximum value, the recordings of any bio-potential activity must reflect measurements which are directly relevant to the functioning of the system being investigated. One of the major purposes for measuring EEG activity is to search for correlations of brain function with other physiological, psychological, and behavioral processes and events. However, as was shown, any effort to correlate the presence of EEG activity with other activity or behavior would be confused by the signal destruction and distortion which is inherent in bipolar recording from two scalp placements (under certain conditions). Referential placements, on the contrary, permit recording of all the relevant EEG data with less, or no, distortion, under the conditions of this example. Thus referential placements support more accurate and meaningful correlations with other processes and events.

REFERENTIAL PLACEMENT UNDER ACTUAL RECORDING CONDITIONS

Unfortunately, the actual measurement of brain wave activity is not resolved as simply as it has been depicted above. Recording of brainwave activity between one measuring point on the scalp and one distant reference point produces complex recordings. These recordings represent the difference of brain activity between both points, plus the combination of various other biopotential activity, such as eye movement, heart and striated muscle activity. In addition, the location on the body of the electrodes and the antenna configuration of the electrode wires determine the degree to which unwanted transmitted electrostatic and electromagnetic potentials are induced into the EEG signal recorded by the amplifier.

A most common example of externally induced artifact activity is the 60-cycle noise from power line fields, which is often registered by the measuring device or biofeedback instrument. Various physical and electrical means are presently available to reduce the amplitude of electrostatic and electromagnetic artifact activity. Under many conditions, however, it is quite difficult and expensive to employ them. In the mid-1950s, the use of the “differential amplifier” came into vogue for recording EEG activity because, under certain conditions, it made possible a significant attenuation or reduction of in-phase or common biological and transmitted electrical artifact. (Common fluctuations or common activity refers to signals which are exactly in-phase and equal in amplitude.)

EFFECT OF THE DIFFERENTIAL AMPLIFIER UPON RECORDING

The differential or double-ended amplifier actually consists of two amplifiers utilizing a common ground. The signal between one recording electrode (B) and ground (G) is subtracted from the signal obtained between the other recording electrode (A) and the same ground. This subtraction process results in the potential difference between A and B, that is, (A − G) − (B − G) results in A − B.

The amplified output of the differential amplifier represents brain wave activity largely exclusive of common artifact and is independent of the placement of the ground electrode. All ground point fluctuations get subtracted, no matter what their phase or amplitude. Using a differential amplifier, the B placement takes over the role as the reference point for potential measurements at A. All waves common to inputs A and B, when subtracted from each other, are completely cancelled. Other waves which are in-phase and unequal in amplitude, or not common to both amplifier inputs, are subtracted and recorded as having polarity which depends upon whether A or B has the larger amplitude.

The properly balanced differential amplifier can attenuate common artifact as much as one million-fold, while retaining non-in-phase signals and unequal amplitude signals between A and B. One volt of common artifact or equal-amplitude, in-phase signal would be reduced to one microvolt (one millionth of the input) at the output of the differential amplifier. At the same time, any remainder of the subtraction process, the uncommon or non-in-phase signal measured between A and B, would be amplified. This preferential rejection of common activity over out-of-phase or unequal amplitude activity is called "the common mode rejection" (CMR) ratio of the amplifier.

Due to this CMR function, putting both A and B electrodes on the scalp results in an output from the differential amplifier which is subject to the same criticism that is applied to the ordinary "single-ended" amplifiers discussed previously. When no output is observed in the recording, it is not clear whether the flat trace represents no activity in the brain or whether it represents in-phase, equal-amplitude EEG activity at A and B with respect to G . By analogy to previous situations, distortion in the measurement of amplitude is also introduced when bipolar scalp placements of A and B with respect to G record 180 degrees out-of-phase brain activity. Due to the double subtraction function of the differential amplifier, it is again difficult to observe accurate amplitude measurements of brain wave activity.

Consider a referential placement in which electrode B is placed remote from the scalp, at a point in which brainwave activity normally is significantly attenuated or reduced. In this case, transmitted and bio-potential artifacts, which are common to both A − G and B − G inputs, continue to be cancelled. In contrast, since all wave activity is, by choice, significantly attenuated at (B − C) as compared to (A − G), then the unequal, in-phase brain wave activity at A − G and B − C is not cancelled in the differential recording. The recorded activity, however, is not precisely accurate in amplitude. The recording accuracy of in-phase and 180 degrees out-of-phase amplitudes is directly proportional to the overall attenuation of brain activity which is reflected at B−.

In an example of referential placements, the B reference electrode can be placed on the ear lobe, or better, on the upper inner pinna of the ear (Goff, 1974)., and the A electrode can be placed on the scalp. Since the amplitude of the brain wave activity measured directly on the scalp is significantly greater than it is at the ear lobe or pinna, the difference of in-phase activity, (B − G) subtracted from (A − G,) will reflect a remainder (A − B). Under ordinary conditions, the referential recording trace will accurately detect the presence of in-phase activity and help to distinguish between this in-phase condition from the absence of all brain wave activity. The amplitude of 180 degrees out-of-phase brainwave activity will not be amplified to the degree that such activity is amplified in bipolar recordings. Accuracy of this measurement is also directly proportional to the overall attenuation of brain activity at B − G.

The complexity of the analysis of brainwave activity would be greatly diminished if the B electrode placement of the differential amplifier were completely devoid of brain wave activity. When one removes the B electrode far enough from the calvarium so that it registers no brain wave activity, there is often an increase in recorded artifact potentials, such as eye movement or cardiac activity, in the EEG. This is particularly annoying in biofeedback training, since the feedback will reflect these artifacts, e.g., heart rate, which will obscure brainwave feedback. Although not ideal for some purposes, the use of a B electrode placement on the ear lobe or upper pinna serves as a robust, satisfactory compromise. With this relatively close placement of B to A, B − G reflects attenuated brain activity while reflecting bio-potential and transmitted artifacts, which are approximately equal in amplitude to that recorded on the scalp at A − G. As a result, there is little, or no, loss in the rejection (CMR) of these artifacts. Ear and other similar B (or reference) electrode placements (e.g., tip of nose, chin, etc.) represent a significant improvement over traditional bipolar (i.e., scalp to scalp) recordings. Engaging in muscular relaxation through electromyographic (EMG) biofeedback training serves to facilitate the reduction of muscle artifact for both referential and bipolar recording techniques. The ear lobe or pinna and other remote placements on the head do, in fact, reflect brain wave activity, since brain wave activity is carried by volume conduction to all parts of the head and body. Among other factors, attenuation is directly (albeit roughly) related to the distance of the electrode from the signal source. The possibility of reflecting exactly equal amplitude, in-phase brain activity at (A − C) and also at remotely placed (B − C) remains unlikely. This equality of amplitude can be approached under certain conditions, as for example, when the A electrode is placed on the temporal lobe in close proximity to an ear placement of electrode B. Using other distant loci for the B electrode placement, such as the opposite car, would rectify this problem (Goff, 1974).

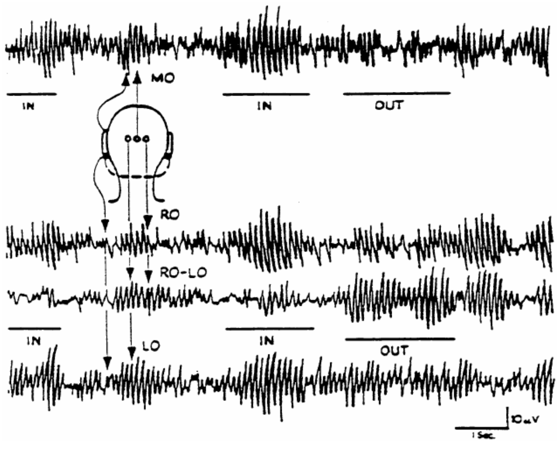
Two interconnected ear lobes can be used as the B reference electrode for research purposes when it is important to accurately reflect an ordinate or ratio relationship between the amplitudes of right and left hemisphere activity. With linked ear lobes, as with other types of placement, analysis of the resultant recordings must reflect consideration of conditions in which the waves in brain regions physically close to the reference electrode (e.g., temporal lobes and ears) are in-phase, directly 180 degrees out-of-phase, at equal and at different amplitudes, and when they maintain other phase relationships with each other. Only such considerations will provide an understanding of the possible significance of observed data and provide a basis for the generation of permissible conclusions from the results.

EXAMPLES OF REFERENTIAL AND BIPOLAR

An example of actual recording data (Fehmi, 1978) which reflects the differences in referential and bipolar recording techniques is presented in Figure 3. The head diagram shows interconnected ear placements for the B electrode and three A occipital electrode placements: midline (MO), right (RO), and left (LO) occipital lobe placements. The ground G, which is not shown, is at the seventh cervical vertebrae. The first (MO), second (RO), and fourth (LO) tracings are referential recordings of occipital lobe activity referenced to interconnected ear lobes (B electrode placement). The third tracing (RO − LO) represents the bipolar placement configuration, in which electrode A is placed at RO, and the B reference electrode is placed at LO.

At the portions of the traces which are marked IN, to signify approximately in-phase

FIGURE 3. A comparison of referential and bipolar EEG recordings from right and left occipital lobes when brainwave activity is in phase and out of phase. (RO = right occipital; LO = left occipital; MO-mid occipital).



activity, the referential recordings MO, RO, and LO are measured to be large and approximately equal potentials. At the same time, RO − LO, the bipolar recording, is much smaller in amplitude because, as discussed earlier, it represents the subtraction of in-phase activity at LO from that at RO. If one were to interpret the bipolar recording (RO − LO) for the period of in-phase activity, without the benefit of also observing the referential recordings in Figure 3, one could easily be left with the erroneous view that occipital EEG activity was of significantly smaller amplitude than is actually observed to be the case in the referential recordings at MO, RO, and LO.

The reader's attention is now referred to another portion of the traces of Figure 3, which is marked OUT and represents approximately 180 degrees out-of-phase activity between LO and RO. Here, the monopolar activity recorded at MO, RO, and LO is again approximately equal in amplitude, while the activity recorded at the bipolar recording site, RO − LO is approximately twice the amplitude of these other tracings. When RO and LO reflect approximately 180 degrees out-of-phase activity with respect to each other, then the referential recording of MO reflects this asynchrony by showing a slightly attenuated trace. When RO and LO are producing in-phase activity with respect to each other, the referential recording of MO reflects this synchrony by showing a slightly larger amplitude trace. These differences observed in the MO trace are the result of the cancellation or summation of volume conducted fluctuations in the two hemispheres at the midline. Observing this bipolar recording of approximately 180 degrees out-of-phase activity, in the absence of the other traces shown in Figure 3, could again lead one to the erroneous viewpoint that occipital activity was greater than is actually observed to be present at MO, RO, and LO.

The actual recordings of occipital EEG activity and their relationship shown in Figure 3 are in general agreement with the discussion presented earlier in this article. For in-phase activity, bipolar recordings of RO − LO are small in amplitude when referential recordings of MO, RO, and LO (relative to a distant reference point) are large. Conversely, for 180 degrees out-of-phase activity, bipolar recordings are larger in amplitude than their respective referential recordings. The traces shown in Figure 3 also reflect the fact that the occurrence of nearly in- and approximately 180 degrees out-of-phase activity are not unusual. The finding that in-phase and 180 degrees out-of-phase activity are common occurrences in EEG recordings has been supported by observations of many referential recordings at various scalp loci in our laboratory (Fehmi, 1978). It is our opinion that in-phase synchrony and phase relations between waves in the brain are a vehicle for, or a reflection of, certain types of attentional behavior (Fehmi, 1978; Hutchison, 1986; Fehmi & Selzer, 1980; Fritz & Fehmi, 1982). The hypothesis that information processing in the central nervous system depends upon in-phase synchrony is supported by visual evoked response research of pattern recognition in primates (Fehmi, Lindsley, & Adkins, 1965; Adkins, Fehmi, & Lindsley, 1969).

In EEG biofeedback training for amplitude or abundance enhancement, the use of bipolar electrode placements is biased toward learning to generate 180 degrees out-of-phase and against producing in-phase activity at A − G and B − G. The results of EEG biofeedback experiments cited below will provide evidence that in-phase activity can be trained and is relevant to behavioral and experimental effects. In the event that this conclusion is confirmed by subsequent experimental research, then replication of the many previous EEG biofeedback experiments that used bipolar electrode techniques will be necessary in order to vericidally assess the controllability and the relationship of EEG in-phase synchrony to other physical and psychological events. Similar arguments can be made with respect to referential and bipolar EMG recording for the reasons cited above, in connection with in-phase and 180 degrees out-of-phase activity.

EXPERIMENTS ILLUSTRATING USE OF REFERENTIAL PLACEMENTS IN EEG BIOFEEDBACK IN SYNCHRONY

What follows are brief descriptions of four experiments which illustrate the application of referential recording in EEG biofeedback training and research. They are representative of research conducted in an effort to increase the effectiveness of EEG biofeedback training and to evaluate the role of in-phase synchrony in information processing in the central nervous system, in experience, and in behavior. In the event that bipolar recording techniques had been utilized, the cited experimental results would have been unlikely, and our interpretations of the obtained results would have been impossible, because our conclusions are concerned with the in-phase synchrony of brainwave activity. In-phase brainwave activity is largely destroyed by recordings made with bipolar electrode placements.

AUTOREGULATION OF OCCIPITAL EEG PHASE RELATIONS

In an experiment which demonstrated that individuals could learn to control the phase relatedness of their brain wave activity, 10 experimental participants received feedback from a commercial phase meter which detected when brainwave activity from the left and right occipital lobes (O1 and O2) were within plus or minus 15 degrees of being perfectly in-phase (Fehmi, 1978; Fehmi, 1974). Referential placements used interconnected ear lobes as the reference, with the ground connected to the seventh cervical vertebra. During one session of training, experimental participants demonstrated an ability to increase the amount of time spent in-phase during the "on" periods as compared to the base rate scores ($t = 2.1$; $p < 0.05$) and to decrease the amount of time spent in-phase during the "off periods as compared to base rate scores ($t = 2.5$; $p < 0.025$). Similar comparisons for yoked control participants were not significant.

Verbal reports obtained from nine of the experimental participants indicated that the maintenance of phase agreement is tiring and difficult, requiring concentration on a relatively stable mental image. The participant with the largest alpha activity was the only one who failed to report the association of fatigue with single-minded concentration upon a mental image. The effortful orientation used by the majority of participants was an effective technique, since phase parity, irrespective of the frequency of brainwave activity, was the sole feedback parameter in this experiment. Occipital EMG, which was also monitored in this experiment, indicated no differences in EMG activity during the on and off periods. The results of this experiment indicate that phase parity between the hemispheres can be precisely controlled, and that such parity is associated with distinctive mental events. In addition, the results suggested that in-phase training, in conjunction with increased amplitude training, can yield behavioral strategies for the production of in-phase activity which are less oriented toward effort.

EFFECTS OF EEG BIOFEEDBACK TRAINING ON MIDDLE MANAGEMENT EXECUTIVES

In this research that was supported by a grant from the Kane-Miller Corporation, six experimental participants received 20 sessions of EEG biofeedback training (Fehmi, 1978; 1974). A five-channel, phase sensitive EEG biofeedback computer was utilized, in order to provide amplitude-modulated feedback for one to five lobes of brainwave activity. The cortical electrode placements corresponded to Fz, Pz, Oz, T3, and T4 of the International Ten-Twenty System (Jasper, 1958). Ear clip electrodes served as reference and ground. During the first six sessions, participants received feedback for alpha activity from only one recording site, either the occipital, parietal, frontal, left temporal or right temporal lobes. As the experiment progressed, additional channels of brain wave activity were added, so that the feedback tone reflected simultaneous in-phase alpha activity from two or more pre-selected recording sites.

Six yoked-control participants received feedback identical to the feedback received by the experimental participant with whom each was matched. Double blind implementation of the training protocol was made possible through the utilization of a switch control console, a randomized schedule of switch positions, and a randomized schedule of room assignments for the experimental and yoked-control participants.

During the baseline periods of the last two sessions, all six of the experimental participants showed a higher integrated alpha score, as compared with the baseline scores from the first two sessions ($p < 0.01$). An analysis of variance performed on the alpha activity scores from the ON and OFF test periods of the last four sessions for the EEG activity for five lobes indicated that the experimental participants demonstrated ON-OFF control over their wave activity ($p < 0.01$). Similar control was observed during ON and OFF test periods conducted without feedback ($p < 0.01$). ON-OFF control was not demonstrated in the performances of the yoked-control participants.

Results from a semantic differential questionnaire completed by each participant showed statistically significant ($p < 0.05$) changes as training progressed. After training, middle managers experienced themselves as: (1) more calm; (2) less depressed; (3) more able to concentrate; (4) more self-initiating; (5) more detached from the experience; (6) more observant; (7) more personal (as opposed to formal); (8) more in oneness (as opposed to separateness); (9) more insightful; and (10) more satisfied with life. None of these changes were found in the responses of the control participants. The results of this double blind experiment demonstrate the efficiency of EEG biofeedback training utilizing referential recording techniques and of phase-sensitive, multi-channel methods of delivering feedback.

THE EFFECTS OF RHYTHMICAL AUDITORY SIGNALS ON THE ELECTROENCEPHALOGRAM

Ten participants each received one 54-min session, which was divided into five periods: (1) base rate period; (2) stimulation period; (3) base rate period; (4) stimulation period; and (5) base rate period (Fehmi & Selzer, 1980; Selzer & Fehmi, 1975). During the base rate periods, the participant received no auditory stimulation. During the stimulation periods, each participant received one period of auditory stimulation at alpha frequency (10 Hz) and one period of auditory stimulation at theta frequency (5 Hz). EEG activity was monitored from the mid-frontal, mid-occipital, and left and right temporal lobes using one ear lobe as the "B" electrode reference and the other ear lobe as ground. One-minute integrated energy scores were computed separately for alpha activity and for theta activity recorded from the occipital lobe, the frontal lobe, the combination of the right and left temporal lobes, and the combination of all four lobes. When the lobes were combined, the integrated energy score was computed of the phase-sensitive algebraic sum of the activity recorded at the individual sites divided by the number of sites included.

F-tests performed on the alpha and theta scores from the base rate periods indicated that there were no significant changes in the base rate of alpha or theta production across the three base rate periods. T-tests on both the alpha or theta scores during alpha and theta stimulation indicated that the frequency of frontal lobe activity was affected by the frequency of stimulation: more alpha activity was produced during the alpha stimulation period than during the theta stimulation period ($p < 0.05$); whereas, more theta activity was produced during the theta stimulation period than during the alpha stimulation period ($p < 0.05$). Similar results were obtained for the theta scores from the average of the four channels; that is, the average integrated theta energy was greater during the theta stimulation period than when compared to those scores from the alpha stimulation period ($p < 0.05$). Other individual comparisons of scores during alpha and theta stimulation periods showed that there were no significant differences.

The results of this experiment indicate that auditory entrainment of alpha and/or theta activity occurs. As a result, rhythmical amplitude-modulated feedback is superior to other types in EEG biofeedback training for the achievement of increased amplitude. In the present experiment, when brainwave activity is generated, it gives rise to feedback which is rhythmical and at the same frequency as brain activity. This feedback, in turn, can stimulate the brain's production of more and larger waves than before biofeedback. The above results, however, also suggest that the phase relationship between the occurrence of brainwave activity and the presentation of feedback can affect the amplitude of brain wave activity during training. This is the hypothesis which is investigated in the following experiment and is relevant to behavioral and experimental effects. In the event that this conclusion is confirmed by subsequent experimental research, then replication of the many previous EEG biofeedback experiments that used bipolar electrode techniques will be necessary in order to vericidally assess the controllability and the relationship of EEG in-phase synchrony to other physical and psychological events. Similar arguments can be made with respect to referential and bipolar EMG recording for the reasons cited above, in connection with in-phase and 180 degrees out-of-phase activity.

EFFECTS OF PHASE DELAY OF AUDITORY BIOFEEDBACK ON EEG ACTIVITY

To evaluate the effects of feedback delay upon EEG activity and subjective experience, the phase relationship between the monitored brain wave and the feedback signal was varied (Fehmi & Selzer, 1976). Twelve experienced participants each received one session of EEG biofeedback during which the amplitude-modulated auditory feedback was determined by the alpha activity on the mid-frontal lobe, using one ear lobe as the B reference and the other as ground. The feedback signal was delayed by 12.5, 102.5, 192.5, 282.5, or 372.5 degrees, depending upon the period. All of the possible pair orders of phase delays were presented in a randomly determined sequence of 15-s periods. After each period, the experimenter recorded the integrated energy score for the alpha activity during this period and asked the participant for his (or her) preference rating of the period as compared to the preceding period. Alpha activity scores and a preference hierarchy for the various phase delays were thereby obtained for each S. A Kruskal-Wallis analysis of variance on the preference data indicated the feedback delay did affect the preference responses ($p < 0.0001$). Individual Mann-Whitney U-tests comparing preference scores for each pair of delay periods indicated that 192.5 and 282.5 degrees delays were significantly preferred when compared to any of the other delay periods ($p < 0.01$). There were no preference differences among the remaining three periods. An analysis of variance of the frontal lobe integrated alpha energy scores indicated that alpha scores were affected by the feedback delay ($p < 0.01$). During the 282.5 degrees phase delay periods, there was more alpha energy produced than during the 102.5 degrees delay periods. Other comparisons were not statistically significant. The results from this experiment indicate that the feedback signal delay can affect brainwave activity during biofeedback training and also affect the perceived pleasantness or ease of the task.

The findings of the four preceding experiments suggest that increases in amplitude and in-phase activity can be trained by using rhythmical feedback signals, properly delayed in time, with feedback reflecting the in-phase synchrony of two to five lobes of EEG activity simultaneously, when referential recording techniques are used. Bipolar recordings distort in-phase amplitude and polarity measures, and, thus, reduce or destroy altogether, the effectiveness of amplitude and in-phase neurofeedback training.

ADDITIONAL BENEFITS OF SUMMING AND SUBTRACTING REFERENTIAL PLACEMENTS

The considerations presented here are of significant importance relative to underlying brain mechanisms. We are not merely interested in recording the condition of a particular brain site, in terms of its amplitude or frequency, as if it were steady, unchanging, and independent of other brain sites. It is critical to consider the intersite dependencies and interactions, as part of a coordinated whole. There are sites that will be in communication with each other or with other "third party" sites. In addition, there are interactions that means that it is of less importance exactly what one site is doing, but more on what it is doing relative to somewhere else. Overall, addressing the relative dynamic binding or unbinding of brain sites is a key component of effective EEG training. Moreover, we will see that only be recording and processing individual referential site data is it possible to obtain an unambiguous indicator of site interdependencies, and to measure changes in real time.

Bipolar recording is one way to address the inter-site dependence. It is an attempt to "see" both sites, and to somehow train the information coming from them. As we shall see, it provides only a very limited way of combining the site information, when compared to a referential approach.

When considering the brain dynamics that underlie EEG measurements, it is important to appeal to the concepts of coupled vs. uncoupled activity, also referred to as binding versus unbound activity. These are ways of viewing the degree of dependence, or independence, of the involved brain sites. When sites are observed to wax and wane together, we say that they are dependent. This is generally taken to reflect either communication between the sites, or mutual communication with a third site. The degree of binding is variable from moment-to-moment, and reflects the degree of dynamic connectedness. That is, at any moment, two sites may be more or less bound, owing to the amount of communication that is causing them to be connected.

In order to compare referential versus bipolar measurements, it is appropriate to consider the signals from the two leads in both their independent, and in their combined forms. In the case of the independent signals, we consider two separate channels of EEG, and examine their properties. For these considerations, we assume that the signals are taken with regard to a common reference, such as linked ears. In order to understand the bipolar signal, we consider the difference between two channels as obtained by subtracting one from the other. This performs the same operation as is provided by a single differential amplifier, when connected to the leads in a bipolar configuration. In a similar fashion, it is possible to examine the sum of the referential channels, in order to understand how the combined signal relates to the original waveforms.

We first examine the sensitivity of each measurement to the amplitude of the signals at each location. The amplitude sensitivity of referential versus bipolar signals can be determined by assuming that the signals are always aligned, that is, in phase. In this case it is clear that, because similar parts of the waveform line up, the instantaneous amplitudes of the combined signals will be:

$$\text{Amplitude}_{\text{sum}} = \text{Amplitude}_1 + \text{Amplitude}_2$$

$$\text{Amplitude}_{\text{difference}} = \text{Amplitude}_1 - \text{Amplitude}_2$$

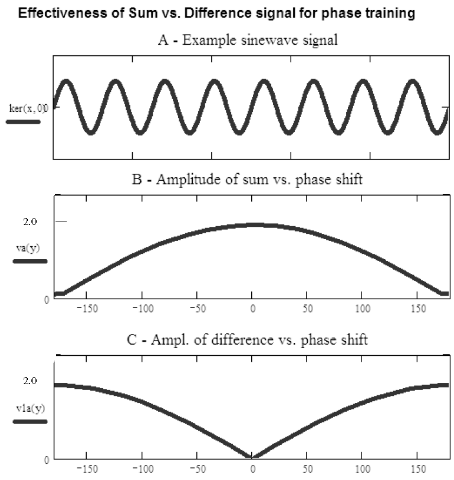
In these expressions, it is important to note that polarity matters. That is, it is possible for either signal to have a positive or negative amplitude, depending on the excursion of the signal above and below the baseline, which is zero. Thus, Amplitude_1 might be 10, while Amplitude_2 is -10. The arithmetic sign must be preserved when applying these equations, to calculate the correct result.

These relationships are straightforward and linear yet reveal an important difference. As either or both signals vary their amplitude, it is clear that the resulting amplitudes in the sum or difference will reflect the changes directly. Thus, if one signal changes its amplitude by 5.0, all else being equal, the amplitude of the sum or difference will also change by 5.0. However, it is evident that the amplitude of the difference has a stronger dependence on the output, when the output is small. That is, if the two individual amplitudes are in-phase and equal, so that the difference signal is zero, any small change in either amplitude will produce a significant change in the difference signal; that is, changing from 0.0 to 5.0. For example, if the individual amplitudes initially differ by 10 percent and Amplitude_1 changes by a further 10 percent, then the value of $\text{Amplitude}_{\text{sum}}$ would be observed to change by about 9 percent, while the value of $\text{Amplitude}_{\text{difference}}$ would be observed to double, which is a change of 100 percent.

Perhaps more significant than amplitude sensitivity of the measures is phase sensitivity. The amplitude of the sum or difference signal will depend on the relative phases of the two signals, in a well-defined manner. The phase sensitivity of referential and bipolar signals provides a critical indicator of the relative usefulness of the methods. Assume that two signals begin in phase, and then move out of phase. As they shift relative to each other, the amplitude of the output signals will change, as follows (see Figure 4).

Figure 4 shows the relative phase sensitivity of the sum and difference signals, when plotted as a function of the phase difference of a simple sine wave. It is evident that the sum signal has a maximum when the two input signals are in phase, and that it has a relatively soft dependence on the signal phases. For example, when

FIGURE 4. Dependence of sum and difference signal amplitudes on relative phase



the signals are fully 50 degrees out of phase, the amplitude change (decrease) will be less than 10 percent. The difference signal has a significantly stronger dependence on phase, in the region near in-phase signals. When the signals move 50 degrees out of phase, the difference signal will change (increase) by as much as 20 percent.

The sum of referential signals exhibits phase sensitivity, according to the following formula:

$$\text{Amplitude}^2_{\text{sum}}\,(\text{phase shift}) = 2 \times (1 + \cos(\text{phase shift}))$$

This relationship is shown in the Figure 4(B) in which the amplitude is seen to peak at a value of 2, when there is a phase shift of 0 degrees (in phase). The amplitude decreases as the phase difference shifts in either the positive or negative direction.

For the bipolar (subtracted or "difference") signals, the amplitude relationship to phase is:

$$\text{Amplitude}^2_{\text{diff}}\,(\text{phase shift}) = 2 \times (1 + \cos(\text{phase shift} + 180))$$

This is seen in Figure 4(C) to be zero when the phase shift is zero, and to rise as the phase shifts in either direction. Thus it might seem that training on a bipolar (difference) signal, one may effectively train for phase synchrony, by training this component down. However, there are other ways for this value to become small. This includes when either or both referential signals themselves become small in amplitude, independent of their relative size or phase relationship. Therefore, down-training the amplitude of a bipolar signal is not guaranteed effective, when used alone to train synchrony.

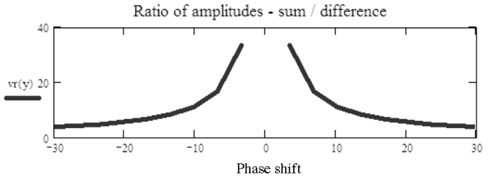
Thus, the phase and amplitude sensitivity of a bipolar or difference signal cannot reliably be used by itself in the interest of training the synchrony or alignment of the signals. This is because the condition of signal equivalence providing an output of "zero" in the difference signal, can also be obtained in conditions when the signals are not synchronous or in alignment. By combining the sum and difference, however, (e.g., training the ratio sum/diff) it is possible to address this need.

The amplitude and phase sensitivity provides an advantage to referential recordings, when used with channel recombination for the purpose of synchrony training. The derived sum channel has a well-defined relationship to the input signals, such that it can only be at a maximum when both signals are at their maximum values, and when the signals are also in phase. It is also possible to combine more than one channel at a time, toward this purpose, as was described earlier. In any method that combines the signal waveforms by adding them as raw waveforms, there will be a strong dependence of the resulting training variables on both the amplitude and the phase alignment of the input signals.

If we examine the ratio of the responses of the sum and difference channels, we see that the two response curves combine to provide a very sharp phase sensitivity (see Figure 5). Because the difference term goes to zero as the signals match phase perfectly, the metric sum/diff has an extreme rise near the center of the phase dependency, becoming theoretically infinite. Based on this response curve, it would appear to be practical to train for phase alignment within a tolerance of 5 to 10 degrees, seeing differences of a factor of 10 or more, using even a simple feedback method applied to this signal.

In order to compare referential and bipolar recordings of real EEG, one must acquire 2 channels of EEG, and independently inspect the individual referential recordings as well as a reconstructed "difference" signal. Since the

FIGURE 5. Dependence of ratio of sum to difference on relative phase



referential recordings are acquired with a common (linked ears) reference, it is possible to accurately reconstruct the equivalent bipolar signal, because the two identical references cancel out in the input-output equation.

The following examples use a Joint Time-Frequency Analysis (JTFA) of the signals obtained by using individual referential signals, as well as their sum and difference. Each plot shows approximately 1 minute of EEG, analyzed over the frequency range of 1 to 45 Hz. Signals were obtained referenced to linked ears, using the BrainMaster 2E 2-channel EEG with the BrainMaster 2.5 software.

We shall examine two examples of homologous pairs, one with relatively uncoupled (independent) EEG signals, and another with relatively coupled (synchronous) EEG signals. In addition to revealing the signal characteristics, this example will also serve to illustrate the relative value of the sum and difference signals, in practical EEG assessment and training.

The first example, Figure 6, shows signals obtained from T3 and T4 referenced to linked ears. In the individual traces, the two signals look relatively similar. Both have a certain amount of visible delta and alpha activity, plus very slight activity visible as small, irregular peaks lying between 12 and 24 Hz.

The relative amount of independence in the EEG activity is clear when comparing the sum and difference signals (Figure 7). While the delta activity is clearly strong in the sum, it is significantly smaller in the difference signal. This shows that the delta activity in T3 and T4 is largely coupled. On the other hand, the size of the alpha peaks in the difference is clearly larger in the difference signal. This indicates that the alpha activity at T3 and T4 is largely out of phase, or that individual alpha bursts are predominantly in either T3 or T4, but not both. This clearly illustrates the independence of the alpha generators at the sites T3 and T4. In addition, it is evident that the appearance of the beta energy (20-35 Hz) shows a similar rippling pattern in both the sum and difference signals. Whenever the sum and the difference of two signals look similar, the signals must be independent of each other.

FIGURE 6. Referential signals from T3 (left) and T4 (right) referenced to linked ears

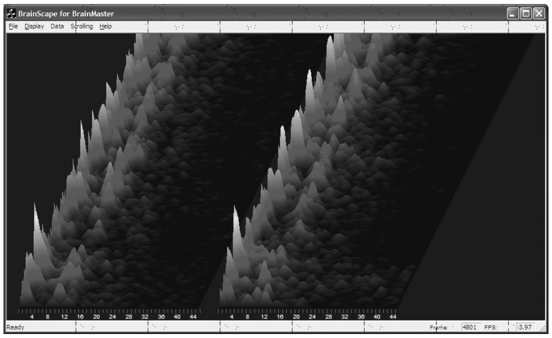


FIGURE 7. Sum (left) and difference (right) signals from T3 and T4, each to linked ears

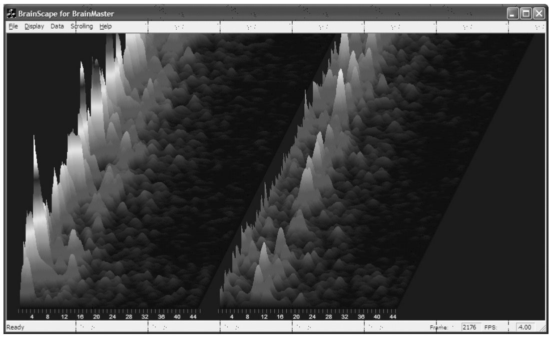


Figure 7 also provides some clarification of the circumstances of training T3 and T4 using a single channel bipolar configuration. In this case, the signal being trained is that on the right side of Figure 7. This signal is observed to have significant energy and complexity, and in fact has the "lion's share" of the alpha energy. Thus, for training purposes, a T3-T4 bipolar connection would be expected to have a rich "engagement" with the underlying generators, as they are well able to express themselves in the derived signal. When uptrained, this signal will encourage any independent activity, regardless of its source or nature, to the extent that phase is controllable. For example, were the brain capable of generating exactly out-of-phase alpha, then it would do so, producing an even larger difference signal. Thus, much of the effect of bipolar uptraining will depend more on what the brain can do with the information, than on the specificity of the training variable.

At the same time, it is apparent that, in addition to bipolar training in this case, it is also of value to include the individual channels, and to train the sum channel, or individual referential channels, as well. By training both the sum and difference, it becomes possible to provide more detailed and specific information relating to the interhemispheric dynamics.

The situation is visibly different in the example of O1 and O2 (see Figure 8). In this example, the degree of synchrony is evident in the clear differences between the two JTFA displays for the sum and difference signals.

In the individual channels (Figure 8), we again see rather similar appearances in both channels. One can visibly see large alpha bursts that appear symmetric, that is, equal in size in both channels. Some degree of independence is also suggested, but difficult to quantify visually from this display.

Figure 9 shows the sum and difference signals based upon these recordings. Several features are clearly evident. First of all, both alpha and delta are clearly much larger in the sum than in the difference. Visibly, the difference is a factor of 10 or more. This indicates that both alpha and delta are generated in a very synchronous manner, between O1 and O2. It is of further interest to observe the difference signal. One does see a moderate amount of independent alpha, and a lesser amount of independent delta, between O1 and O2. This means that, at times, the left and right hemispheres do operate independently, and do produce an individual lateralized alpha burst, or possibly bilateral alpha bursts that are asymmetric. Whatever the origin, this is the signal that would be trained if one were to train O1 and O2 using a bipolar derivation. It is evident that this lead configuration would be rewarding something rather different than the individual referential, or summed, leads. For example, were one to train O1, O2, or Oz for that matter, relative to an ear, one would be seeing a signal such as that in either side of Figure 8. Were one to attach leads from O1 to O2, however, one would be seeing the right side of Figure 9, which is a very different scenario.

The beta activity in Figure 9 is also of interest. One sees a rippled plain on the sum channel, and a much cleaner "landscape" in the difference. Again, this indicates that the bulk of the beta activity is largely synchronous. Any asynchronous non-alpha activity that occurs is negligible, being barely visible near 14 Hz and 21 Hz.

In considering the changes in these signals and their dependence on underlying signal properties, it is helpful to use the concept of joint energy or power, as a general property. It is possible to interpret this concept in terms of its effect on the measured values. Generally, we consider signals to have more joint power when they are both large, and consistently aligned rel-

FIGURE 8. Referential signals from O1(left) and O2 (right) referenced to linked ears

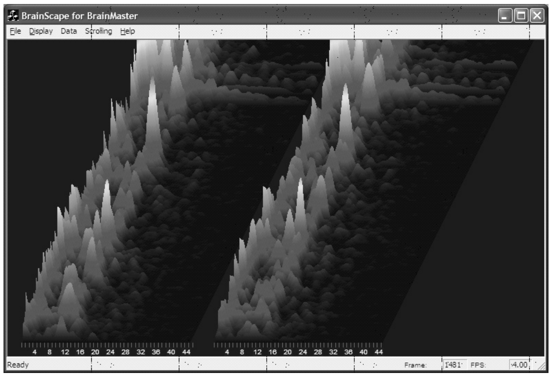
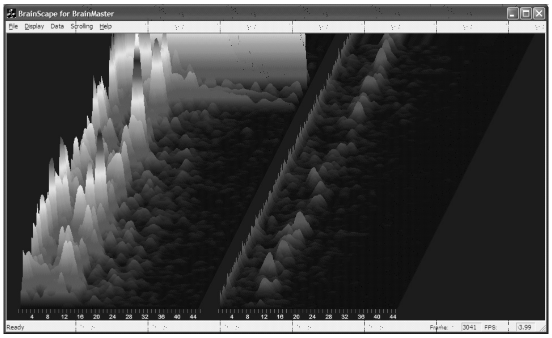


FIGURE 9. Sum (left) and difference (right) signals from O1 and O1, each to linked ears



ative to each other. The various training metrics (coherence, synchrony, phase, etc.) are all estimators that bear some relationship to the joint power in the signals. For example, coherence depends on a constant phase relationship, but not phase alignment of the signals (zero phase difference). The sum and difference channels do depend on the phase alignment of the signals, as we have described.

As a final example of the effectiveness of channel recombination, Figure 10 shows sum and difference data taken from F3 and F4. What is most notable about this data is the presence of a few small, single burst of gamma (40 Hz) visible on the sum trace. These bursts are not visible in the difference trace, indicating that the bursts are largely synchronous, being in phase for each cycle of the brief 40 Hz burst. This is a dramatic illustration of the power of channel recombination, when acquiring referential channels. It is evident from this recording that a simple threshold mechanism, when applied to the sum channel, would be capable of detecting these rare, minute bursts of gamma activity, and using them for neurofeedback purposes.

Synchronous gamma bursting was observed by Collura et al. (2004) in a psi-related paradigm. Lutz et al. (2004) observed continuous synchronous gamma in experienced meditators. These studies point to the importance of observing synchronous activity in relation to elevated mental states.

It is possible to make certain statements about the underlying signals, when changes in the amplitude or phase of the training signals occur. These include the following:

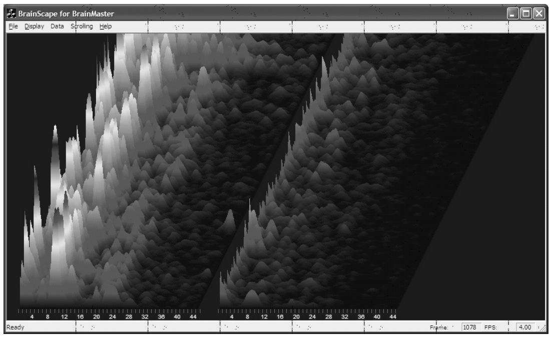


FIGURE 10. Sum (left) and difference (right) signals from F3 and F4

If a bipolar signal is seen to increase, one or a combination of the following may be the case:

- The signals have moved out of phase (reduced joint power).
- Signal 1 has changed (up or down) in amplitude (increased or reduced joint power).
- Signal 2 has changed (up or down) in amplitude (increased or reduced joint power).
- Both signals 1 and 2 have changed (in either direction) in amplitude (increased or reduced joint power).

If the bipolar signal is seen to decrease, one or a combination of the following may be the case:

- The signals have moved into phase alignment (increased joint power).
- Signal 1 has become smaller (reduced joint power).
- Signal 2 has become smaller (reduced joint power).
- Both have become smaller (no change in joint power).

If the sum of referential signals is seen to increase, one or a combination of the following may be the case:

- The signals have moved into alignment (increased joint power).
- Signal 1 has increased (increased joint power).
- Signal 2 has increased (increased joint power).
- Both have increased (no change in joint power).

If the sum of referential signals is seen to decrease, one or more of the following may be the case.

- The signals have moved out of alignment (reduced joint power).
- Signal 1 has decreased (reduced joint power).
- Signal 2 has decreased (reduced joint power).
- Both signals have decreased (no change in joint power).

There are of course other possibilities that lead to changes in the observed signals. However, only the sum of referential signals is capable of providing unambiguous information regarding increases or decreases in joint power. In order to unambiguously interpret changes in bipolar signals, it is necessary to have the additional information regarding either the individual signals, or the sum of the referential signals. Note that in order to adequately train symmetry, it will be necessary to have the individual signals, since a bipolar configuration is not capable of providing information that unambiguously reflects the symmetry between the two sites being monitored.

From the foregoing, it is clear that it is possible to train for increased or reduced joint power (coherence, synchrony, or phase alignment), by using the sum of the referential signals. This is not, however, possible when using bipolar signals alone, because any given change may reflect either an increase or an increase in joint power, depending on the exact signal changes that have occurred. As we have seen, the possibility of uptraining the sum and downtraining the difference overcomes this limitation, and provides additional specificity. This is possible in systems that first acquire the two channels independently, and then provide the ability to compute the derived signals, and produce training displays and feedback based upon the derived signals.

It is also possible to train asymmetry as well as symmetry using individual referential signals, whereas this is not possible with a single bipolar channel. Any attempt to increase asymmetry (by uptraining the difference) will only cause the expected "desynchrony" training, as noted above. Without specific knowledge of the source laterality of the difference signal, it is not possible to train either hemisphere in a specific fashion.

This analysis also highlights the relative value of channel recombination (sum and/or differencing) as a method for assessing and training EEG. It is common to employ numerical methods (FFT, cross-correlation, coherence metrics) when addressing brain synchrony issues. However, by simply combining individual referential channels, it is possible to obtain effective training metrics, without resorting to additional calculations. This provides an element of directness to the protocol, and also allows one to apply an existing 1-channel training infrastructure to sum and difference channels, simply by treating them as additional, virtual, channels. Modern computer-based EEG biofeedback systems that provide signal recombination and user-defined calculations (e.g., BrainMaster, Thought Technologies, etc.) are capable of displaying and training signals thus derived, providing the benefits of this approach.

In addition, it is evident that when two channels are acquired instead of a single bipolar channel, it is possible to create more complex protocols that process the channels independently, for separate hemispheric training. This is in addition to the ability to compute and train on real-time metrics such as overt coherence calculations, phase calculations, and so on. Overall, with 2 or more bipolar channels, it is possible to perform overt training for inter-site binding (communication and sharing of inter-site brain activity, hence EEG energy), unbinding (breaking apart or making independent), coherence, synchrony, asymmetry, or simply for complex protocols. None of these are possible with one or more bipolar channels, when they are the only signals available for feedback.

These considerations are relevant to conventional multichannel EEG or QEEG in that it is valuable for the reader to view both the referential recording, and derived bipolar "chains." In the field of clinical neurophysiology, it is now commonplace to record the EEG to a chosen reference, and to reformat the data when reviewing it. For example, when unusual focal activity is seen at one or more referential sites, it is generally possible to compute a reformatted EEG, in which various bipolar derivations are constructed and analyzed. Focal spikes, sharp waves, and seizure activity in particular are best characterized by viewing both the referential and one or more bipolar montages. In this way, the benefits of both types of EEG are obtained. However, when looking at amplitude or power in the form of numerical displays, graphics, or topographic maps, it is essential to use referential recordings, to provide an unambiguous display of the signal power without the confounding effects of the bipolar derivation.

Hjorth (1991) has observed that estimates of source distribution in general, and the

Laplacian in particular, consist essentially of linear transformations of the amplitudes obtained from referential EEG tracings, most commonly the 10-20 derivations. Therefore, the information contained in any possible transformation is, in principle, contained in the original referential data.

It is instructive to observe the monopolar / bipolar contrast in its most general form. Any bipolar montage can be thought of as a transformation on a standard monopolar set. Furthermore, many derived representations are also transformations on this set. The Laplacian is clearly of this form. Another technique that rests upon the transformation of monopolar data is the LORETA (Pascual-Marqui et al. 1994, 1999). If one attempts to use localization data, and to train in a manner that reflects this localization, the training variables again consist of linear combinations of amplitude data taken from a monopolar placement. As noted by Menendez and Andino (1999), the inverse problem is underdetermined because a large number of degrees of freedom (source solutions) are determined by only a few constraints (number of sensors). When neurofeedback training is conducted using LORETA-based data, the training variable consists of a metric derived from a linear transformation of the raw EEG amplitude data. Despite the conceptual interpretation that we are training "to a location," the fact remains that the training signal is a particular combination of the monopolar EEG data, weighted to "prefer" a given weighted sum of amplitudes.

In clinical EEG, data are most generally acquired in monopolar form, and transformed as necessary for analytical needs into bipolar chains, source derivations, common average reference, or localization-based representations (Collura et al. 1993). It is of interest to note that while the information contained in bipolar recordings can be recovered from referential recordings, the converse is not generally true. This is also true of other transformations, including source derivation or localization-based methods. There is a many-to-one problem that persists in all such approaches. Whereas it is possible to predict exactly, from first principles, the surface potential resulting from any known charge distribution and boundary conditions (anatomy, skull, etc.), it is possible to find infinitely many "putative" sources that can account for the same observed EEG distribution. Therefore, no transformed representation can be considered unique, given a single monopolar data set, unless various assumptions are made (single dipole source, no cortical surface sheets, etc.).

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