CHAPTER 2

FUNDAMENTALS OF EEG METHODOLOGY IN CONCUSSION RESEARCH

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Abstract: The EEG in humans was first demonstrated by Hans Berger in the 1920s. His initial speculation that EEG could give us insight into physiological and cognitive processes has been validated in a variety of situations ranging from sleep to wakefulness as well as physiological concomitants of a variety of cognitive events. The current chapter will review basic EEG processes and present the background for understanding its usefulness in identification of changes related to motor processes in general and brain trauma, in specific.

Keywords: Brain imaging; EEG; Frequency domain; Evoke Potentials.

1. INTRODUCTION

One important turning point in the history of electrophysiology was the report by Galvani in 1791 that nerves contain an intrinsic form of electrical activity. Some 60 year later Du Bois-Reymond demonstrated that activity in a peripheral nerve was accompanied by recordable changes in the electrical potential of the nerve. With this discovery, the scientific community began to search for various factors that would be associated with this electrical activity. During this period one important theoretical question was the location of various forms of activity in the brain. Richard Carton studying rabbits and monkeys was able to demonstrate a connection between external sensory stimulation such as light and concomitant electrical activity in the brain. In specific he was able to show that electrodes on the scalp of these animals could reflect "feeble currents" associated with a variety of stimuli. This marked one of the initial demonstrations of the EEG with animals.

From the initial demonstration of the EEG with animals, it was some 54 years later that the techniques was demonstrated in humans. In 1920s Hans Berger was able to show potential differences between recording sites related to cortical processes. He named this electrical activity the "Elektrenkephalogramm." In his first set of papers, Berger sought to determine what factors were involved in the production of the EEG and was able to determine that EEG was related to activity within the brain and to rule out other physiological activity such as cerebral pulsations, cerebral blood flow, blood flow through scalp vessels, heart rate activity, muscle activity, eye movements and electrical properties of the skin (Berger, 1929). Berger took his studies beyond the physiological level and was one of the first to suggest that periodic fluctuations of the EEG might be related in humans to cognitive processes such as arousal, memory and consciousness. In determining the nature of the EEG Berger was initially surprised to discover that EEG changes were ones of quality rather than quantity. For example, as an individual moved from a relaxed state to one of stimulation and activity, Berger noted that the EEG did not increase in amplitude but rather changed in the quality of the wave forms. He initially identified these two different EEG wave forms as that of alpha activity and that of beta activity with alpha being associated in cortical inactivity and beta with cortical activity.

2. PHYSIOLOGICAL BASIS

During the past century there was some debate as to the nature of the EEG. Although initially thought to result from summated action potential which fire in an all or none fashion (cf., Adrian & Matthews, 1934), this has been shown not to be the case. For example, Li & Jasper (1953) were able to record EEG in cats even after neural action potentials were abolished using deep anesthesia. Current views suggest that the EEG originates in the depolarizations of the dendritic trees of pyramidal cells (Lutzenberger, Elbert, & Rockstroh, 1987; Lopes da Silva, 1991). In specific, graded postsynaptic potentials of the cell body and dendrites of vertically orientated pyramidal cells in cortical layers three to five give rise to the EEG recorded on the scalp. The ability to record the relatively small voltage at the scalp from these actions results from the fact that pyramidal cells tend to be share a similar orientation and polarity and may be synchronously activated.

2.1. Recording and Patterns of EEG Activity

To record the EEG, electrical signals of only a few microvolts must be detected on the scalp. This can be accomplished by amplifying the differential between two electrodes at least one of which is placed on the scalp. Since the signal must be amplified almost 1 million times, care must be taken that the resulting signal is indeed actual EEG and not artifact. Where the electrodes are placed and how many are used depend on the purpose of the recording. Today, almost all EEG procedures use a variety of EEG helmets with up to 256 electrodes build into the helmet although it is always possible to record EEG from only two electrodes. Those recording helmets that use 128 to 256 electrodes are generally referred to as dense array EEG recordings. If the spatial distribution of some aspect of the EEG is the research question, then multiple electrodes distributed over the scalp are required. Of course, one can record from many fewer electrodes depending upon the empirical questions that are being asked. For example, if one is only interested in EEG responses associated with movement, then one may chose to record from regions of the scalp lying above the motor areas of the brain.

Historically, the system of locating electrodes in EEG is referred to as the International 10-20 system (Jasper, 1958). The name 10-20 refers to the fact that electrodes in this system are placed at sites 10% and 20% from four anatomical landmarks. In the front the nasion (the bridge of the nose) is used. In the rear of the head, the inion (the bump at the back of the head just above the neck) is used. The left and right landmarks are the preauricular points (depressions in front of the ears above the cheekbone). In this system, the letters refer to areas of the brain; 0 = occipital, P = parietal, C = central, F = frontal, and T = temporal. Numerical subscripts indicate laterality (odd numbers left, even right) and degree of displacement from the midline (subscripted z). Thus, C_3 describes an electrode over the central region of the brain on the left side whereas C_z would refer to an electrode placed at the top of the scalp above the central area. With the development of dense array systems, the historical 10-20 system has been greatly expanded.

Two specific types of EEG recording are called monopolar and bipolar recordings. In order to understand this point let us remember that EEG recordings reflect the difference in voltage between signals at two electrodes. What this means is that if the exact cortical signal were present at two separate sites on which our electrodes were placed then we would record a straight line reflecting no difference in activity between the two sites. Of course, this never happens since there are always differences in activity between recording sites. In monopolar recordings the idea is to find a site that is not reflective of EEG activity per se to use as a reference site. Common sites used for this purpose are the ear (or ears), the mastoid, or even the nose. Other researchers have suggested that a useful reference to use is that of the average reference. This procedure basically takes a network of electrodes spaced across the scalp and mathematically averages these together. This mathematical average value is then used as the reference.

In bipolar recording, each electrode is located to record from an active site on the scalp. Thus, one could compare the difference in EEG activity between the right frontal area with that of the left frontal area. One might use such a procedure to infer whether the left or right hemisphere, for example, was more involved in a particular task. This type of procedure has traditionally been used in clinical settings to identify unusual pathological waveforms such as epileptic discharges.

The rhythmic variations of the EEG are continually present at the surface of the scalp from well before birth to death. In fact, the absence of the EEG for twenty-four hours has been used as an indicator of "brain death." Additionally, EEG has been used to denote states of consciousness as found in sleep, epilepsy and brain pathology. As we will see in this book, EEG has also been used to denote brain trauma as found in stroke and concussion. The various frequencies and distributions of specific patterns of the EEG wax and wane, providing the brain researcher and clinician with a constant record of the changing patterns of electrical activity of the brain. Some aspects of the EEG may appear almost random while other fluctuations appear periodic. We have a variety of signal processing techniques to help us describe the EEG but in general we use two basic parameters. These are amplitude and frequency. Some EEG patterns are extremely reliable and can be visually observed as would have been required in the days before computer analysis. These patterns have been identified in their order of discovery by the Greek letters α (alpha), ß (beta), δ(delta), and so forth.

2.2. Types of EEG Activity

Alpha activity can be seen in about three-fourths of all individuals when they are awake and relaxed. Asking these individuals to relax and close their eyes will result in recurring periods of several seconds in which the EEG consists of relatively large, rhythmic waves of about 8-12 Hz. This is the *alpha rhythm*, the presence of which has been related to relaxation and the lack of active cognitive processes. If someone who displays alpha activity is asked to perform cognitive activity such as solving an arithmetic problem in their head, alpha activity will no longer be present in the EEG. This is referred to as alpha blocking. Typically, with cognitive activity the alpha rhythm is replaced by high frequency low amplitude EEG activity referred to as beta activity. Since Berger's first discovered the alpha rhythm, a variety of studies have focused on its relationship to psychological processes and the broad developments of the cognitive and affective neurosciences amplified this interest (see Shaw, 2003 for a review). Based on factor analysis of alpha activity some have suggested that alpha activity be divided into two or three separate frequency bands (Klimesch, 1999).

Beta activity occurs when one is alert. Traditionally, lower-voltage variations ranging from about 18 to 30 Hz have been referred to as beta and higher frequency lower-voltage variations ranging from about 30 to 70 Hz or higher as gamma. Initial work suggested that gamma activity is related to the brain's ability to integrate a variety of stimuli into a coherent whole. For example, Catherine Tallon-Baudry and her colleagues (Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1997) showed individuals pictures of a hidden Dalmatian dog which was difficult to see because of the black and white background. After training individuals to see the dog, there were differences in the gamma band response suggesting differential responses to meaningful versuss non-meaningful stimuli.

Additional patterns of spontaneous EEG activity include delta activity (0.5-4 Hz), theta activity (5-7 Hz), and lambda and K-complex waves and sleep spindles, which are not defined solely in terms of frequency. Theta activity refers to EEG activity in the 4-8 Hz range. Grey Walter (1953) who introduced the term theta rhythm suggested that theta was seen at the cessation of a pleasurable activity. More recent research has theta associated with such processes as hypnagogic imagery, REM (rapid eye movement) sleep, problem solving, attention, and hypnosis. Source analysis of midline theta suggests that the anterior cingulated is involved in it generation (Luu & Tucker, 2003). Schacter (1977) in an early review of theta activity suggested that there are actually two different types of theta activity: First there is theta activity associated with low levels of alertness as would be seen as one falls asleep. And second, there is theta activity associated with attention and active and efficient processing of cognitive and perceptual tasks. This is consistent with the suggestion of Vogel et al (1968) that there two types of behavioral inhibition, one associated with a gross inactivation of an entire excitatory process resulting in less active behavioral states and one associated with selective inactivity as seen in over-learned processes.

Delta activity is low frequency (.5-4Hz.) and has been traditionally associated with sleep in healthy humans as well as pathological conditions. The pathological conditions associated with dealt have included cerebral infarct, contusion, local infection, tumor, epileptic foci and subdural hematoma. The basis idea is that these types of disorders influence the neural tissue which in turn creates abnormal neural activity in the delta range by cutting off these tissues from major input sources. Although these observations were first seen with intracranial electrodes, more recent work has used MEG and EEG techniques. EEG delta activity is also the predominant frequency of human infants during the first two years of life.

2.3. Analysis and Quantification

Historically, EEG technicians in clinical settings underwent extensive training in order to be able to recognize the visual patterns of EEG related to sleep stages and neurological disorders. Some frequencies are easy to recognize such as the alpha rhythm while the presence of other EEG frequencies are more difficult. Since visual pattern recognition is subjective, EEG researchers sought quantitative procedures for describing EEG activity. With the advent of integrated computer chips, quantitative analysis of the EEG has become less of practical problem. In order to do a quantitative analysis, it is first necessary to convert the continuous analog EEG signal into a digital form, which is accomplished by an analog to digital converter. Once the signal is represented as individual numbers in a time series, then these numbers can be manipulated mathematically. One of the first questions that must be determined is the sampling rate of the digital converter so that an accurate EEG record can be obtained. Based on a variety of engineering studies, the smallest sampling rate recommended is that of twice the highest frequency that one wishes to detect. Thus, if one wanted to study an EEG signal between 4 and 30 Hz, then one would have to record the EEG at a sampling rate of at least 60 Hz. However, most researchers sample at four to eight times the highest frequency under consideration to ensure accurate detection of the EEG.

2.4. Frequency Analysis

One of the most common frequency analysis techniques is that of Fourier analysis. The technique is named after the French mathematician Fourier, who suggested that any given time series can be described as a corresponding sum of sine and cosine functions. Using this information he described how to determine in the frequency domain the amplitude and phase information of a known temporal signal. One simple way of understanding this procedure is to imagine that one had a variety of templates which represent each frequency band under consideration. Thus, one could have a 8 Hz template, a 9 Hz template, a 10 Hz template and so forth. By simply placing each template on top of the signal, you could determine how closely the signal fit that template. This is basically the procedure that Fourier analysis uses. It takes an EEG signal in time and describes it in term of the how much of each frequency is represented in the signal. Thus, Fourier converts a time-based signal to a frequency-based signal. In the 1960s a mathematical algorithm was developed that speeds computations of this procedure referred to as the Fast Fourier Transform (FFT) which is used by most computer programs today.

An analysis technique related to Fourier analysis is that of coherence analysis. Whereas Fourier analysis gives the frequency for a given electrode, coherence gives the covariance of this measure for a pair of electrodes. Thus, coherence tells you how the EEG signal at each of two electrodes is related to one another. In simple terms, coherence reflects the manner in which two signals covary at a particular frequency. That is to say if the EEG at the right frontal electrode and the left frontal electrode both demonstrated a frequency of 8 Hz, then we would see greater coherence between the two electrodes than if they did not. In doing the coherence analysis, one can also obtain a measure of phase or synchrony. That is to say, we can determine if two signals of the same frequency have peaks and valleys at the same time. Using coherence, Thatcher and his colleagues have studied how the brains of children develop patterns of EEG activity in different areas as they mature as well as EEG changes with brain damage which he discusses in this volume.

3. EVENT-RELATED POTENTIALS

When EEG activity is recorded in relation to a specific stimuli, it is called an event related or evoked potential. For example, if a flash of light is viewed by a subject who has one electrode on the rear of his scalp and another on his earlobe, a predictable sequence of voltage variations will be recorded. A very small positive deflection (less than a microvolt) will follow the flash by about 40 msec. This response will be followed by a large negative deflection lasting 10 to 30 msec and peaking around 60 msec after the flash. Immediately following this wave there appears a fairly large, positive wave with a maximum amplitude occurring about 80 msec after the flash. This pattern is quite predictable; it follows each successive light flash, although, it should be stressed, with some variability from flash to flash. By averaging individual stimulus presentations into a grand average, it is possible to note stable response patterns to a variety of stimuli. This succession of waveforms to visual stimulation is termed the visual evoked response. When the distribution of the responses is examined, it is found to be of maximum amplitude over the occipital area of the brain, and to be less widely distributed than most spontaneous rhythms.

Other sensory evoked responses also can be demonstrated. A sharp sound reliably produces an auditory evoked response. The response is maximal over the vertex of the brain and usually entirely absent from the occipital area. It has been shown that the brain's response to discrete sounds can be traced from the brain stem to the cortex in recordings from an electrode on the scalp. In such records (termed brain stem evoked responses, or BSERs), a distinct wave of positive voltage reflects each level of neural activity as the effects of the stimulus move through the brain. In the same manner, local stimulation of the skin surface in most body locations results in a somatic evoked potential, the waveform and distribution of which are dependent upon the area stimulated.

In general, evoked responses regardless of the nature of the stimulus are referred to as event-related responses or ERPs. Unlike the spontaneous EEG which is recorded in a continuous fashion over a period of time, ERPs are time locked to specific stimuli or responses. In the literature a distinction is sometimes made between endogenous and exogenous ERPs. Exogenous ERPs are seen to be controlled largely by the physical nature of the stimulus itself. Endogenous ERPs, on the other hand, are those that are influenced by the individual's perception or interpretation of the event. Overall, the ERP is smaller in voltage than the EEG and requires averaging procedures over many trials for patterns to be clearly seen. The most common ERP procedure is to time lock the EEG signal to a particular tone or visual stimulus. The basic procedure is to repeat the stimulus a number of times and then average the electrocortical signal to each of these stimuli. This results in a wave that is seen to represent the brain's response to a particular type of stimulation. Traditionally ERPs are referred to in terms of whether the deflection is negative or positive and when the deflection occurs. Thus, a P300 component is a positive component occurring about 300 milliseconds after the stimulus. It should be noted that the timing of the components are not precise but relative. While it is true that a P300 will follow an N200, the P300 may occur later than 300 milliseconds. In viewing graphs of the ERP, a general procedure is to show the negative components as going upwards and the positive ones as downward. Unfortunately, this protocol is not always followed and one should carefully check the axes of a particular graph to determine how the ERP is plotted. To add to the confusion, ERP components may be abbreviated so that a N100 negative component may be referred to as N1, and a negative deflection that occurs approximately 200 milliseconds after the stimulus referred to as N2.

In terms of time, the initial components of the ERP are seen as reflecting automatic processing with the later components being more controlled and related to the cognitive processing of the stimulus. For example, if a pain stimulus was delivered to your right finger then an initial response would be seen on the left side of the cortex. At about 250 milliseconds, an evoked response is seen that some researchers believe to be associated with the subjective response of pain. One of the most well known of the ERP components is that of P300 which in actuality can appear anywhere from 300 to 800 milliseconds after the response. P300 is seen as reflecting cognitive processing and has been used in a variety of paradigms. For example, this component is larger if individuals are told to respond to a stimulus than if they are instructed to ignore it. One common P300 paradigm is that of the oddball. In this procedure, a series of tones with a similar frequency is played in which a tone of a different frequency is played randomly. The novel stimulus or "oddball" results in an increase in the amplitude of the P300. A related component involved with linguistic processing is that of the N400. This component is seen to be especially related to linguistic expectation. For example, if you were to hear Mary had a little ? you would probably expect the word "lamb" to come next. However, if you heard "Mary had a little pizza" then you would see an increase in the N400 component of an ERP.

Duncan, Kosmidis, & Mirsky (2005) used ERPs to study closed head injury. Overall, they reported that cognitive components are more influenced by closed head injury than sensory components and that within the sensory system, auditory ERPs are more influenced by injury than visual ERPs. A review of event related potentials in relation to neurological pathophysiology can be found in Verleger (2003).

3.1. Slow Potentials

If you were told that once you heard a tone a picture would follow a few seconds later, you would notice a slow negative potential being generated once the tone sounded. This slow negative potential generally measured at the vertex is the contingent negative variation, or CNV. The CNV is generated in the laboratory by presenting a first or warning stimulus which signals that a second stimulus will follow in a specific time period. In most studies the second stimulus signals cognitive or task processing. Walter et al., (1964) described the CNV as an expectancy measure since the first stimulus suggests the second will follow.

Another form of event related potentials are very slow potentials which precede and accompany movement or other activities. If a person is asked to press a button as he or she wishes, it can be seen that as early as a second before movement begins, a recognizable EEG waveform starts to develop. A recording made with an electrode placed over the central areas of the cortex displays increasingly negative until, in the few milliseconds before a movement occurs, there is often a slight positive dip in the wave followed by a steep negative slope, which is terminated simultaneously with the beginning of the movement. The beginning of the movement is accompanied by a large positive deflection and a recovery to the original baseline. This complex of waveforms is not uniformly distributed. Technically, this slow increase in surface negativity is referred to as the *Bereitschaftspotential* (BP) or the *Readiness potential (RP)*.

The readiness potential is maximal at the vertex and initially equal in amplitude over both hemispheres of the brain. One research paradigm is to signal to the person which hand to use to make the movement. Prior to the movement, this potential begins to lateralize and becomes maximal over the motor cortex contralateral to the body part moved. Early speculation (e.g., Kutas and Donchin, 1980) suggested that this beginning of lateralization reflects the point in time at which the response side is determined (i.e., to move the left or right hand). Since the information contained within the RP includes non-motor processes as well as motor processes, researchers have suggested that by subtracting the response from one hemisphere from that of the opposite hemisphere, it would be possible to obtain a more pure measure of motoric preparation for a response. This measure has been referred to as the lateralized readiness potential (LRP) and has become an important tool in the study of the neural basis of human cognitive-motor processing. For example, the LRP has been shown to be related to preparations for differential rates of force development and that speeded tasks versus accuracy tasks show the largest LRPs (Ray et al., 2000).

To summarize, the development of this measure was based upon the assumption that the asymmetry of the RP could be used as an index for the preparation of specific motor acts. To eliminate any RP asymmetries that may contain activity lateralized with respect to nonmotoric processes, the LRP was calculated as the difference between recording sites contralateral and ipsilateral to the responding hand, averaged over left-and right-hand responses (see de

Jong, Wierda, Mulder & Mulder, 1988; Gratton, Coles, Sirevaag, Eriksen & Donchin, 1985; 1988 for alternative ways to calculate the LRP). The LRP's special significance in cognitive and sensorimotor research stems from the fact that this component offers a continuous analog measure of the differential engagement of the left versus right hand associated with cued or uncued voluntary reactions (see Hackley & Miller, 1995 for a review of this work).

The growing popularity of the LRP is due to the fact that its neuroanatomical and functional correlates are better understood than those of most other endogenous event-related potentials. Surface and depth recording indicate that the LRP is mainly generated by primary motor cortex. Moreover, the foreperiod LRP was found to be twice as large preceding complex movements (subjects were requested to press a sequence of three keys, using the index, ring and middle fingers) than preceding simple ones (only index finger keystroke was required). Also, it has been reported that lateralization tends to be larger preceding a short sequence (one press with the index finger) than preceding a longer sequence (three presses with the same finger). These and other studies support the hypothesis that lateralized preparatory activity in motor cortex varies with specific properties of the planned movement.

The event related potentials-including evoked responses, the readiness potentials, and CNVs are generally much smaller in amplitude than spontaneous EEGs and are therefore often not discernible in the raw or untreated record. In order to examine ERPs, special recording and data treatment procedures are necessary.

4. EEG RESEARCH ON VOLUNTARY MOVEMENT

4.1. Introduction

EEG work related to understanding human voluntary movement in a single task state has a fairly long, yet sporadic history. With the early work of Kornhuber and Deecke (1965) in Europe and Kutas and Donchin (1974) in the United States, there have been brief forays into examining human cortical patterns associated with movement in both time – movement-related cortical potentials, MRCP (Kristeva et al., 1990; Cooper et al., 1989; Lang et al., 1989) and frequency (Pfurtscheller & da Silva, 1999, for review) domains. In the following paragraphs, representative research concerning the sensitivity of EEG recordings towards experimental manipulations of movement parameters primarily in a single task state is briefly discussed.

4.2. Brain activation – movement kinematics relationship.

It is generally assumed that voluntary movement in a single task state is controlled by a limited number of variables (Bernstein, 1967; Enoka, 1983; Gordon

& Ghez, 1987). At the behavioral level of analysis, the major research interest has been the search for invariant properties that the central nervous system (CNS) uses to optimize movement production. Numerous studies in the area of motor control have evaluated the relative importance of amplitude or movement distance cues (Bock & Eckmiller, 1986; Nougier et al., 1996) and mechanisms involving interference of position and distance programming (Ghez, et al., 1995; Jaric, et al., 1992). Consistent with motor control findings, numerous electro-cortical studies suggested that a high correlation exists between movement kinematics (i.e. speed, amplitude etc.) and the amplitude of the cortical potentials preceding (Cooper et al., 1989) and accompanying a unilateral motor response (Grünewald & Grünewald-Zuberbier, 1983a, b). Further, Grünewald and Grünewald-Zuberbier (1983a) reported DC potential amplitudes to be higher before *ballistic* (brief and fast) than before *ramp* movements (slow and smooth). Using a LRP paradigm, we recently demonstrated that speeded tasks produced larger LRPs than accuracy tasks regardless of whether the movement type was discrete or repetitive (Ray et al., 2000).

The faster response rate (movement velocity) has been found to be proportionally related with mean amplitude of the DC shift along with early onset time while subjects performed a series of rhythmic bilateral finger movement tasks (Wallenstein et al., 1995). However, this relationship might be end-effector specific as was well-documented in more recent study (Slobounov et al., 2000e) where the amplitude of DC potentials along midline (Cz & Fz electrodes known to overlie approximately the mesial frontocentral cortex including the SMA (Steinmetz et al., 1989; Gerloff et al., 1998) were found to be inversely related with the amplitude of the wrist flexion movement.

In the frequency domain, it has been reported in numerous EEG studies that hand movement is accompanied by event-related desynchronization, a power decrease within the 10 Hz frequency band, preceding the movement (Pfurtscheller, 1981); *beta* (frequency below 30 Hz) desynchronization with movement and its dominance during immobility (Jasper & Penfield, 1949; Rougeul et al., 1979); *beta* bursts due to event-related synchronization in frequencies below 30 Hz after movement termination (Stancak & Pfurtscheller, 1995); oscillations with frequencies around 40 Hz, also known as the *gamma* rhythm, which is present shortly before and/or during movement (Basar et al., 1995; De France & Sheer, 1988; Salenius et al., 1996). Similar findings were obtained during direct cortical recordings taken from patients with implanted subdural electrodes during visually guided multi-joint arm movements (Toro et al., 1994). In specific, the amplitude of electrical oscillations generated over the rolandic cortex was correlated with the direction and amplitude of arm movements.

Within this line of research, we have reported recently that the amount of the *alpha* and *beta* pre-movement desynchronization as well as the dominant energy within these frequency clusters were found to be task and hand non-specific (Slobounov et al., 2000a). This finding is consistent with previous data from

Stancák and Pfurtscheller (1995) who reported a similar size event-related desynchronization (ERD) preceding both *fast* and *slow* movements whether one finger, all fingers or the wrist was moved. It appeared that both the dominant energy and the amount of movement-related power increase (synchronization) within 30-50 Hz frequency cluster over fronto-central areas were extremely sensitive to experimental manipulations of movement kinematics (i.e., amplitude and velocity of wrist flexion).

The regional activation of the fronto-central areas as revealed by task-related power increase within 30-50 Hz frequency cluster is an interesting finding that needs to be addressed systematically. In fact, numerous studies in humans have demonstrated regional cerebral blood flow (rCBF) changes within the primary motor cortex and SMA in response to different movement rate and/or movement velocity using fMRI (Schlaug et al., 1996; Wexler et al., 1997) or PET techniques (Turner et al., 1998; Jenkins et al., 1997). Moreover, the cortical population output correlates with direction of movement as confirmed by combined fMRI and EEG results. In specific, higher brain activation was observed during thumb extension rather than thumb flexion movement that may be a result of differential cortico-spinal projections to the motoneuron pools of extensor and flexor muscles (Yue et al., 2000).

Electrophysiological research on movement kinematics has been conducted on both human and animal levels. For example, a robust relationship has been reported between time dependent activity in the sensorimotor cortex and movement velocity, independent of explicit task requirements (cf. Kelso et al., 1998) suggesting important correlates between cognitive and neural phenomena in terms of dynamics (Bressler & Kelso, 2001). Other work has focused more on correlates of cortical single cell activation with hand kinematics in monkeys and patients with implanted subdural electrodes. For example, high fidelity neural representation of velocity was found in motor cortex of Rhesus monkey as evidenced by the dynamics of motor cortical activity during reaching and drawing tasks (Schwartz & Moran, 2000). In a series of early studies on monkeys using single cell activity recordings and neuronal population vector analysis (Georgopoulos et al., 1986), the effect of movement speed and movement direction during tasks involving tracing spirals was also well documented (Schwartz & Moran, 1999; Moran & Schwartz, 1999a & b). Moreover, the simple spatial and temporal relationship between cortical activity and finger trajectory was observed suggesting that the *figural* aspects of tracing tasks are major components of motor cortical activity. This observation is in agreement with a number of other studies suggesting that neuronal population activity in motor cortex does indeed specify a particular movement pattern (Georgopoulos et al., 1999) and is highly correlated with hand kinematics that afford unified control of posture and movement (Todorov, 2000). More recently, the differential contribution of Purkinje cells in cerebellum and in motor cortices in terms of representation of movement direction and speed was reported (Johnson & Ebner, 2000). In specific, it was found that Purkinje cells discharge encodes a combination of direction and speed, a "preferred velocity", while the motor cortical neurons use a temporal parcellation scheme to encode multiple parameters of movement. Thus, the cerebellum and motor cortical processes use kinematic information in a distinct way that may underlie the functional uniqueness of these two motor control structures.

4.3. Brain activation-kinetic (force level) relationships.

The study of the cortical mechanisms that provide the appropriate neural drive for producing various magnitudes of force output in peripheral musculature using surface EEG in human is a relatively recent research area. Originally studied by Kutas and Donchin (1974), interest in how electro-cortical patterns vary as function of force output in time (Kristeva et al., 1990) and frequency (Pfurtscheller & da Silva, 1999, for review) domains, has been recently re-examined. This re-examination becomes especially important when comparisons are made with ongoing work using higher mammalian models and subdural recordings with similar research questions (Hepp-Reymond et al., 1999; Muir & Lemon, 1983). A majority of subdural research indicates that a linear relationship exists between cell firing amplitude (also frequency, but less work, Wannier et al., 1991) and overall force output (Evarts, 1968; see also Ashe, 1997, for review). A few recent studies of regional blood flow in human, using fMRI and PET techniques consistently showed a higher activation of primary and supplementary motor areas as a function of nominal force (Dettmers et al., 1995) and movement rate (Schlaug et al., 1996). Consistent with these findings, it was originally reported that the amplitude of the DC potentials prior to ballistic isometric presses which require a larger force is higher than those which require a lower one (Kutas & Donchin, 1974). Other studies also report a positive correlation between the DC shift amplitude and force level (Wilke & Lansing, 1973; Hazemann et al., 1978; Becker & Kristeva, 1980).

Recently, the brain-movement relations under both nominal force output (Slobounov et al., 1999; Semionow et al., 2000) and rate of force development (Sommer et al., 1994; Slobounov et al., 1998; Slobounov & Ray 1998, Ray et al., 2000) and with various manipulations of end-effectors (Rearick & Slobounov, 2000; Slobounov et al., 2000d,) have been under rigorous re-examination. One of the major limitations in previous research examining the effects of force output on EEG potentials was the lack of control of the motor output. The problem is that changes in one movement parameter often lead to related changes in other movement parameters (Carlton & Newell, 1988). For example, manipulation of external load in a study by Kristeva et al. (1990) induced changes in not only kinetic variables (*torque*, rotational analog of force) but also changes in kinematic variables (e.g., movement time, range of motion, time-to-peak acceleration, movement velocity, acceleration duration, etc.). The concurrent changes in movement parameters makes the task of drawing empirical conclusions about which movement parameters are reflected in EEG components difficult. The findings from motor control studies suggest that it is the dynamic aspects of movement production rather than a single discrete variable such as movement amplitude or amount of force that reflect an invariant that is related to the organization of the response outcome (Carlton & Newell, 1988).

More careful control of dynamic aspects of movement has elicited several primary themes regarding the sensitivity of slow-modulating (Slobounov et al., 1999; Rearick & Slobounov, 2000) and frequency-related EEG characteristics (Pfurtscheller et al., 1998) towards manipulations of nominal force outputs. First, rate of force development (i.e., the rate of change of force over time), not absolute force per se appears to influence measures of DC potentials more robustly (Slobounov et al. 1998b). Second, under identical task conditions, the end-effector utilized differentially influences the amplitude of DC potentials (Slobounov et al, 2000e) and event-related desynchronization (Pfurtscheller et al., 1998). Lastly, depending on the force and the end-effectors utilized, even an inverse relationship between the magnitude of force output and overall cortical excitation as revealed by EEG can be elicited (Rearick & Slobounov, 2000).

Recent electro-cortical findings on brain-movement dynamics relationship are consistent with several subdural studies. In specific, it was reported that the relationship between cell activity of pyramidal tract neurons and force output is only monotonic over small portions of the functional force range, often with either nonlinearities existent in this association at both high and low force levels (Cheney & Fetz, 1980) or negative correlations between cell firing amplitude and force output (Maier et al., 1993). In addition, the slope of this relationship may vary relative to the end-effectors utilized of which there has been many used throughout the literature (see Ashe, 1997 for review). Moreover, it appears that cell types are not only sensitive to various manipulations in force output but are susceptible to the context within which behavioral output is required. Both a recent study by Hepp-Reymond and colleagues (1978) and other work by Fetz and Finocchio (1975) have illustrated this context-dependency of cell firing patterns associated with variations in task (force step and direction), color of cues and operant conditioning.

5. EEG BRAIN IMAGING TECHNIQUE

EEG and ERPs have a real value in determining the time course of a response since they reflect millisecond changes within the electrical activity of the cortex. However, knowing where EEG activity takes place on the scalp does not in turn give you certainty concerning where the activity originated in the brain. This is referred to as the inverse problem. The problem reflects the fact that given a distribution of EEG activity on the scalp, there a variety of possible distribution in the cortex that could lead to the same pattern of scalp activity. Other factors, such as the fact that electrical activity does not move uniformly through the brain and that there exists variation in the thickness of different individuals' skulls influencing how the brain's activity is distributed on the scalp also add to the problem.

5.1. Dipole Models

Moving a magnet under a piece of paper covered with iron filings results in changing patterns of the filings as the magnet is moved. A similar procedure occurs in relation to electrical activity generated within the brain. Such a procedure is called dipole modeling. Using computers, one determines what type of pattern on the scalp would be produced by different generators in the brain. The pattern generated by the computer could then be compared to actual recorded EEG data. The computer can continue to move the dipole within the imagined brain until the theoretical pattern of EEG matches the actual pattern of EEG activity. Although dipole modeling offers one way of determining localization of activity, there are better methods for determining more exact localization of processes in the cortex including structural techniques such as MEG, PET, and fMRI.

5.2. Other Brain Imaging Techniques

Magnetoencephalogram (MEG) uses a SQUID (Superconducting Quantum Interference Device) to detect the small magnetic field gradients exiting and entering the surface of the head that are produced when neurons are active. MEG signals are similar to EEG ones but have one important advantage. This advantage stems from the fact that magnetic fields are not distorted when they pass through the cortex and the skull which makes localization of sources more accurate than EEG. It should be noted that MEG is only sensitive to tangential activity which limits it to activity located in the sulci or cortical folds. In order to make a measurement, an individual simply places his or her head within the sensing device typically containing a large array of sensors which do not require physical contact with the head. Since measuring magnetic fields using MEG is a complex process requiring liquid helium which must be super-cooled 24 hours a day, the price of this system is expensive both to acquire and to maintain.

Positron emission tomography (PET) systems measure variations in cerebral blood flow that are correlated with brain activity. It is through blood flow that the brain obtains oxygen and glucose from which it gets its energy. By measuring changes in blood flow in different brain areas, it is possible to infer which areas of the brain are more or less active during particular tasks. Blood flow using PET is measured by injecting a tracer (a radioactive isotope) into the blood stream which is recorded by the PET scanner (a gamma ray detector). The general procedure is to make a measurement during a control task which is subtracted from the reading taken during an experimental task. Although it takes some time to make a PET reading which reduces its value in terms of temporal resolution, it is able to determine specific areas of the brain that are active during different types of processing. Since PET can measure almost any molecule that can be radioactively labeled, it can be used to answer specific questions about perfusion, metabolism, and neurotransmitter turnover. Some of PET's main disadvantages include expense, the need for a cyclotron to create radioactive agents, the injection of radioactive tracers which limit the number of experimental sessions that can be run for a given individual, and limited temporal resolution.

Like PET, functional magnetic resonance imaging (fMRI) is based on the fact that blood flow increases in active areas of the cortex. However, it uses a different technology from PET in that in fMRI local magnetic fields are measured in relation to an external magnet. Specifically, hemoglobin which carries oxygen in the bloodstream has different magnetic properties before and after oxygen is absorbed. Thus by measuring the ratio of hemoglobin with and without oxygen, the fMRI is able to map changes in cortical blood and infer neuronal activity. Although fMRI has the same temporal disadvantage as PET, it has a number of advantages including better spatial resolution and the ability to do repeated images on one individual.

CONCLUSION

The purpose of this chapter is to overview the electrical activity of the brain as measured by the EEG. EEG activity is described in terms of frequency bands including *alpha, beta, delta, theta* and *gamma.* Although EEG is generally reduced following head trauma, EEG delta has been shown to be particularly sensitive to trauma and pathology. In addition to measuring ongoing EEG activity, researchers have also examined time locked EEG segments in relation to particular stimuli. Cognitive as opposed to sensory evoked potential have been shown to be more influenced by cortical trauma. Finally, various EEG measures including slow wave potentials, event-related desynchronization, and lateral readiness potential were illustrated by describing studies that have focused on motor related activities. In other chapters in this book, the EEG will be examined in relation to mild traumatic brain injury (see Thatcher, this volume) and balance (Thompson this volume).

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