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EEG MEASURES OF CEREBRAL ASYMMETRY: CONCEPTUAL AND METHODOLOGICAL ISSUES

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An overview of the use of EEG to assess hemispheric differences in cognitive and affective processes is presented. Some of the advantages of using EEG to assess asymmetric hemispheric differences in the study of complex mental activity are described. Following this brief introduction, two conceptual issues which are central to studies of EEG asymmetries are introduced: (1) the distinction between hemispheric *specialization* and *activation*, and (2) the importance of *rostral-caudal* differences for the understanding of both specialization and activation. Three methodological issues in the use of EEG to assess hemispheric differences are then presented: (1) the use of asymmetry metrics, (2) muscle artifact, and (3) appropriate reference electrode location. Finally, some empirical examples of using EEG to assess affective and cognitive processes which illustrate these conceptual and methodological issues are described.

Keywords: cerebral asymmetry, EEG

The electroencephalogram (EEG) has been used to make inferences about asymmetrical processing (Lindsley, 1939; Travis and Knott, 1937) almost since the time that it was first reported in humans (Berger, 1929). These early reports were strikingly similar to modern research in the types of questions which were addressed. The primitive and cumbersome instrumentation which was available at this time was probably largely responsible for the sporadic use of EEG procedures during the mid 1900s. The availability of computer-based data acquisition and analysis systems has made the study of EEG much more feasible within the past 5-10 years.

The measurement of scalp-recorded brain electrical activity during behavioral tasks offers several unique advantages in the study of the neural concomitants of psychological processes. As a measure of regional brain activation, it is a noninvasive procedure and relatively inexpensive. Repeated testing poses no hazard for the subject. In contrast, other functional neuroimaging technologies involve the administration of radioisotopes which limit their use in human testing. Perhaps most importantly, the time resolution of the EEG is excellent. Changes in the amplitude and latency of brain electrical activity can be measured on the order of milliseconds. Information in the frequency domain can be obtained as frequently as every half second. This fine-grained temporal resolution will make the EEG irreplaceable for the study of the neural concomitants of certain cognitive and affective processes in humans for at least the foreseeable future.† Other methods

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†The only exception to this statement is magnetoencephalography which has the same time resolution as the EEG. This methodology is considerably less well-developed than the EEG, although it does offer great promise. Unfortunately, multichannel systems are not yet commercially available. See Beatty, Barth, Richer and Johnson (1986) for a discussion of this methodology.

for the assessment of regional brain activation such as cerebral blood flow or positron emission tomography (PET) have considerably coarser time resolutions. For example, a PET scan obtained with fluoro-deoxyglucose (FDG) represents the metabolic activity integrated over a duration of approximately 45 minutes. The temporal constraint in studies using emission computed tomography is a function of the half-life of the radioisotopes which are used. While the use of markers other than F^{18} in PET studies can potentially improve the time resolution, it is very unlikely that it will ever be within the same order of magnitude as the EEG.

Another advantage of using EEG methods to assess asymmetric hemispheric engagement is that it can be recorded during the performance of "ecologically valid" tasks. In other words, special constraints on task presentation need not necessarily be imposed as would occur with either event-related potential (ERP) methods or blood flow or metabolic methods. ERP methods require the presentation of brief discrete stimuli while with blood flow and metabolic methods, the data collection period cannot easily be restricted to the component of a task during which processing is occurring. The latter is a particularly noteworthy feature for studies of affective processing. With EEG, one can flag "critical periods" during which intense emotion is occurring by examining, for example, the epoch during which brief facial expressions appear. Only with the temporal resolution of measures of brain electrical activity can the data be restricted to those periods during which such brief expressions are present.

CONCEPTUAL ISSUES IN THE USE OF EEG TO ASSESS HEMISPHERIC ASYMMETRY

Hemispheric Specialization and Activation

A variety of terms has been used to describe differences in function between the hemispheres. Cerebral dominance, hemispheric asymmetry, hemispheric specialization, and hemispheric activation have all been used to refer to functional differences between the hemispheres. Often, these terms are used with very little precision. For example, if an investigator finds differences between two groups on a CVC dichotic listening measure, he/she might conclude that the groups differ in hemispheric specialization or cerebral dominance. It is not really possible to make clear sense of what these terms might refer to in this context. Differences between groups in dichotic performance may arise for a number of different reasons and unless additional information is provided, little can be said of a very specific nature about the differences. For example, it is possible that this hypothetical finding reflects differences between groups in activation asymmetry, not in hemispheric specialization. The two groups might both show left-sided specialization for the perception of CVC syllables as determined by sodium amytal testing. However, one group might show more tonic right-sided activation across tasks compared with the other group.

The two terms which have been used most widely and which do refer to identifiably different processes are hemispheric specialization and hemispheric activation. *Hemispheric Specialization* refers to the "preparedness" of a hemisphere to process a certain type of information, or to process information in a certain manner. In this sense, the posterior regions of the left hemisphere may be said to be specialized for processing information serially, while the corresponding regions of the right hemisphere may be described as being specialized for parallel processing

(Cohen, 1973).† Asymmetries in behavioral performance on dichotic listening and divided visual field studies may reflect differences between the hemispheres in their competence to engage in the processes required for successful task completion. Such differences between the hemispheres in specialization are usually not absolute. Some of the tasks for which one hemisphere may be said to be specialized may also be performed by the other hemisphere, albeit in a less accomplished fashion.

The differences between the hemispheres in specialization may take a variety of forms. For example, the hemispheres may differ in the speed with which they perform a particular task. In a divided visual field study of word identification, the left hemisphere (right visual field) may respond more quickly compared with the right hemisphere in the absence of any visual field differences in accuracy. Such data would imply that the hemispheres differ only in the speed with which they perform a particular task. Of course, in studies with normal subjects, it is also possible that the difference in speed of response is a function not of differences in the rate at which each hemisphere performs the task, but rather in interhemispheric transmission. According to this notion, only one hemisphere is involved in task performance in response to stimuli from *either* visual field. What produces the reaction time difference is the duration required to transfer the information from the hemisphere which received it to the hemisphere "prepared" to process that type of information. Definitive analyses of the significance of differences in response speed require the study of callosotomy patients in whom interhemispheric transfer can reasonly be said not to occur. A less direct approach to this problem might simply involve careful examination of the absolute magnitude of the time differences to ascertain that the difference which occurs is longer than that which conceivably could be produced by interhemispheric transfer time.

In addition to (or instead of) differences in speed, the hemispheres might also differ in the accuracy with which they perform a particular task. For example, in response to right-versus left-sided visual field presentations of verbal material, the hemispheres might not differ in the speed with which each responds, but rather in accuracy of responding. One hemipshere may simply be less adept at performing a particular task compared with the other hemisphere. Such differences are more easily interpreted than reaction time differences as being manifestations of *hemispheric specialization.*

Asymmetries in activation refers to the degree to which a hemisphere or a region within a hemisphere is differentially activated, i.e., is more or less activated than the homologous region on the other side. Activation is typically defined operationally on the basis of the methods used in a particular study to measure this construct. In general, all measures assume that increases in activation are associated with increases in neural activity—an increase in the number of depolarizing cells per unit time in large populations of neurons. In the case of EEG, it has been shown that desynchronized activity (which corresponds to the blocking of the alpha rhythm) is associated with an increase in the number of action potentials from neighboring populations of neurons (see Thatcher & John, 1977 for a review). It is not necessarily the case that differences in specialization are paralleled by differences in activation. For example, the left hemisphere may be specialized for a certain linguistic process in a particular individual although this hemisphere might not be

†It is important to note that dimensions of hemispheric specialization such as serial–parallel apply to particular regions within the hemispheres and not to the hemisphere as a whole. As I will argue later, there is probably no single unifying underlying dimension which could be said to characterize an entire hemisphere.

the more activated one during the occurrence of the target process. In other words, the subject in question may have a bias which results in accentuated activation of the right hemisphere across a wide variety of tasks. Presumably, this particular pattern of activation would not be optimal for the performance of the linguistic task although it might confer an advantage upon the individual in the execution of other tasks which are preferentially processed by the right hemisphere.

In her recent writings, Levy (e.g., 1983) has underscored the importance of asymmetries in activation and the pronounced individual variability in such biases which are found in the population. For example, she has suggested (Levy, 1983) that the diversity among dextrals in the magnitude and direction of asymmetries on behavioral measures of "cerebral lateralization" may reflect true variations in "patterns of asymmetric hemispheric arousal that were superimposed on a relatively invariant pattern of hemispheric specialization" (p. 476). Levy has highlighted the inconsistency between the percentage of subjects who would be expected to show lateralization of verbal processing to the left hemisphere and the percentage who actually show right field advantages for verbal material on dichotic and divided visual field tasks. She attributes this discrepancy to individual differences in asymmetric hemispheric arousal. EEG measures of activation asymmetry tend to be very stable within subjects over time. For example, Gasser, Bacher and Steinberg (1985) have found that the test–retest reliability of resting EEG measures of activation (based upon alpha power) over a 10-month period were in the .70s. Attention to the difference between specialization and activation has helped to make sense of both the behavioral and electrophysiological literature where findings on an individual subject basis (e.g., the number of subjects to show left-sided activation during the performance of a verbal task) are often discrepant with what would be expected on the basis of the known specialization of the hemispheres.

It is important to note that individual differences exist in both activation and specialization. Individual differences in the latter pertain to the degree to which each hemisphere is "prepared" to perform a particular type of task or to process information in a specific way. For example, some left-handed individuals have speech represented in the right hemisphere. Individual differences in specialization are often associated with handedness and/or other motor asymmetries which tend to be extemely stable over time. Individual differences in activation can exist among persons who all have the same pattern of specialization. Another way in which these concepts differ is that individual differences in activation predict performance on tasks which differentially require the engagement of the hemispheres, while individual differences in specialization are not necessarily related in such a straightforward manner to task performance. For example, a number of workers have reported that greater left-sided posterior activation at rest is correlated with increased performance on certain verbal tasks (e.g., Glass & Butler, 1977; Davidson, Taylor & Saron, 1979). On the same measures of verbal performance, it would be surprising to find differences between right- and left-handed subjects. There may be certain patterns of hemispheric specialization which are associated with bilateral representation of particular functions (e.g., in certain groups of left-handers) and which might confer an advantage (or disadvantage) for performance on tasks requiring the utilization of both types of processes. However, the nature of the relation between individual differences in specialization and patterns of task performance is complex and frequently is associated with the consequences of bilateral representation of certain functions which in some contexts might be advantageous, while in others may be disruptive. One example of the relation between individual differences in specialization and task performance is Levy's 1969; 1976) finding of impaired spatial ability among at least certain groups of left-handed subjects. These subjects are assumed to have bilateral representation of language which is hypothesized to result in competition between language and visuospatial skills within the right hemisphere. It is argued that this competition impairs performance on visuospatial tasks.

Discrepancies between activation and specialization need not arise only as a function of individual differences in the former which, in particular task contexts, are at odds with latter. A hemisphere may become selectively activated as a function of priming (e.g., Kinsbourne and Hiscock, 1983). For example, a number of workers have found that the use of letters which require identification as a fixation point in divided visual field studies can bias the performance asymmetries which are observed (see Bryden, 1982 for review). The letter identification task can presumably prime (activate) the left hemisphere which in turn facilitates performance on certain tasks and results in deteriorated performance on other tasks. Other parameters of task performance can also selectively activate a hemisphere. For example, a unimanual response requirement might serve selectively to activiate the hemisphere contralateral to the response. Just what the precise time course is of these priming induced changes in activation, is currently not well known.

When might measures of activation be used to make inferences about the specialization of the hemispheres for particular behavioral functions? We believe that activation measures can legitimately be used to assess specialization in certain restricted contexts. Testing must be performed on a sample assumed to be homogeneous with respect to individual differences in specialization. In other words, the sample should be restricted to members of one handedness group and possibly to one sex as well (to the extent that there might be sex differences in specialization). At least two tasks should be compared which are carefully matched on psychometric characteristics. This matching procedure is essential in order to eliminate any differences between tasks in difficulty level from affecting the Group × Task interaction. The comparison between tasks must be performed in a complete within-subjects design in order to eliminate any possibility that individual differences in activation asymmetry will affect the findings. This strategy assumes that task-dependent activation asymmetries will be sumperimposed upon individual differences in activation asymmetry so that by computing *differences* between tasks in asymmetry, baseline differences in activation asymmetry among subjects will be removed. This strategy is a reasonable one to the extent that large floor and ceiling effects are not a problem. However, if, for example, a particular subject is already close to his/her most extreme right-sided activation as measured by the EEG, the imposition of a task designed to activate the right hemisphere would presumably have little effect. The relation between baseline activation asymmetry and task-dependent activation asymmetry requires assessment in a large group of subjects. If task-dependent asymmetry is found to diminish among subjects who are at the extremes on baseline measures of asymmetry, these subjects can be removed. An alternative would be to attempt to remove the contributions of individual differences in baseline asymmetry using a regression-based approach.

Three aspects of hemispheric asymmetry which might influence task performance have been highlighted above. First is hemispheric specialization which refers to the differential competence of each hemisphere to perform a particular task or process. Then, there are individual differences in asymmetric hemispheric activation which reflect the degree to which each hemisphere is "engaged." These individual differences tend to be very stable over time. Finally, phasic differences in activation which are brought about by selective priming can be superimposed upon these more tonic features.

Rostral–Caudal Differences in Hemispheric Specialization and Activation

Research using a diverse array of methods has converged around the notion of differences in the functional nature of hemispheric specialization in anterior versus posterior cortical regions. Asymmetries in the anterior regions are more closely associated with affective processing, while those in posterior regions are more related to cognitive processing. For example, stimuli which differ in affective valence systematically influence activation asymmetries in frontal brain electrical activity in the absence of any influence on simultaneous measures of parietal asymmetry, while tasks which are designed differentially to require verbal versus visuospatial processing produce changes in parietal and temporal asymmetry in the absence of any modifications in frontal asymmetry (see Davidson, 1984 for a review of the relevant literature). Furthermore, individual differences in parietal activation asymmetry are correlated with biases in cognitive task performance (e.g., Davidson, Taylor & Saron, 1979); frontal asymmetry recorded from the same points in time are unrelated to task performance. Individual differences in frontal asymmetry are correlated with "affective style" (e.g., Schaffer, Davidson & Saron, 1983; Davidson & Fox, 1987); simultaneous recordings from the parietal regions fail to show any relation to affective behavior.

The data referred to above imply not only that the functional significance of hemispheric specialization difers in anterior and posterior cortical regions, but that activation asymmetries in these regions are relatively orthogonal. In other words, when the parietal region is showing left-sided activation, it is not necessarily the case that the frontal region would show a similar activation bias. If the asymmetry of activation patterns was highly correlated in these different regions, then frontal and parietal asymmetry would not show such differential associations with affective and cognitive behavior. In a recent study (Davidson & Tomarken, in preparation) of the stability of resting measures of EEG asymmetry, we found that the correlations between indices of frontal and parietal asymmetry taken from the identical points in time were low and nonsignificant (values ranging from −.30 to +.30). The functional significance of asymmetries in these regions seems to differ and the degree to which one hemisphere is relatively more activated than the other in the frontal region is relatively independent of activation asymmetry in the parietal region *at the same moment in time*. It should be noted in passing that the relation between activation asymmetries in these regions may differ in certain clinical populations (Davidson, Schaffer & Saron, 1985).

METHODOLOGICAL ISSUES IN EEG STUDIES OF CEREBRAL ASYMMETRY

Metrics of Asymmetry

Studies in which the EEG is used to provide a measure of asymmetric hemispheric engagement involve the recording of at least two channels of EEG from homologous locations on the two sides of the head. The EEG is amplified and then digitized in some fashion. Typically, measures of power in different frequency bands are computed and serve as the principal dependent measures. To summarize the direction and magnitude of asymmetry, investigators often compute an asymmetry index for homologous leads such as right- divided by left-hemisphere power or the difference in power between the hemispheres divided by the sum of the power (e.g., right—left/right + left). While providing a convenient description of the data, comparisons between conditions or groups should include, in addition to these asymmetry metrics, the raw hemisphere power.† For example, assume that in a particular study it was found that Group A exhibited a larger alpha ratio score (right—left/right + left alpha power) compared with Group B. This would be indicative of greater relative left-sided activation in the former compared with the latter group, since higher numbers on the ratio score could be produced by less alpha in the left hemisphere and/or more alpha in the right hemisphere, both of which are associated with more relative left-sided activation (less alpha is taken to be indicative of more activation). It would be theoretically significant, however, to know whether Group A had greater absolute left hemisphere activation or less right-sided activation compared with Group B. Answers to these questions require the analysis of the separate contributions of each hemisphere to the effect in question. If two groups were found to differ on the ratio score, we would expect to find a significant Group × Hemisphere interaction with an analysis of variance. Post-hoc paired comparisons can then be used to decompose the significant interaction and specify where the locus to the effect resides.

The strategy described above is particularly useful in studies of EEG asymmetries associated with affect. For example, we reported that depressed subjects differed from nondepressed subjects on a measure of resting frontal asymmetry (Schaffer, Davidson & Saron, 1983). Depressed subjects had a lower R—L/R + L alpha ratio score compared with nondepressed subjects. Some workers have interpreted our data as indicating that depressed subjects had greater right-sided frontal activation compared with nondepressed subjects. However, examination of the individual hemisphere data which were presented in the original report indicates that the difference between groups is principally in the left frontal region, with depressed subjects showing *less left frontal* activation (i.e., more alpha) compared with nondepressed subjects. The specification of the locus of the effect in this study is extremely important for theoretical reasons, since Robinson and his coworkers have reported that the severity of poststroke depressive symptoms among patients with lesions in the left hemisphere is highly correlated with the proximity of the lesion to the frontal pole as assessed by CT scan (Robinson et al., 1984). In other words, the most severe depressive symptoms were observed in patients with lesions in the left frontal region. Our electrophysiological data nicely complement these findings from brain-damaged subjects in indicating that functional depressive symptoms are most pronounced among subjects with *less* left frontal activation.

The computation of an asymmetry metric is most useful when relations between EEG asymmetry and behavior are assessed. In this case, a single index of asymmetry for a particular scalp region is required. Scores on this index are then correlated with the behavioral measure of interest. It is noteworthy that when relations are compared between asymmetry in alpha power and task performance

†In addition to the problem of masking the individual contributions of each hemisphere to the effect in question, another problem with some asymmetry metrics is their nonlinear and nonsymmetric properties. The reader interested in a general discussion of this issue should consult Bryden (1982).

thought to be hemispheric-specific versus absolute alpha power and the same indices of performance, invariably the asymmetry index accounts for a greater proportion of variance in behavioral task performance compared with absolute alpha power (e.g., Davidson, Taylor & Saron, 1979). Such findings suggest that at least for certain types of task performance, small *differences* in the balance of activation between the hemispheres are more significant for behavior compared with overall levels of activation.

Artifact

It might appear initially surprising to include a special section on artifact in this discussion since the elimination of epochs confounded by artifact would appear to be relatively straightforward. However, when EEG *asymmetry* is the primary focus of a study, several less obvious issues gain in importance and should be carefully addressed. Much has already been written on eye movement artifact (e.g., Gasser, Sroka & Mocks, 1985; Gevins, Yeager, Zeitlin, Ancoli & Dedon, 1977; Girton & Kamiya, 1973) and consequently little will be said about this here. For the purpose of the present discussion, it should simply be noted that frontal recordings are particularly susceptible to eye movement artifact. Blinks are readily observable in frontal EEG recordings and can easily be eliminated. Slow eye movements are sometimes considerably more difficult to detect in the raw EEG and should be examined with direct electrooculographic (EOG) recordings. Artifact from such slow eye movements will particularly influence power in the low frequency bands (delta and theta). Whether eye movement artifact can asymmetrically affect the EEG is not well known at present.

Less easily treated is muscle artifact. Although muscle activity contains energy in frequencies above the EEG, it cannot be easily filtered to prevent its intrusion into the traditional EEG frequency bands. This is due to the fact that the frequency spectrum of EMG is very broad and power can be detected at frequencies as low as 10 Hz. While filtering the EEG with a low-pass filter set, for example, at 40 Hz will eliminate most EMG activity, it will not affect EMG activity at the EEG frequencies in the alpha and beta band range. This problem is particularly important in EEG studies of affect where movement is likely to occur. We (e.g., Davidson, Ekman, Saron & Friesen, in preparation) and others (e.g., Ekman, Levenson & Frieson, 1983) have been studying physiological activity during the spontaneous generation of facial expressions of emotion. These expressions are brief in duration and are often associated with considerable muscle activity. Particularly disturbing for studies of EEG asymmetries associated with emotion are reports of asymmetries in facial expressions of certain emotions (e.g., Hager & Ekman, 1985; Schwartz, Ahern & Brown, 1979). These asymmetries have been detected with both visual scoring techniques and facial EMG methods (see Fridlund & Izard, 1983 for a review). The presence of such facial asymmetries raises the possibility of asymmetries in muscle artifact which can bias EEG measures of asymmetry. In our experience, muscle artifact is more severe in the beta frequency range. In studies which involve the elicitation of actual emotion, the presence of muscle artifact is sufficiently likely in certain scalp locations (e.g., temporal leads) as to make meaningful assessment of beta almost impossible. Beta asymmetries should only be seriously examined when elaborate precautions have been taken to extract the muscle activity component from the EEG. In our laboratory, we sample the EEG at 250 Hz and compute power density in a high frequency band (70–80 Hz) which does not contain any neurogenic activity and is presumably a function of muscle activity exclusively. We can then eliminate any epoch associated with power in this high frequency band. If, because of the particular paradigm used, an excessive number of epochs occurs which contain high frequency power, we can use this information to estimate the influence of muscle activity in the traditional EEG bands and residualize the EEG band power data to remove the EMG contribution. Unless such elaborate procedures have been implemented and in light of the by now extensive literature on asymmetries in facial signs of emotion, it would be most prudent to regard with considerable caution any reports of beta EEG asymmetries associated with emotion (e.g., Ray & Cole, 1985), particularly when recorded from the temporal leads which are very prone to muscle activity at the outset.

Reference Electrode Location

The recording of EEG involves the measurement of the potential difference between two electrodes. Often, scalp leads are referred to a noncephalic site which is considered relatively inactive. In actual fact, no site on the body is truly inactive (see Nunez, 1981 for review). One common site which is used as a reference in EEG studies of cerebral asymmetry is the linked ears or the linked mastoids. The rationale for linking the two sides together is to provide a common reference for electrodes on both sides of the scalp. Unfortunately, this practice has been criticized by Nunez (1981) because it provides a low-resistive shunt across the head and forces the two sides toward the same voltage, thus attenuating the magnitude of asymmetry. Empirically, a number of investigators have reported a decreased magnitude of task-dependent asymmetry with linked ears or mastoids compared with other references (e.g., Davidson, Taylor, Saron & Stenger, 1980; Kutas & Neville, 1986). Another popular reference has been the vertex. Investigators assumed that since the reference was common to all lateral leads, any differences between the left and right sides were a function of changes at the lateral sites. Unfortunately, the problem is more complex. It can be shown that if the vertex changes and the lateral sites remain constant, the result can be a change in the magnitude of asymmetry between the two sides.

There are several potential solutions to the reference electrode problem. The use of newer mathematical procedures for source localization of brain electrical activity based upon the Laplacian operator and other similar techniques offer considerable promise in improving the spatial resolution of the EEG and avoiding many of the problems of conventional recording montages (e.g., Hjorth, 1975; Kavanagh, Darcey, Lehmann & Fender, 1981). The Laplacian procedure is a true reference-free data analytic technique. It is reference-free in the sense that the output of the Laplacian transform does not depend upon the specific reference montage used in the initial recording of the data. This type of procedure acts to decrease the correlation between adjacent pairs of electrodes and thus highlights the unique contribution of each electrode site to the overall pattern of brain activity observed across the scalp. If conventional recording procedures are preferred or are required because too few channels are recorded for source localization computations to be performed, we have utilized the following procedure in an attempt to circumvent the problems noted above in connection with the use of a linked ears or mastoids reference. We record each of our scalp leads referenced to Cz. We also record two additional channels: Cz referenced to the left ear (A1) and Cz referenced to the right ear (A2). We then average these channels in the computer and derive a new montage of all scalp leads referenced to the computer-averaged A1–A2 reference. In this way, we can achieve what is desired with the use of a linked ears reference avoiding the problems associated with an electrical link between the ears. However, we must note that data are not yet available which directly compare physical linking of the ears to computer-derived linked ears.

SOME EMPIRICAL EXAMPLES

Rostral-Caudal Differences in EEG Asymmetry

We have conducted a number of studies in which EEG was recorded from the frontal and parietal regions while subjects were exposed to either affective or cognitive challenges. Taken together, these studies suggest that frontal asymmetries are more closely related to affective experience while parietal asymmetries are more affected by cognitive demands. For example, in one of the first studies designed to evaluate anterior and posterior EEG asymmetries associated with differential affective responding, Davidson et al. (1979) exposed 16 right-handed subjects to videotaped segments of popular television programs which differed in affective content. Subjects were instructed to continuously rate the degree to which they experienced positive and negative affect by pressing up or down on a pressure sensitive gauge whose output was quantified. EEG was recorded from the left and right frontal and parietal scalp regions referred to a common vertex. Activity in the alpha band was extracted from the EEG, integrated and digitized. To test the major hypothesis of the study, the 30 second epoch each subject judged to be most positive was compared with the one rated as most negative on measures of frontal and parietal asymmetry. We initially compared these epochs on a laterality ratio score (R − L/R + L alpha power). We found that the positive epochs were associated with significantly higher frontal ratio scores, indicative of greater left-sided activation compared with the negative epochs. Importantly, parietal asymmetry extracted from the same points in time failed to differentiate between the positive and negative conditions. Right-sided parietal activation was present during both positive and negative conditions. Examination of the data from the individual hemispheres indicated that the negative epochs were associated with less right, and more left, frontal alpha compared with positive epochs.

More recently, we have attempted to specify with more precision the essential difference in affective behavior controlled by the left and right frontal regions. In order to do this, we (Davidson, Ekman, Saron & Friesen, 1987) presented a series of positive and negative emotional film clips to subjects while we recorded EEG and simultaneously videotaped their facial behavior unobtrusively. The films were selected to produce positive and negative emotions—happiness and disgust—associated with approach and withdrawal respectively. The subjects' facial behavior was coded in response to the films and epochs during which facial signs of happiness and disgust were present were flagged. Artifact-free EEG during these expressions was extracted for analysis. As we predicted, facial signs of disgust were associated with right frontal activation compared with facial expressions of happiness. No difference between these emotional conditions was found in parietal EEG extracted during the identical points in time. When the individual hemisphere data were examined, the largest difference between conditions was at the right frontal lead where disgust expressions were associated with significantly less alpha power compared with happy expressions. These findings are consistent with the view that disgust, an emotion associated with behavioral signs of withdrawal, is associated with greater absolute right frontal activation compared with happiness.

The findings described above underscore the importance of asymmetries in the frontal region for affect and demonstrate the specificity of this association. Simultaneous recording from the parietal region show no difference between affect conditions. In none of our studies with adults have we found reliable differences in parietal EEG asymmetry which discriminated between conditions differing in valence.

Asymmetries in posterior brain regions appear to be more related to the nature of the cognitive demands placed on the subject. In a large number of experiments using a variety of different task manipulations we have reported that verbal tasks produce greater left-sided parietal activation compared to spatial tasks (see Davidson, 1983 for a review). This difference appears to be unrelated to the motor requirements of the task and occurs when the tasks are very carefully matched on difficulty level, motor demands and internal consistency (Davidson, Chapman & Chapman, 1987). Importantly, recordings of frontal EEG from the same points in time fail to differentiate consistently between verbal and spatial tasks (e.g., Davidson et al., 1980; Davidson, Chapman & Chapman, 1987). These latter findings indicate that verbal and spatial cognitive tasks systematically influence parietal EEG asymmetry, but simultaneous recordings of frontal asymmetry are not reliably affected by such cognitive requirements.

Individual Differences in Activation Asymmetry: Relation to Affective Style

A number of workers have reported that individual differences in measures of resting posterior EEG asymmetry reliably predict performance differences on verbal and spatial cognitive tasks (e.g., Davidson et al., 1979; Furst, 1976; Glass & Butler, 1977). For example, in two separate studies ($N=18$ and $N=27$) we found that the greater the right parietal activation during the rest the better the performance on the Group Embedded Figures Task ($r=.47$ for Study I and .35 for Study II) (Davidson et al., 1979; Davidson et al., 1980). We also found resting parietal asymmetry to predict performance on other measures of spatial cognition, such as a face recognition task ($r=.41$; Davidson et al., 1979) and the Kohs Block Design Task ($r=.43$; Davidson et al., 1980). Conversely, the greater the left parietal activation at rest, the better the performance on a word recognition task ($r=.58$; Davidson et al., 1979). Similar findings have been obtained in studies assessing the cognitive correlates of cerebral blood flow (e.g., Dabbs & Chou, 1980; Gur & Reivich, 1980). As was indicated above, in some of our own studies of relations between posterior asymmetries and cognitive performance, we also recorded frontal EEG and found that asymmetries in this region were not related to the cognitive requirements of the task.

The evidence that stable individual differences in resting posterior brain activation are related to features of cognitive style raises the possibility that individual differences in frontal EEG asymmetry are related to "affective style." If, as described above, frontal asysmmetries are linked to selective processing of positive and negative affective cues, individual differences in these asymmetries may index enduring predispositions for such selective biases.

In our first attempt to explore relations between resting frontal asymmetries and individual differences in emotion (Schaffer, Davidson & Saron, 1983), we selected subjects on the basis of extreme scores on the Beck Depression Inventory (BDI). To be selected for participation, depressed subjects had to report significant depression on both a BDI administered at the beginning of the semester and on a trait version of the BDI administered eight weeks later, at the beginning of the experimental session. Similar criteria were used for the selection of nondepressed subjects. Thus, we explicitly chose subjects whose affective state was stable over time.

We compared depressed and nondepressed subjects on frontal and parietal activation asymmetries during resting eyes-closed baselines. These were recorded before and after a series of experimental tasks which lasted approximately 2 hours. Analyses of EEG alpha power during baselines revealed that frontal asymmetry discriminated between the depressed and nondepressed groups. Specifically, depressed subjects showed greater relative right-sided frontal activation compared with the nondepressed subjects. Figure 1 displays frontal laterality ratio scores (R−L/R + L alpha power) for individual depressed and nondepressed subjects. Parietal asymmetry recorded from the same points in time failed to discriminate between groups.

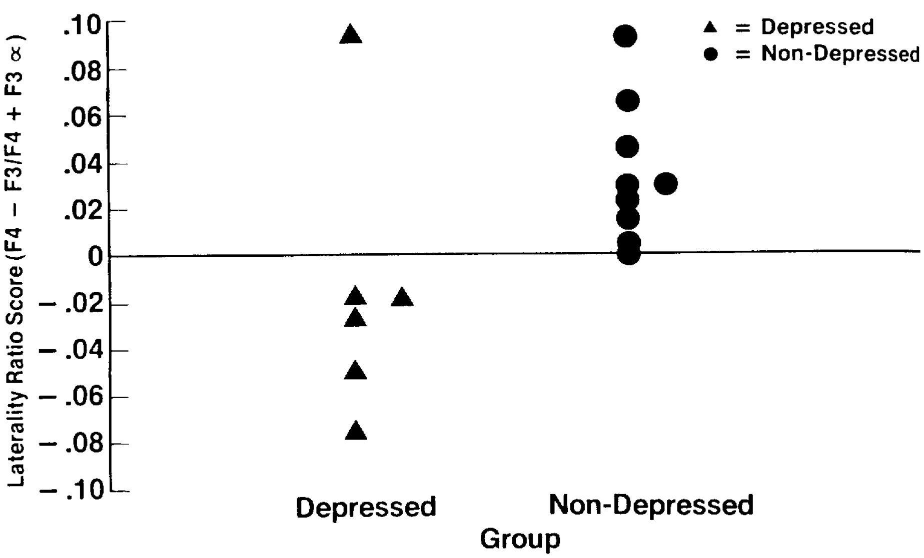

FIGURE 1 Frontal laterality ratio scores (R—L/R + L alpha) for individual subjects split by group. Positive numbers on this score are indicative of left-sided frontal activation while negative numbers are indicative of right-sided frontal activation. From Schaffer, Davidson and Saron (1983).

When we examined the separate right and left frontal leads to determine which hemisphere was contributing most to the group difference, we found that the largest difference was in the left frontal region, with depressed subjects showing less left frontal activation than nondepressed subjects. These findings correspond closely with the brain damage evidence reported by Robinson and his colleagues (e.g., Robinson et al., 1984). Robinson's data indicate that the most extreme depressive symptoms were found among patients with lesions in the left frontal region. Just as Robinson's data highlight the importance of the frontal region, our findings underscore the specific relationship between frontal asymmetry and

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individual differences in emotion. Yet, it should be emphasized that several questions are left unanswered by the Schaffer et al. study. In particular, the temporal and causal relationship between resting frontal asymmetry and depression is left unclear. If anterior asymmetry can predate the onset of depression, it may represent a risk factor predicting the occurrence of dysphoria given the co-occurrence of as yet unspecified additional factors.

That resting frontal asymmetry can indeed predate and predict emotional responding is more convincingly demonstrated by a second study recently conducted in our laboratory (Davidson, in preparation). In this study, EEG was recorded from P3, P4, F3 and F4 during an eyes-open 30 second baseline period in a sample of 22 normal right-handed female subjects. Following this baseline period, subjects were exposed to several emotional film clips designed to elict negative affect. Following each film clip, subjects reported their emotional responses to the film on several rating scales. Baseline EEG was Fourier transformed and power density on the alpha band (8–13 Hz) was computed. Log difference scores were then derived to provide a single metric of asymmetry.†

Analyses revealed that greater relative right frontal activation during rest was significantly correlated with increased intensity of fear in response to films designed to elicit negative affect. This pattern was present in response to each of the two negative films which were presented ($rs = .47$ and $.42$ for each of the two films). Parietal asymmetry from the same points in time was unrelated to subject's rating of emotional intensity ($rs = .16$ for both films).

In addition to assessing self-reported emotion following each of the film clips, we also assessed subjects' emotional experience following resting baselines in order to determine if resting asymmetries are related to spontaneous emotion during the baseline periods themselves. Importantly, we found that resting activation asymmetry was unrelated to emotion reported during the baseline period. Thus, those subjects who showed heightened right frontal activation during baselines were not simply in a dysphoric mood when they arrived for the experiment. These findings suggest that the presence of right frontal activation is not itself sufficient to index the presence of a negative affective state. Rather, right frontal activation may be necessary but not sufficient for the experience of negative emotion. Its presence may mark a vulnerability for negative affect, given an appropriate elicitor.

In a third recent experiment pointing to similar conclusions, we have assessed the relation between resting frontal asymmetries and affective behavior in infants (Davidson & Fox, 1987). Resting EEG was recorded from the left and right frontal and parietal scalp regions for a 30 second period from 19 normal 10-month-old infants (all born to two right-handed parents). The mother was present in the room during the baseline measurement. Following this period, two standardized approach sequences were presented. In the first, a stranger approach the infant (with mother present) and in the second the mother approached the infant (with the stranger absent). Following the mother approach sequence, the mother was instructed to turn around and leave the room. The duration of this period was 60 s unless the infant was judged by the experimenter to be extremely upset, at which

†The log difference score used here is equivalent to the laterality ratio score (R–L/R + L) discussed earlier. We use the log difference score because all of our data are now expressed in units of power or power density since they are based upon the output of a Fourier transform. Because power values are expressed in units of voltage squared, the distributions tend to be skewed and the data are typically log transformed to normalize the distributions. The difference is the log power values is virtually equivalent to the ratio score based upon the raw voltages. We have empirically examined the correlation between these two metrics of asymmetry and have found them to be consistently in the .90s.

time the trial was terminated by having the mother re-enter the room and comfort her baby. The infant was videotaped during all periods of the experiment.

In response to the maternal separation period, we coded the presence or absence of crying. Of the 14 infants with usable EEG during the baseline period (five infants were eliminated because of excessive movement artifact), 7 were coded as criers and 7 as noncriers. We then examined EEG during the baseline period to determine whether the infants who subsequently cried in response to maternal separation could be discriminated electrophysiologically from those who did not. Power density (in $\mu V^2/Hz$) was computed for each frequency in 1-Hz bins from 7 to 9 Hz since the majority of power contained in the spectrum for this age group was between these frequencies. Power values were then log-transformed to normalize distribution.

A multivariate analysis of variance (MANOVA) with Region (frontal–parietal) and Hemisphere (left–right) as repeated factors and Group (crier–noncrier) as a between-groups factor was computed, with log power in the 7-, 8-, and 9-Hz bins as the multiple dependent measures. A significant triple-order interaction was obtained [$F(3, 8) = 4.58$, $p < .05$]. Subsequent univariate ANOVAs computed on each of the three frequency bands revealed that the triple interaction was significant for 8-Hz power [$F(1, 10) = 9.74$, $p = .01$]. Two-way ANOVAs computed on the frontal and parietal data separately revealed a significant Group × Hemisphere effect only for the frontal region [$F(1, 12) = 6.08$, $p < .05$]. Table 1 presents the power densities (at 8 Hz) for the left and right frontal leads, separately for the criers and noncriers. As can be seen from this table, during baselines, criers showed more power in the left (i.e., less activation) and less power in the right frontal lead compared with non-criers. Paired post-hoc comparisons (Neuman–Keuls) indicate that the difference between groups is significant only in the left frontal region ($p < .05$). Noncriers showed more left frontal activation (i.e., less power) compared with criers. In addition, criers showed significantly more right compared with left frontal activation (i.e., less power in the 8 Hz band) ($p < .02$) while the noncriers showed a nonsignificant effect in the opposite direction.

TABLE 1
Power density in the 8 Hz band (in $\mu V^2/Hz$) for the left and right frontal leads during the baseline period for the criers ($N = 7$) and noncriers ($N = 7$) from Davidson and Fox (1987)

Group		*Left*	*Right*
Criers	*M*	6.78	2.54
	SD	3.83	1.22
Noncriers	*M*	3.55	4.85
	SD	1.77	2.99

As would be expected, similar results were obtained when a laterality difference score (log right power–log left power) was computed from the 8 Hz power data for each subject, separately for each region. A Group × Region ANOVA on this measure yielded a significant two-way interaction, $F(1, 12) = 6.21$, $p < .05$, which is graphically displayed in Figure 2. As this figure indicates, the difference between groups is in the frontal region only ($p < .01$), with no differences in parietal recordings. Also noteworthy is the magnitude of the group difference in the frontal

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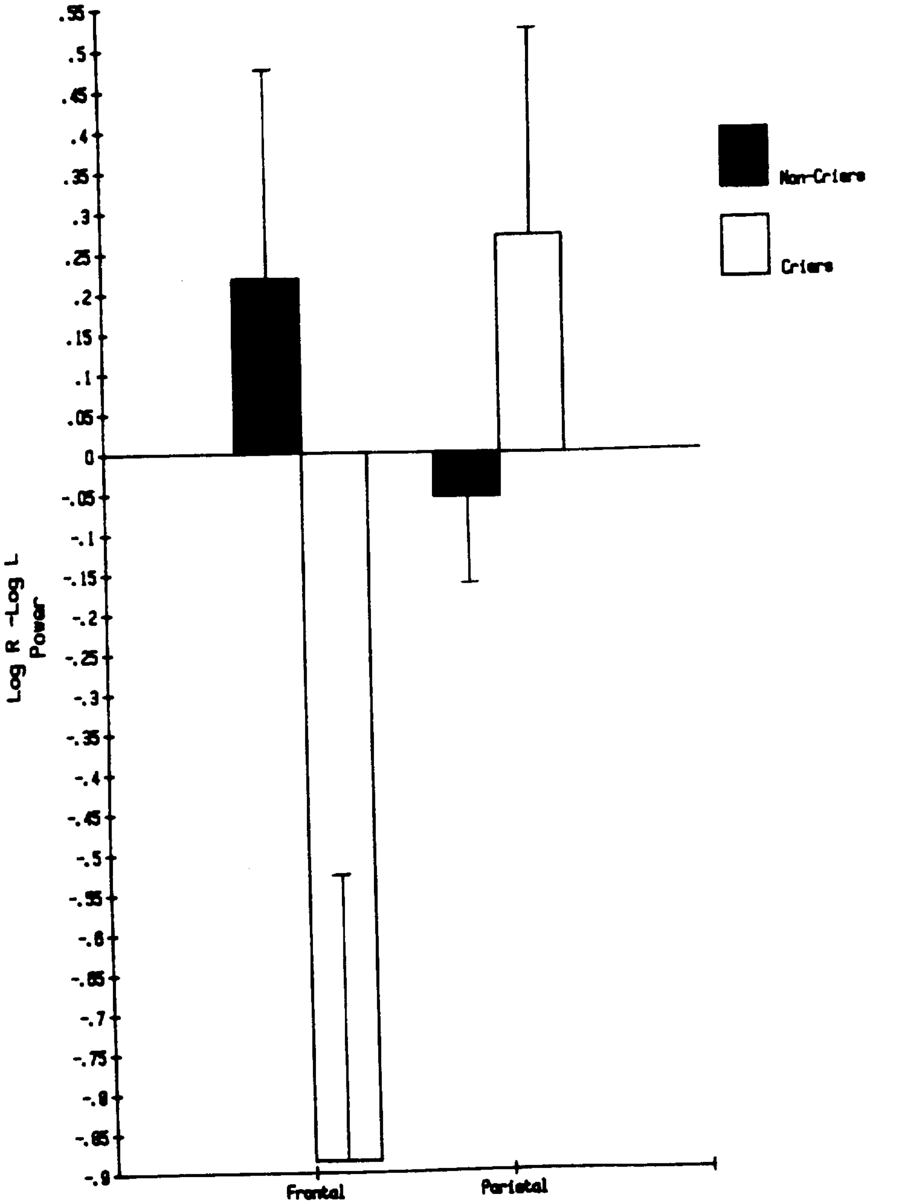

FIGURE 2 Laterality difference scores (log right–log left power) for the 8 Hz band, separately for frontal and parietal electrode locations, for criers ($N=7$) and noncriers ($N=7$). Higher numbers are indicative of greater left-sided activation. From Davidson and Fox (1987).

region. Specifically, six of the seven criers had a frontal difference score which was below the mean for the noncriers and all seven of the noncriers had frontal difference scores which were above the mean for the criers. These findings indicate that infants' affective responses to separation can be predicted from baseline frontal activation asymmetry. Those infants who showed less left-sided frontal activation during rest were more likely to cry upon maternal separation. Of the 7 infants who cried in this situation, only one did not show absolute right frontal activation during the baseline period (i.e., more 8 Hz power in the left versus right frontal lead).

The facial behavior of the infants during the baseline period was also coded in order to ascertain whether subjects who subsequently cried in response to maternal separation were simply experiencing dysphoria before exposure to maternal separation. Since self-report data are obviously unavailable from infants, we coded facial behavior from videotape as an index of emotional reactivity. Table 2 presents the data on the duration of different emotion expressions during the baseline period produced by infants who subsequently cried or did not cry in response to maternal separation. As can be seen from this table, there were no differences in the incidence of any of the baseline emotion expressions between criers and noncriers.

TABLE 2
Mean duration in seconds of facial affect for criers ($N = 7$) and noncriers ($N = 7$) during the baseline period. The no expression category represents the mean number of seconds during which no facial signs of emotion were present. The negative affect category represents the mean number of seconds during which facial signs of any of the negative emotions (anger, fear, distress, sadness and disgust) were expressed. From Davidson and Fox (1987)

		Criers	*Noncriers*
Interest	*M*	12.0	11.3
	SD	9.4	7.8
No expression	*M*	19.0	15.1
	SD	6.4	8.9
Joy/Surprise	*M*	3.4	3.2
	SD	4.0	3.2
Negative affect	*M*	1.5	1.4
	SD	1.1	1.3

The finding of no behavioral differences in affect between criers and noncriers during the baseline period has important implications. It suggests that the frontal EEG asymmetry observed during this period might best be viewed as a state-independent marker of vulnerability to respond with negative affect in stressful situations. In this respect, the results and conclusions of this experiment are congruent with those of our previously cited study using adult subjects (Davidson, in preparation). In that study, resting frontal asymmetries similarly predicted subsequent affective responses to a stressful stimulus (fear-provoking film clips) although EEG during the baseline period was unrelated to concurrent self-reports of mood.

SUMMARY AND CONCLUSIONS

Several conceptual and methodological issues central to EEG studies of cerebral asymmetry were reviewed. The paper began by making a distinction between hemispheric specialization and activation. Specialization refers to the preparedness of a hemisphere to process information of a specific type (e.g., verbal or spatial) or in a particular manner. Activation refers to the degree to which a particular hemisphere is working or engaged. Dissociations between these two aspects of cerebral asymmetry are common. The hemisphere specialized to process a particular stimulus is not necessarily the one most activated. A second critical conceptual issue addressed at several points is the importance of rostral–caudal differences in both specialization and activation. The functional significance of cerebral asymmetry differs in the anterior and posterior cortical regions. Asymmetries in the frontal region are more closely associated with affective processing, while asymmetries in posterior regions are more related to the nature of the cognitive requirements of a task. Activation asymmetries in these different regions are not highly correlated and are sometimes even inversely correlated. Therefore, it makes little sense to talk of a whole hemisphere being activated or specialized for a particular function.

Three methodological problems in the use of EEG to assess asymmetric hemispheric activation were described. These included the use of metrics of asymmetry, the problem of muscle and other forms of artifact, and the choice of reference electrode location. A number of solutions to each of these methodological problems was described.

Finally, the paper concluded with the provision of several examples chosen to illustrate some of the conceptual and methodological points described above. The differential effects of positive and negative affective arousal on frontal versus parietal EEG asymmetry were noted. Manipulations of emotion systematically affected asymmetries in the frontal leads, in the absence of any reliable effects in parietal asymmetry at the identical points in time. Conversely, data were described which illustrated the effects of cognitive task demands on parietal asymmetry in the absence of any effects on frontal recordings at the same moments in time. These data underscore the importance of rostral–caudal differences in cerebral asymmetry.

Data were also presented on individual differences in resting EEG asymmetry and their relation to affective and cognitive behavior. It was first noted that individual differences in resting EEG asymmetries are stable over time. These stable individual differences are related to a variety of important trait-like characteristics. Individual differences in parietal asymmetry are related to patterns of cognitive strength and weakness. The greater the right-sided parietal activation at rest, the better the performance on measures of spatial cognition and face recognition. Conversely, greater left-sided resting asymmetry is associated with better performance on a word recognition task. Invdividual differences in frontal asymmetry are unrelated to these cognitive patterns. However, differences in frontal asymmetry are related to affective style. Subjects who report more depression show more relative right-sided frontal activation during rest compared with normal subjects. Subjects who show more right-sided activation during rest report heightened intensities of fear and disgust in response to negative films designed to elicit these emotions. Taken together, these findings underscore the importance of anterior–posterior differences in EEG measures of hemispheric activation and highlight the significance of individual differences in regional patterns of asymmetric activation.

Although the complexity of the EEG is difficult to overstate, the advantages of its use as a noninvasive and temporally fine-grained measure of regional hemispheric activation are considerable. Very little of the extant research on cerebral asymmetries has made full use of the capabilities of the EEG to provide information which is temporally precise and regionally specific. We have much to look forward to in the years ahead using the EEG in this way.

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