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Asymmetrical Brain Electrical Activity Discriminates Between Psychometrically-Matched Verbal and Spatial Cognitive Tasks

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ABSTRACT

This study compared the asymmetry of different features of brain electrical activity during the performance of a verbal task (word finding) and a spatial task (dot localization) that had been carefully matched on psychometric properties and accompanying motor activity. Nineteen right-handed subjects were tested. EEG was recorded from F_3, F_4, C_3, C_4, P_3, and P_4, referred to both C_Z and computer-derived averaged-ears references, and Fourier transformed. Power in the delta, theta, alpha, and beta bands was computed. There were significant Task × Hemisphere effects in all bands for C_Z-referenced data and for the alpha and beta bands for ears-referenced data. The effects were always either greater power suppression in the hemisphere putatively most engaged in task processing or greater power in the opposite hemisphere. Correlations between EEG and task performance indicated that C_Z-referenced parietal alpha asymmetry accounted for the most variance in verbal task performance. Power within individual hemispheres or across hemispheres was unrelated to task performance. The findings indicate robust differences in asymmetrical brain physiology that are produced by well-matched verbal and spatial cognitive tasks.

DESCRIPTORS: EEG power, Brain asymmetry, Cognitive tasks, Lateralization.

There is a long tradition of research on EEG correlates of putative "right" and "left" hemisphere cognitive tasks. Although such studies date back to the late 1930's and early 1940's (e.g., Knott & Tjossem, 1943; Travis & Knott, 1937), modern research in this area can be traced to the 1972 paper of Galin and Ornstein. In that study, the investigators compared several putative right and left hemisphere tasks on the asymmetry of whole band power recorded during task performance. No attempt was made to match the tasks on either performance-related or motor requirements. The importance of matching tasks on these dimensions in studies of EEG asymmetry has been noted by Donchin, Kutas, and McCarthy (1977) and by Gevins (Gevins, 1983; Gevins et al., 1979). Gevins argued that many of the asymmetries in brain electrical activity that have been reported may be artifacts of motor and/or performance-related differences between tasks. He showed that under certain circumstances, when these artifacts were removed, EEG differences between tasks were greatly reduced. Although matching "left" and "right" hemisphere tasks on motor requirements is now routinely performed, comparatively less attention has been directed to matching tasks on basic psychometric properties that index the task's cognitive demands as measured by difficulty level.

EEG activation has been shown to relate to task demands as measured by difficulty level (e.g., Lindsley & Wicke, 1974). If the task demands of a left-hemisphere and a right-hemisphere task should differ, one task might yield a difference in activation between the two hemispheres, but not the other. Donchin et al. (1977) reported that increasing cognitive demands accentuate lateral asymmetries in contingent negative variation. Other investigators have reported a similar relation for EEG measures

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of activation asymmetry within certain ranges of task difficulty (e.g., Earle, 1985; Galin, Johnstone, & Herron, 1978).

The tasks should be matched not only for the average subject, but also for both the less able and more able subjects because otherwise the EEG activation of some subjects may be affected differentially for the two tasks. Chapman and Chapman (1973) pointed out that such equivalence of difficulty for subjects at all ability levels requires pairs of tasks that are matched in the manner of psychometrically parallel tests, with the exception of their differing item content. That is, the tests should be matched on mean and variance of test score, on the coefficient-alpha estimate of reliability, on the standard deviation of item difficulty, and on the shape of the distribution of item difficulty.

One aim of this study was to examine EEG asymmetries during the performance of psychometrically matched verbal and spatial tasks. A second aim of this study was to use such tasks, in response to which reliable measures of performance can be obtained, to examine which metrics of EEG asymmetry account for the most variance in task performance. Most studies of EEG asymmetry in response to cognitive tasks have examined asymmetries in alpha band activity (e.g., Davidson & Schwartz, 1977; Doktor & Bloom, 1977; Ehrlichman & Wiener, 1979; Robbins & McAdam, 1974). Although some studies have examined power in frequency bands other than alpha (e.g., Doyle, Ornstein, & Galin, 1974; Papanicolaou, Loring, Deutsch, & Eisenberg, 1986; Rugg & Dickens, 1982; Tucker, Dawson, Roth, & Penland, 1985), none have used tasks with reliable performance measures to which one may relate the EEG changes. For example, a number of studies have used tasks in response to which either performance measures were not obtained (e.g., speaking and writing—Doyle et al., 1974) or were not presented (e.g., Loring & Sheer, 1984). Other studies indicate that measures of performance were obtained, but present no data on relations between performance and EEG asymmetry (e.g., Papanicolaou et al., 1986). Still other studies present performance data or provide other information that clearly indicates that the verbal and spatial tasks were not well-matched (e.g., Rugg & Dickens, 1982; Tucker et al., 1985). In this study, we examine EEG in the delta, theta, alpha, and beta bands in response to matched verbal and spatial tasks. Moreover, we derive asymmetry indices for power in each of these bands and examine their correlation with measures of performance.

The third major issue addressed by this study is the choice of an appropriate reference location for studies of EEG asymmetry. Considerable discussion has taken place in the literature concerning the optimal location of the reference electrode in studies of EEG asymmetry. For example, Nunez (1981) has argued that use of a linked ears or linked mastoids reference may provide a shunt across the head which attenuates the magnitude of the observed asymmetry. Van Petten and Kutas (1988) have reported such asymmetry attenuation using a linked ears reference in studies of event-related potential asymmetry during linguistic tasks. In the present study, rather than linking the ears, we implemented a computer-derived equivalent that did not require the physical linking of the two ears. This procedure involved the recording of separate channels of C_Z-A_1 and C_Z-A_2 which are then averaged off-line and used to derive a computed averaged-ears reference.

The vertex has been used as reference in many studies of EEG asymmetry (e.g., Doyle et al., 1974; Ehrlichman & Wiener, 1979, 1980; Papanicolaou et al., 1986; Scarone et al., 1988; Spydell & Sheer, 1982), although its use has also been criticized (e.g., Nunez, 1981). The major argument against the use of vertex as a reference is that changes at the vertex alone could result in changes in measures of lateralized EEG power (see Davidson, 1988 for discussion). Very few studies in the asymmetry area have directly compared different reference locations. Moreover, no published study has used reliable performance measures against which to relate measures of EEG based upon different reference montages. In the present study, we were able to examine correlations between measures of asymmetry (computed from both vertex-referenced and averaged-ears referenced data, derived from the identical points in time) and verbal and spatial performance. We were thus able to address the question of choice of reference location on an empirical basis by determining which reference montage best predicted task performance. Moreover, we also examined differences in power at the vertex between the verbal and spatial tasks to ascertain whether the tasks did produce differential amounts of power at this midline site.

Methods

Subjects

A total of 21 completely right-handed (as assessed with the Chapman & Chapman (1987) scale) undergraduate females served as subjects. Inasmuch as individual differences in depression have been found to affect task-dependent EEG asymmetries (Davidson, Schaffer, & Saron, 1985), subjects were specifically selected to be non-depressed on the basis of the Beck Depression Inventory (BDI). Subjects were required to score 6 or below on the BDI administered approximately 6 weeks prior to the laboratory session and below 8 just prior to the lab session. Two subjects who were selected on the basis of the first BDI criterion did not meet the second, leaving a total of 19 subjects for analysis. Subjects participated for extra course credit.

Procedure

Subjects were tested individually. They were told that the experiment was concerned with the relationship between brain activity and cognitive processing. After signing a consent form, an experimenter applied electrodes to measure EEG. The subject was given general instructions about the verbal and spatial tasks and told which task was to be presented first. The order of task presentation was randomized across subjects.

Prior to the presentation of the cognitive tasks, one 30-s trial each of eyes open and eyes closed baseline EEG was obtained. The order in which these trials were presented was randomized across subjects. Following the baseline trials, either the verbal or spatial task was presented.

Subjects were seated in a straight-backed chair 54 cm from the screen on which the tasks were presented. They were seated in front of a small desk on which response sheets were placed, and instructed to keep their hands flat on the table until they made their response.

Tasks

Two tasks designed to differentially engage the hemispheres were used that had previously been adapted by Fujioka (1986) and Miller (1986) as paper-and-pencil versions of two neuropsychological measures. The Dot Localization task was chosen as a measure of visuospatial right hemisphere functioning and the Word Finding task as a measure of left hemisphere functioning. Although no tasks are purely uni-hemispheric, data from research on patients with discrete unilateral lesions support each of these tasks as primarily dependent on one hemisphere. Problems in naming ability or word finding is a widely studied symptom that is usually associated, among right-handed patients, with left hemisphere lesions. The Dot Localization task is supported as a right hemisphere task by findings, in lesioned patients, by Hannay, Varney, and Benton (1976), Warrington and Rabin (1970), and Ratcliff and Davies-Jones (1972).

The Dot Localization task was adapted from a measure developed by Hannay et al. (1976). The subject is shown a drawing of two open rectangles, one above the other. The top rectangle contains two dots and the bottom rectangle contains an array of numbers. The bottom rectangle is slightly offset to the right or left of the top rectangle. The side to which it was offset was randomized from trial-to-trial with the constraint that half the trials be offset to each side. The subject is asked to indicate the numbers that the two dots would cover if the two rectangles were superimposed. The difficulty of the task was manipulated by using five different size arrays of numbers with the smallest containing eight numbers and the largest containing 50 numbers.

The Word Finding task was modeled after the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1978). In the present task the subject is presented with definitions of words and is asked to identify the word that is defined by the phrase. An example is: "a box or house for bees to live in." The correct answer is "hive." The usual forms of these tasks are too easy to measure individual differences among healthy college students. Therefore, Fujioka (1986) and Miller (1986) constructed more difficult items.

Fujioka (1986) and Miller (1986) matched the Dot Localization and Word Finding tasks on relevant psychometric characteristics so that the tasks would yield differential performance scores if an individual should have a greater deficit in the ability measured by one of the two tasks, regardless of the individual's overall level of functioning. In the present experiment, we shortened the two tasks to 24 items each, choosing items of the same distribution of difficulty for the two tasks, according to the normative data of Fujioka and Miller. There were five additional practice items on each task. The tasks were transferred to slide format for presentation during psychophysiological recording. Each trial was presented on a single slide. Because the change in mode of presentation might affect the item difficulties, the tasks were administered to a group of 151 college students to cross-validate the matching. The tasks were presented in the same rear-projected slide format that was used in the present study. Psychometric characteristics of the tasks are shown in Table 1. As seen there, the tasks appear to have been closely matched. The distributions of item difficulty also appeared similar. Thus, the task matching cross-validated very well. The means and standard deviations of item difficulty as well as the coefficient-alpha measures of internal consistency reliability indicate that the level of difficulty was suitable for measuring individual differences in the group tested.

The sentences presented for the Word Finding task varied between 7.5 and 33.5 cm in width and between .7 and 2 cm in height (depending upon whether they were one or two lines). The stimuli for the Dot Localization task varied between 20 and 24 cm in width and between 22 and 31 cm in height. The stimulus intensity was 8.1 cd/m^2 and the overhead ambient light was 53.8 cd/m^2.

During the actual experiment, subjects were instructed to attend to each slide and decide on the appropriate response. For the Word Finding task, this consisted of the word that corresponded to the defi-

Table 1

Psychometric properties for the Dot Localization and Word Finding tasks

Tasks	Mean Accuracy (SDs in Parentheses)	Coefficient Alpha	Mean Item Difficulty (SDs in Parentheses)
Dot Localization	20.2 (3.2)	.75	.84 (.11)
Word Finding	19.9 (3.2)	.73	.83 (.10)

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nition presented. For the Dot Localization task, it consisted of the two numbers whose spatial location corresponded to the position of the dots. When the subject arrived at her response, she was instructed to press a button and then write her response in the appropriate position on an answer sheet. After making her response, the subject then pressed the button once more to initiate the next trial.

Coincident with onset of the slide was a trigger sent to a PDP 11/34A computer which started digitization. Data were continuously digitized until the subject pressed the button to indicate that a response had been chosen. The slide was terminated by the subject's button press. Thus, EEG was collected only during the time the slide was present on the screen, prior to the subject's written response.

Apparatus and Recording Procedure

EEG was recorded from the left and right mid-frontal (F_3, F_4), central (C_3, C_4), and parietal (P_3, P_4) locations, referred to a common vertex (C_Z). Two additional channels were recorded in order to re-derive the EEG off-line using a different montage. These channels were C_Z-left ear (A_1) and C_Z-right ear (A_2). One important concern in EEG studies of lateral asymmetries is whether electrodes that are symmetrically placed are indeed over homologous cortical locations. Symmetrically placed electrodes might not necessarily be over the same location in each hemisphere because of the known anatomical asymmetries that are present in the human brain (see Geschwind & Galaburda, 1987 for review). However, the electrode sites from which we measured EEG in this study are ones that are indeed over homologous Brodmann's locations based upon CT-scan evidence (Homan, Herman, & Purdy, 1987). The frontal sites (F_3, F_4) are over Brodmann's area 46, the central sites (C_3, C_4) are over Brodmann's area 4, and the parietal sites (P_3, P_4) are over Brodmann's area 7 (Homan et al., 1987). All scalp recordings were performed using a stretchable lycra electrode cap (Electro-Cap Inc.). The ear recordings were made with Grass ear clip electrodes. Eye movements were recorded with Beckman miniature electrodes from the external canthus to the supra-orbit of the left eye and were displayed on one channel of the chart paper.[1] The impedances of all electrodes were below 5K ohms and less than 500 ohms separated the impedances of homologous electrode pairs.

The EEG was amplified with a Grass Model 12 Neurodata system using Model 12A5 amplifiers with the bandpass set to 1 and 100 Hz. The EEG was then low-pass filtered (48 dB/octave) at 85 Hz to prevent aliasing. The output of the amplifiers was displayed on chart paper for the purpose of artifact-editing. In addition, the filtered signals were fed into the A/D converter of the PDP-11/34A computer system. The EEG was sampled at 250 samples per second. The EEG was calibrated by inputting before and after each subject a series of 25 and 50 microvolt sine waves.

Data Analysis

Artifact editing of EEG. All EEG records were visually scored for artifact. All eye movement and muscle artifacts were removed from the data prior to analysis. In addition, the 1-s period just prior to the subject's response was edited out at this stage to eliminate response-related activity. If artifact was present on any channel, data from all channels were removed so that the EEG data in each channel were always from coincident points in time.

EEG analysis. EEG data from all artifact-free periods during the two tasks constituted the data that were analyzed for this report. Two sets of data were analyzed. One set was the EEG referenced to vertex. The second set consisted of the re-derived EEG referenced to computer-averaged ears. This latter analysis used the C_Z-A_1 and C_Z-A_2 data channels to obtain the computer-derived linked ears reference. Data were extracted for chunks of continuous EEG 1.02 s in duration. Chunks were extracted using a Hamming window. Chunks were overlapped by 75% to capture data at the tails of the chunks that would otherwise be attenuated if contiguous windows were applied. A Fast Fourier Transform (FFT) was applied to each chunk of EEG. Power values from all chunks within a task-type were averaged. The mean duration of artifact-free EEG (across items) for the verbal task was 33.9 s and for the spatial task it was 42.3 s. The distribution of artifact-free EEG across items of differing difficulty was comparable for the two tasks.

The dependent measures that were obtained from this analysis were power density (in $\mu V^2/Hz$) in the delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–20 Hz) frequency bands. These data were log-transformed to normalize their distributions because power values are positively skewed (see Davidson, 1988)[2]. The major sets of analyses consisted of analyses of variance (ANOVAs) with task (verbal/spatial) and hemisphere (left/right) as variables. These analyses were performed separately on band powers from each of the two reference derivations, for each region. A difference in asymmetrical brain electrical activity during verbal compared with spatial task performance would be supported by a significant Task × Hemi-

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[1] Unfortunately, the EOG was recorded only on paper for the purpose of artifact-editing. We were therefore unable to digitize the EOG.

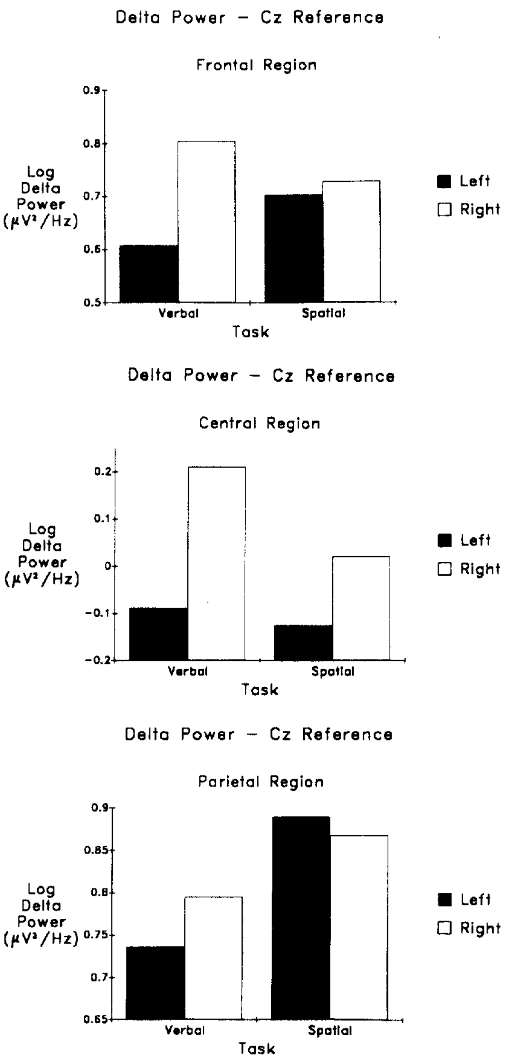
[2] A log-transform was performed rather than a square root transform because we found that the former resulted in a less skewed distribution, particularly in the alpha and beta bands. We compared the absolute skewness separately for each band, for log-transformed and square-root transformed data. The mean absolute skewness (averaged across electrode, task, and reference montage) for the delta band was .29 for the log-transform and .38 for the square root transform; for the theta band these values were .48 and .64; for the alpha band these values were .35 and 1.39; and for the beta band these values were .33 and .80. Thus, in every frequency band the log-transform resulted in less skewed distributions than the square root transform.

sphere interaction. Our analyses were therefore focused on this effect. Paired comparisons within significant interactions were evaluated with two-tailed t-tests and the p-values are reported where significant. In addition, laterality difference scores were computed to express the direction and magnitude of asymmetry in a single metric. The metric computed was log right minus log left power. We then used this metric to examine the relation between asymmetry in each frequency band and task performance, separately for data derived from each of the two references.[3] Alpha power is generally considered to be inversely related to activation in the awake adult, with decreases in alpha power reflecting increases in activation (e.g., Lindsley & Wicke, 1974). When the laterality metric is computed for alpha power, positive numbers therefore reflect left-sided activation and negative numbers reflect right-sided activation. In order to establish that it was asymmetry per se, rather than overall power elicited by a task, that accounted for variance in task performance, we performed three additional types of analyses. The first set of analyses examined the correlations between total power within a region (right+left) and task performance. In the second set of analyses, we examined the relation between power at each individual site and task performance. Finally, we examined the relation between total power within a region and asymmetry in power for those electrode sites where significant asymmetry differences between tasks were obtained. For all correlational analyses, possible curvilinearity was examined and none was found. The purpose of these analyses was to examine whether differences in overall power between tasks accounted for the variance in asymmetry between tasks.

Results

Vertex Montage

Delta. The means for delta power in the left and right hemisphere leads for each of the three regions are displayed in Figure 1. As can be seen for each of the three regions, there is more suppression of power in the left than in the right hemisphere during the verbal task than during the spatial task. ANOVAs were computed to examine task differences in hemispheric asymmetry for each region. The Task × Hemisphere interaction was significant in the frontal region ($F(1/18)=4.79$, $p=.04$) and nonsignificant in the central ($F(1/18)=2.85$) and parietal ($F(1/18)=2.95$) regions. In the frontal region, the verbal task was associated with less delta power in the left hemisphere and more delta power in the right hemisphere than was the case for the spatial task. We evaluated whether the two tasks produced any overall differences in band power across electrode sites. The absence of a main effect for task would imply that the two tasks do not differ in global cortical activation. Importantly, no main effect for task was obtained ($F<1$), indicating that across electrode sites, the two tasks did not elicit differential amounts of delta power. In addition to examining a main effect for task on overall power, we computed correlations between total power in each region and the asymmetry of power in that region (i.e., correlations between right+left and right−left power) separately for each task. In the delta band, none of the correlations reached significance. The mean correlation between total pow-



Delta Power – Cz Reference

Frontal Region

Delta Power – Cz Reference

Central Region

Delta Power – Cz Reference

Parietal Region

Figure 1. Mean log-transformed delta (1–4 Hz) power (in $\mu V^2/Hz$) for vertex-referenced EEG, split by Task and Hemisphere, for each region separately.

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[3] We were unable to directly compare EEG asymmetry during correct versus incorrect trials because we would have had an insufficient amount of artifact-free data for the incorrect trials.

er and the asymmetry of power, across region and task, was $r=.04$. To determine whether the overall pattern of correlation between total power and asymmetry of power differed from zero, we used the procedure recommended by Cohen and Cohen, (1983, p. 57) to test the omnibus null hypothesis. There were a total of 6 correlations for each band (3 regions × 2 tasks). For the delta band, the omnibus test was not significant ($\chi^2(6)=5.93$).

Theta. The means for theta power in the left and right hemispheres for each of three regions are displayed in Figure 2. The general patterning of theta power was similar to that found for delta power. The verbal task elicited greater relative suppression of power in the left than in the right hemisphere compared with the spatial task. ANOVAs computed on each region indicated that the Task × Hemisphere interaction was significant for every region (frontal: $F(1/18)=5.90$, $p=.03$; central: $F(1/18)=5.05$, $p=.04$; parietal: $F(1/18)=7.47$, $p=.01$). The pattern of task difference did differ between the frontal and more posterior scalp regions. In the frontal region, the verbal task was associated with less theta power in the left hemisphere compared with the spatial task. In the central and parietal regions, the major difference between tasks was in the right hemisphere, with the spatial task eliciting significantly more suppression of theta power compared with the verbal task (central region: $p<.01$; parietal region: $p<.02$). Importantly, as was found with delta power, no overall main effect for task was obtained for theta power, indicating that across all electrode sites, the tasks did not differentially produce global differences in theta power. Again, we computed correlations between total power and asymmetry of power for each region and task. None of the correlations reached significance. The mean correlation across region and task was $r=.02$. The omnibus test also showed no significant relation between asymmetry of power and total power ($\chi^2(6)=3.22$).

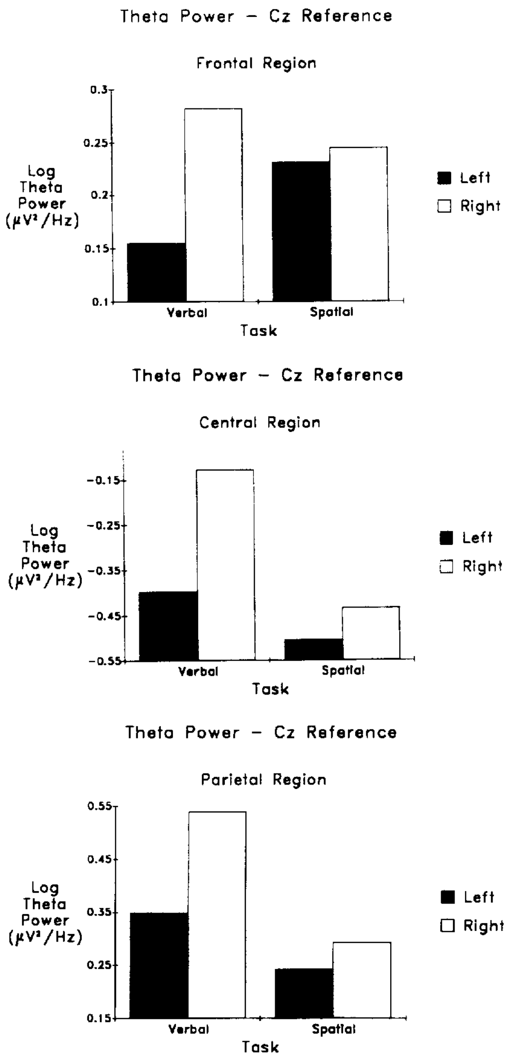

Figure 2. Mean log-transformed theta (4–8 Hz) power (in $\mu V^2/Hz$) for vertex-referenced EEG, split by Task and Hemisphere, for each region separately.

Alpha. The means for alpha power in the left and right hemispheres for each of the three regions are presented in Figure 3. The verbal task produced more relative alpha suppression in the left than in the right hemisphere compared to the spatial task. ANOVAs for each region indicated that the Task × Hemisphere interaction was significant for every region. In the frontal region, the significant Task × Hemisphere interaction ($F(1/18)=9.67$, $p=.006$) was primarily a function of greater suppression of alpha power in the right hemisphere during the spatial compared with the verbal task. In the central region, the significant Task × Hemisphere interaction ($F(1/18)=8.49$, $p<.01$) was primarily a function of significantly greater suppression of alpha power in the left hemisphere in response to the verbal compared with the spatial task ($p<.05$). In the parietal region, the Task × Hemisphere interaction ($F(1/18)=4.66$, $p<.05$) was a function of significantly greater suppression of alpha power in the right hemisphere during the spatial compared with the verbal task ($p<.05$). Importantly, as we found in the other frequency bands, no overall main effect for task across electrodes was found ($F<1$), indicating that the tasks did not produce differences in global cortical activation. Again, when we examined correlations between total power and the asymmetry of power within this band, none of the correlations were significant. The mean correlation

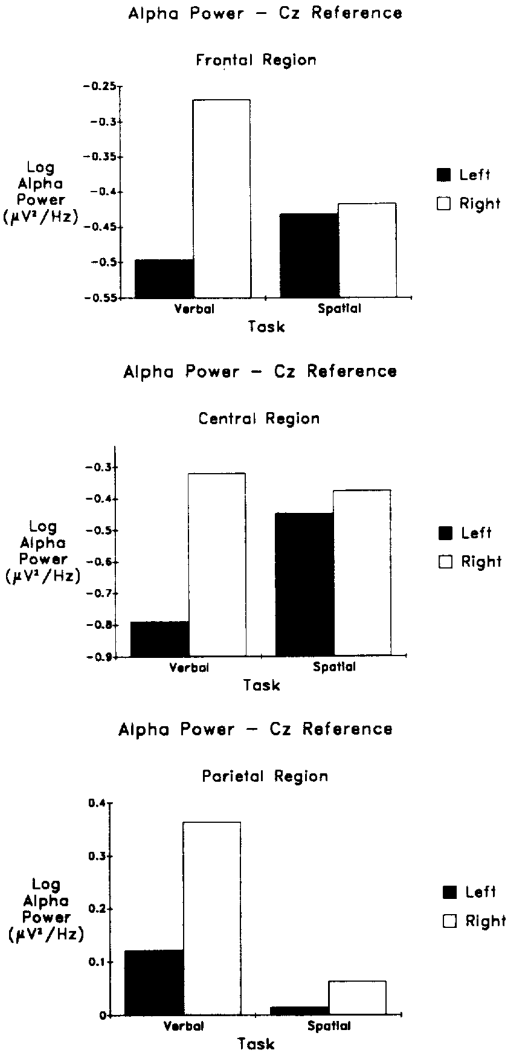

Figure 3. Mean log-transformed alpha (8–13 Hz) power (in $\mu V^2/Hz$) for vertex-referenced EEG, split by Task and Hemisphere, for each region separately.

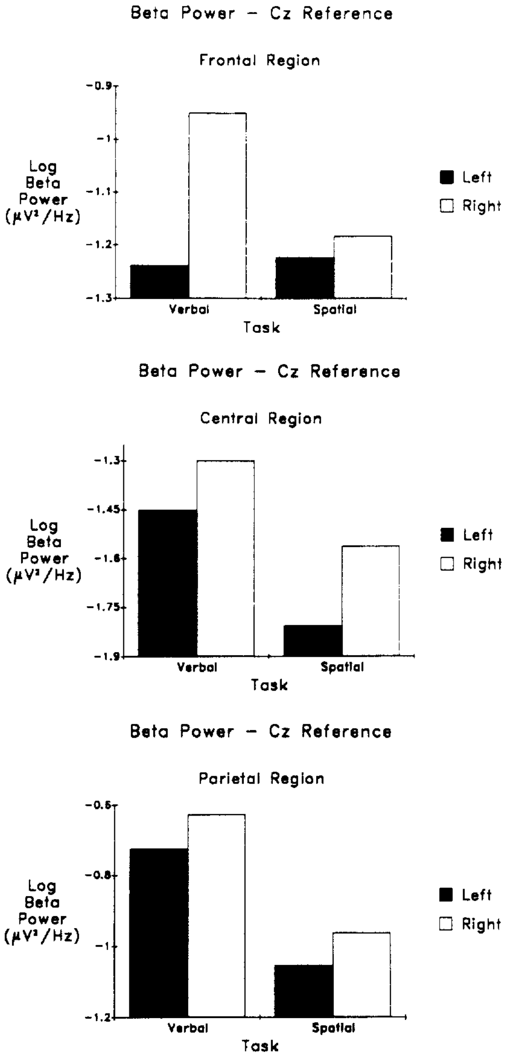

Figure 4. Mean log-transformed beta (13–20 Hz) power (in $\mu V^2/Hz$) for vertex-referenced EEG, split by Task and Hemisphere, for each region separately.

across region and task was $r=.04$. The omnibus test again indicated no overall significant relation between total power and asymmetry of power ($\chi^2(6)=1.63$).

Beta. The means for beta power in each of the three regions for the left and right hemispheres are presented in Figure 4. ANOVAs for each region indicated that the Task × Hemisphere interaction was significant for the frontal region ($F(1/18)=5.26$, $p=.03$). This interaction was a function of significantly less beta power in the right hemisphere during the spatial compared with the verbal task ($p<.05$). No differences were obtained between tasks in left hemisphere power. The Task × Hemisphere interaction was not significant for either central ($F(1/18)=1.23$) or parietal ($F(1/18)=.03$) beta power. Unlike power in other bands, the overall main effect for task across all electrodes was significant ($F(1/18)=13.14$, $p<.002$). This effect was a function of the spatial task producing less power in the central and parietal regions compared with the verbal task (main effect for task for central: $F(1/18)=10.30$, $p<.005$; for parietal: $F(1/18)=14.59$, $p=.001$). Although a main effect for task was obtained, the correlations between asymmetry and total power indicated that these variables were unrelated. As we found in the other frequency bands, none of the correlations between asymmetry and

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total power reached significance. The mean correlation across task and region between total power and power asymmetry was .16. The omnibus test for the 6 correlations also indicated no significant relation between total power and asymmetry of power ($\chi^2(6)=3.20$).

Task Differences in Power at the Vertex

An important question regarding the use of C_Z as a reference is whether there are differences in power at this electrode between the two tasks. Because we also re-derived our data using an averaged-ears reference, we were able to examine power at C_Z (referenced to averaged ears) in response to the verbal and spatial tasks. For alpha power, where the most consistent Task × Hemisphere interactions were obtained, the two tasks did not differ at C_Z ($F(1/18)=3.10$). In addition, no task difference at C_Z was found for beta power ($F(1/18)=2.46$). There were differences at C_Z in delta and theta power, with the verbal task eliciting more power suppression in both of these bands than the spatial task (for delta: $F(1/18)=22.09$, $p<.001$; for theta: $F(1/18)=9.02$, $p<.01$).

Computer-Averaged-Ears Montage

Delta. The analysis of power density in the delta band for each region did not reveal any interaction with task. The overall main effect for task was significant ($F(1/18)=24.33$, $p<.0001$). This task effect was a function of the verbal task eliciting less delta power than the spatial task.

Theta. The analysis of power density in the theta band for each region did not reveal any interactions with task. As with delta power for this montage, the overall main effect for task was significant ($F(1/18)=10.85$, $p=.004$). The direction of this main effect was the same as that for delta power: the verbal task produced less overall theta power than the spatial task.

Alpha. Figure 5 presents the means for alpha power based on the averaged-ears reference for left and right hemispheres in each of the three regions. No significant Task × Hemisphere interaction was obtained for the frontal leads. In the central region, the Task × Hemisphere interaction was significant ($F(1/18)=5.27$, $p=.03$). This interaction is a function of significantly more alpha suppression in the left hemisphere in response to the verbal task than in response to the spatial task ($p<.02$). The Task × Hemisphere interaction was also significant in the parietal region ($F(1/18)=4.97$, $p=.04$). This interaction is a function of greater suppression of alpha power in the right hemisphere during the spatial task than during the verbal task. No significant main effect for task was obtained ($F(1/18)=2.13$), indicating that across all electrodes, no global differences in alpha power between tasks were present. When the correlations between total power and the asymmetry of power were examined for each task in each region, one correlation reached significance: the greater the total frontal alpha power, the more the relative left-sided activation in this region during the verbal task ($r=.50$, $p=.03$). None of the other correlations for any other region in either of the two tasks reached significance. Thus, for the alpha band, the only region showing a significant correlation between asymmetry and power was the one region where no interaction between task and hemisphere was found. The mean correlation

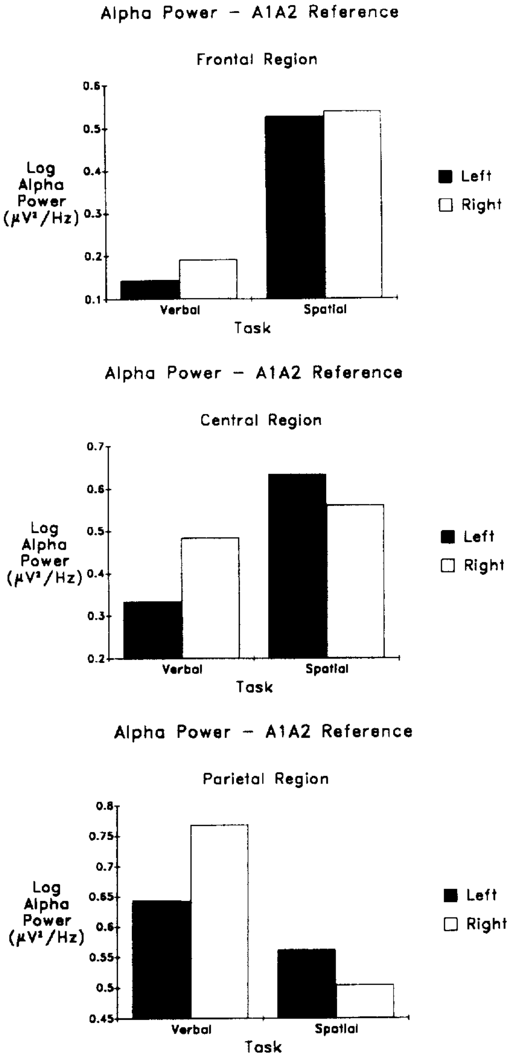

Figure 5. Mean log-transformed alpha (8–13 Hz) power (in μV^2/Hz) for averaged-ears referenced EEG, split by Task and Hemisphere, for each region separately.

across region and task (including the significant correlation in the frontal region for the verbal task) was $r=.17$. The omnibus test for the 6 correlations again indicated no significant relation between asymmetry of power and total power ($\chi^2(6)=6.34$).

Beta. Figure 6 presents the means for beta power based upon the averaged-ears reference for left and right hemispheres in each of three regions. ANOVAs on each region revealed that the Task × Hemisphere interaction was significant only for the central region ($F(1/18)=5.83$, $p=.03$).[4] This interaction is a function of significantly greater suppression of beta power in the right hemisphere during the spatial compared with the verbal task ($p<.03$). No significant main effect for task was obtained ($F(1/18)=1.55$) indicating that across all electrodes, no global differences in beta power between tasks were present. We again computed correlations between power asymmetry and total power, separately for each region, for each task. None of the correlations reached significance. The mean correlation across region and task was $r=.18$. The omnibus test again indicated no significant relation between total power and asymmetry of power ($\chi^2(6)=8.99$).

Correlations Between EEG Asymmetry in Different Bands

Relations between EEG asymmetry in different frequency bands were evaluated in two different ways. One approach was to determine on an individual subject basis if the difference between the two tasks was the same across frequency bands. The group data indicated that when a Task × Hemisphere interaction was found in any frequency band, it was always the case that there was greater relative power suppression in the hemisphere putatively required for task processing. We therefore computed laterality difference scores (log right minus log left power) for each task and region, separately for the vertex and averaged-ears data. We then calculated the number of subjects who showed a higher laterality score during the verbal than during the spatial task for at least three of the four frequency bands. A higher score during the former versus the latter would denote more relative left-sided power suppression during the verbal task. For the averaged-ears reference, out of a total of 19 sub-

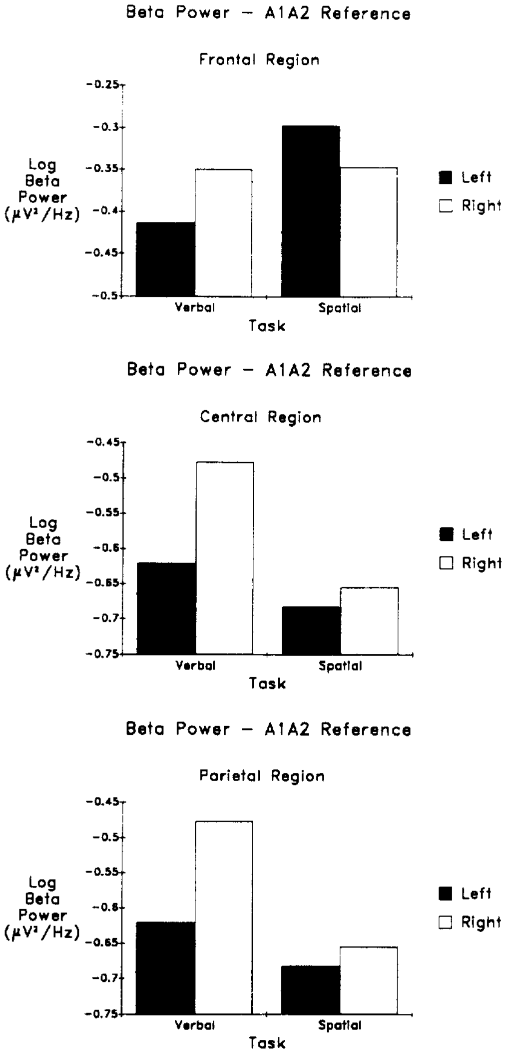

Figure 6. Mean log-transformed beta (13–20 Hz) power (in $\mu V^2/Hz$) for averaged-ears referenced EEG, split by Task and Hemisphere, for each region separately.

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[4] We have examined the Task × Hemisphere interaction in three different regions (frontal, central, and parietal), for four different frequency bands (delta, theta, alpha, and beta), and for two different references (vertex and averaged-ears). What is most striking about our data is the consistency of the effects we have obtained across frequency bands. Even if individual Task × Hemisphere interactions did not reach significance, the overall pattern of greater relative power suppression in the hemisphere putatively most engaged in task processing is the pattern in our data that is most salient. To evaluate the prevalence of this pattern quantitatively, we examined the direction of the effect in each of the 24 comparisons (3 regions × 4 frequency bands × 2 references) by comparing the laterality difference score (log right−log left) in the verbal and spatial tasks. A more positive difference score in the verbal than in the spatial task indicates more relative power suppression in the left than in the right hemisphere during the former compared with the latter task. Of the 24 comparisons performed, 20 showed a task difference in this direction. This effect is highly significant by the binomial test ($p<.0007$).

jects, 17 showed the predicted effect in the frontal leads, 15 in the central leads, and 11 in the parietal leads. For the vertex reference, 16 showed the predicted effect in the frontal leads, 15 in the central leads, and 17 in the parietal leads.

Our second analytic strategy focused on the relation between alpha and beta band power because the traditional view of power in these bands is that they should be reciprocally related in the awake adult performing tasks (Lindsley & Wicke, 1974). In other words, decrements in alpha should be accompanied by increments in beta. On this view, measures of asymmetry derived from alpha and beta band power should be reciprocally related. As was demonstrated above, when reliable differences in beta asymmetry between tasks were found, the direction of the difference was such that *decreases* in beta power were present in the hemisphere putatively more actively involved in task processing, a pattern that we also found to be characteristic of alpha power. To directly examine the relations between asymmetry in these frequency bands, correlations were computed between the asymmetry metric (log right minus log left band power) in each band and the asymmetry metric in every other band. These correlations were performed separately for each task and region, for the two EEG montages. Table 2 presents the correlations between alpha and beta band asymmetry. As can be seen from this table, all but two of these correlations were positive and many were significant. These data suggest that in general, alpha and beta asymmetry are positively correlated, not inversely correlated as the traditional view would hold.[5]

Table 2

Correlations between alpha and beta asymmetry

	Correlations		
Tasks	**Frontal**	**Central**	**Parietal**
	Vertex Reference		
Verbal	.58**	.30	.40
Spatial	.62**	.37	.44*
	Linked Ears Reference		
Verbal	.45*	.26	.42
Spatial	.52*	−.19	−.13

Note. The asymmetry metric is log right minus log left power. $^*p<.05$, $^{**}p<.01$.

The correlations between asymmetry in other bands were also generally positive. For each reference, other than the correlations between alpha and beta asymmetry reported in Table 2, there were 30 additional correlations computed (e.g., alpha with theta for verbal and spatial tasks; beta with theta for each task; theta with delta for each task, etc). For the vertex referenced data, all but two were positive. For the averaged-ears referenced data, 25 of the 30 correlations were positive. These correlational findings, in conjunction with the data reported above, indicate that relative suppression of power across all bands generally occurs in the hemisphere that is putatively most engaged in task performance and that these effects are consistent on an individual subject basis.

Correlations Between EEG Asymmetry and Task Performance

Vertex-referenced data. Asymmetry difference scores (log right minus log left power) for each band in response to each task were correlated with task performance for that task. In general, central and parietal asymmetry were more highly correlated with task performance than was frontal asymmetry. None of the correlations for frontal asymmetry approached significance. Table 3 presents the correlations for central and parietal asymmetry for each band with verbal and spatial task performance. As can be seen from this table, all of the correlations between asymmetry during the verbal task and performance were positive, indicating that greater relative suppression of power in the left central and parietal regions is associated with better performance on the verbal task. The correlations between task performance and parietal asymmetry in the theta and alpha bands were both significant. All but one of the correlations between asymmetry and spatial task performance were negative, indicating that greater relative suppression of power in the right central and parietal regions is associated with better performance on the spatial task. Although the overall direction of the correlations between asymmetry

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[5] We chose to examine relations between alpha and beta band power using laterality indices rather than raw power because of the important influence of skull thickness in modulating the overall amount of power recorded from the scalp. Individual differences in skull thickness would be expected to contribute heavily to the overall amplitude of the EEG and thus correlations of raw power in the alpha and beta bands should be even higher than correlations between asymmetry indices of power in these bands. The laterality index removes the contribution of individual differences in skull thickness from influencing the correlation. In order to evaluate this suggestion, we performed correlations between raw alpha and beta band power separately for each hemisphere, for each task and reference montage. For C_Z-referenced data, the correlations ranged between .49 and .83, with a mean correlation (across electrode and task) of .68. For the averaged-ears referenced data, the correlations ranged between .40 and .89, with a mean correlation of .71.

Table 3

Correlations between EEG asymmetry and task performance for vertex-referenced data

Tasks	Delta Central	Delta Parietal	Theta Central	Theta Parietal	Alpha Central	Alpha Parietal	Beta Central	Beta Parietal
Verbal	.40	.07	.12	.51*	.33	.63**	.28	.38
Spatial	−.40	.01	−.33	−.28	−.31	−.13	−.33	−.36

Note. Correlations are based on log right minus left band power during the task with task performance for that task. Positive correlations denote that relative suppression of power in the left hemisphere is associated with better task performance; negative correlations denote that relative suppression of power in the right hemisphere is associated with better task performance.

*$p<.05$, **$p<.01$.

Table 4

Correlations between EEG asymmetry and task performance for averaged ears-referenced data

Tasks	Delta Central	Delta Parietal	Theta Central	Theta Parietal	Alpha Central	Alpha Parietal	Beta Central	Beta Parietal
Verbal	−.34	.04	.14	.28	.24	.37	−.21	.03
Spatial	.02	.18	.03	.22	−.16	−.08	.17	.14

Note. Correlations are based on log right minus left band power during the task with task performance for that task. Positive correlations denote that relative suppression of power in the left hemisphere is associated with better task performance; negative correlations denote that relative suppression of power in the right hemisphere is associated with better task performance.

and spatial task performance was in the expected direction, none reached significance.

In the analyses described above, we performed a total of 24 correlations: 4 bands × 3 regions × 2 tasks. To determine whether the overall pattern of correlation between asymmetry and task performance differed from zero, we again used the procedure recommended by Cohen and Cohen (1983, p. 57) to test the omnibus null hypothesis. Using all 24 correlations, we can reject the null hypothesis that the correlations are zero ($\chi^2(24)=42.73$, $p=.01$).

To provide information on the question of whether it is asymmetry per se, rather than overall power, that is associated with task performance, we computed correlations between total power (right+left) and task performance, separately for power in each frequency band. None of the correlations reached significance. The correlation between asymmetry and verbal task performance was highest for parietal alpha ($r=.63$). The correlation between total alpha power in this region (R+L) and verbal task performance was .17 ($p>.4$). The omnibus test for the null hypothesis on the correlations between total power and task performance was clearly not significant ($\chi^2(24)=20.48$).

Averaged-ears referenced data. The identical correlations were performed for the averaged-ears referenced data. Unlike the correlations with vertex-referenced data, the correlations based on the averaged-ears data were considerably weaker. Table 4 presents the correlations for the central and parietal asymmetry data. As can be seen from this table, the strongest single correlation was between parietal alpha asymmetry and verbal performance, as we had found for the vertex-derived data. However, none of the correlations reached significance and a number were opposite in sign to those found for the vertex-derived data. Using all 24 correlations, the test for the omnibus null hypothesis was not significant ($\chi^2(24)=13.98$). As we found for the vertex-referenced data, when we examined the correlations between total power within each region and task performance, none of the correlations reached significance. As expected, the test for the omnibus null hypothesis was not significant ($\chi^2(24)=15.08$).

To determine whether the correlations between asymmetry and performance were a function primarily of the relative difference in activation between the hemispheres rather than a function of the absolute levels of activation within a hemisphere, we computed correlations between performance and raw hemisphere power. These correlations were performed for left and right central and parietal leads, separately for power in each band derived with each reference, for each task. Thus, 32 correlations per task were performed (2 hemispheres × 2 regions × 4 bands × 2 references), for a total of 64 correlations. Of these 64 correlations, only one reached significance and most did not approach significance. These data suggest that it is the relative difference in activation between the hemispheres that is most associated with task performance.

Discussion

Power Suppression and Asymmetric Hemispheric Activation

The verbal and spatial tasks used in this study were carefully matched on psychometric properties. EEG was recorded during the component of task processing when no motor response was required. In response to these tasks, reliable differences in asymmetrical brain physiology were produced. These electrophysiological differences provide additional evidence that these tasks differentially activate the left and right hemispheres, and add to the validity of these tasks as indices of hemispheric function.

For vertex-referenced data, reliable Task × Hemisphere interactions were obtained in every band. For theta and alpha power, the Task × Hemisphere interaction was significant for every region. In every instance where a Task × Hemisphere interaction was obtained for a particular region, it was associated with relatively less power in the hemisphere putatively most activated. This finding challenges the conventional wisdom regarding the functional significance of power in different EEG frequency bands (e.g., Shagass, 1972). Particularly striking is the similar pattern of data for alpha and beta band power which is borne out in the correlations reported in Table 2. Correlations between asymmetry in these two bands were consistently positive for every region.

A number of other investigators have reported alpha and beta band power to show similar effects, i.e., decrements in power during task performance (e.g., Spydell & Sheer, 1982; Berfield, Ray, & Newcombe, 1986). However, Papanicolaou et al. (1986) reported increments in left-sided beta band activity during linguistic task performance compared with a control task. The measure they used was RMS amplitude rather than power density, although their choice of variable should not affect the results obtained. Most importantly, however, no procedure was described for the removal of muscle artifacts from the EEG. Their electrode placements were between T_3 and P_3 and between T_4 and P_4. The temporal scalp region is particularly susceptible to muscle artifact, and the linguistic tasks they used likely generated covert speech. Demonstrations of increments in beta power during task performance, especially when recorded from temporal scalp regions, must be accompanied by adequate procedures for the removal of muscle artifact from the EEG (see Davidson, 1988 for a discussion of such procedures). The only convincing demonstrations of increments in beta power during performance unconfounded by muscle artifact have been the findings reported by Sheer and his colleagues of increased power in a high frequency beta band centered around 40 Hz (Spydell & Sheer, 1982; Loring & Sheer, 1984).

For the averaged-ears referenced data, significant Task × Hemisphere interactions were found for alpha and beta band power only. The overall direction of these asymmetrical effects was the same as that found for vertex-referenced data. The Task × Hemisphere interactions for central and parietal alpha power are the only two interactions that were significant for *both* vertex and averaged-ears referenced data. Interestingly, the pattern of asymmetry differences between the tasks differed in the central and parietal regions. In the central region, the major difference between tasks was in the left hemisphere, with the verbal task eliciting less left-sided alpha power (i.e., more activation). In the parietal region, there was no difference between tasks in left hemisphere power. Rather, the interaction was a function of less alpha power in the right hemisphere during the spatial task vs. the verbal task. These findings indicate that at least for the tasks used in this study, the verbal task produces more left central activation whereas the spatial task produces more right parietal activation. Thus, the tasks differ not only in their pattern of asymmetric activation, but also in the specific intra-hemispheric region that was most engaged by task-relevant processing.

It is important to note that the two Task × Hemisphere interactions that were significant for both reference montages (i.e., in the central and parietal regions) were in the alpha band. For this band, for both montages, no main effect for task was obtained, indicating that the two tasks did not differ in overall alpha power. In addition, there were no significant differences in alpha power at the vertex between the two tasks. When correlations between total power within a region and asymmetry of power for that region were computed, no significant relation was found for these brain regions. Taken together, these analyses indicate that the differences between tasks in alpha power were primarily in asymmetry in the central and parietal leads and not in overall power. Whatever slight differences in overall power existed, they did not account for any significant variance in the asymmetry of power in these regions, nor did they account for any significant variance in performance on either the verbal or the spatial task.

Overall, the EEG findings from this study indicate that the Word Finding and Dot Localization tasks produce reliable differences in asymmetric brain physiology. When hemispheric differences occurred in any EEG band, they *always* were associated with either relative decreases in power in the hemisphere putatively most engaged in task processing or relative increases in power in the opposite hemisphere. Moreover, this pattern in the group data was also found on an individual subject basis. We found that the clear majority of subjects showed differences between the two tasks in the direction of the group means for at least three of the four frequency bands. This suggests that the reduction in power across frequency bands is not simply a function of spillover from the alpha band into adjacent frequency bands. Rather, our findings indicate that when matched tasks are used, most subjects show relative power suppression across bands in the engaged hemisphere. This pattern indicates that at least for these tasks, decrements in EEG power across different bands can be interpreted as increased activation. In fact, early studies on EEG asymmetry often used decrements in whole band power as a measure of activation (e.g., Galin & Ornstein, 1972; Harmon & Ray, 1977).

EEG synchronization is associated with greater amplitude than desynchronization because synchronized activity means that large populations of neural generators act in concert. Synchronization occurs in every band, including beta (Thatcher & John, 1977). The notion that beta activity is desynchronized and alpha activity represents synchronized activity is not supported by neurophysiological evidence. Synchronization of the EEG is likely a function of thalamocortical interaction (e.g., Thatcher & Purpura, 1973). The frequencies at which synchronized activity is most likely to occur are dictated by the temporal characteristics of excitatory and inhibitory post-synaptic potentials. In the human awake adult, the dominant frequency of synchronized activity is in the alpha band (approximately 10 Hz), but synchronized activity in other bands also occurs (see Thatcher & John, 1977 for a review). When activation of cortex occurs, thalamocortical synchronizing mechanisms are disrupted and the EEG may be said to become desynchronized. Such desynchronization would be expected to lower the overall power in the EEG across bands.

It may be the case that task-elicited processing activity increases certain forms of synchronous activity whose neural controls are probably not thalamocortical, and might result in actual increases in band power. As previously stated, the only convincing demonstration of such effects is in the high frequency band centered around 40 Hz (e.g., Loring & Sheer, 1984). This possibility is supported by neurophysiological evidence that indicates that isolated cortex in the absence of thalamic afferents is capable of exhibiting fast frequency rhythmic, synchronous activity (Kristiansen & Courtois, 1949).

EEG Asymmetry/Performance Relations

One major purpose of this study was to examine which of the different metrics of EEG asymmetry (i.e., those derived from different bands and with different references) accounted for the most variance in task performance. Rather than make this choice on theoretical grounds alone, we reasoned that with reliable performance measures, one can approach this issue empirically. EEG asymmetry from central and parietal recordings was more highly correlated with performance than was EEG asymmetry from frontal recordings. For vertex-referenced recordings, the direction of the correlations indicated that greater relative power suppression in the left hemisphere is associated with better verbal task performance. The highest correlation found was between alpha asymmetry in the parietal region and verbal task performance. This single measure accounted for 40% of the variance in task performance. All but one of the correlations between vertex-referenced asymmetry and spatial task performance were negative. The inverse correlation indicates that greater relative power suppression in the right hemisphere (i.e., right-sided activation) is associated with better performance on the spatial task. The magnitude of the correlations between EEG asymmetry and spatial task performance was lower than between asymmetry and verbal performance. This raises the possibility that the Dot Localization task, at least as presented in this study, is not as lateralized as the Word Finding task. It should be noted that all of the instructions were verbal, the task was accompanied by the presentation of a number array, and subjects were required to write their responses with their right hands. This format may have attenuated the magnitude of the right hemisphere activation observed.

The pattern of correlations between EEG asymmetry and task performance for the averaged-ears data was less consistent than for the vertex-referenced data, particularly for the delta, theta, and beta bands. Although the correlations in the alpha band were in the same direction, the magnitude of the averaged-ears correlations was lower than the corresponding correlations for the vertex-referenced data.

In general, the pattern of correlations that we obtained between EEG asymmetry and task performance indicates that the greater the magnitude of task-appropriate hemispheric activation, the better the performance. This was especially apparent for the verbal task. In response to this task, the greater the relative left-sided activation, the better the performance. It may be that with tasks carefully selected to reflect unilateral function, greater task-dependent activation asymmetry will be associated with better performance. Increases in task-dependent activation asymmetry may be thought of as selective increases in activation in regions most relevant to task performance along with corresponding decreases in activation in other non-relevant regions. On unilateral tasks, it is this type of selective activation that should be most associated with expert performance.

Power Versus Asymmetry of Power

Several analyses were performed to examine the issue of whether it is overall power rather than asymmetry per se that is related to task performance. The correlation between asymmetry within a region (the log right minus log left difference score) and total power within a region (log right plus log left) was found to be consistently low and nonsignificant. Moreover, we found that total power (right plus left) within a region was uncorrelated with task performance. We also examined the correlations between separate hemisphere power and task performance and found these measures to be unrelated. These findings suggest that it is the *difference* in activation between the hemispheres that is most consistently related to task performance. Thus, within the range of task difficulty tapped by our tasks, greater relative activation of the hemisphere putatively required for task performance is associated with better performance. It may be that with tasks that are either at different difficulty levels, or are less exclusively lateralized, such consistent correlations between asymmetric hemispheric activation and task performance would not be found.

Other Methodological Issues

Given that our linking of the ears for the averaged-ears reference was performed mathematically, rather than with a physical wire link, Nunez' (1981) criticism of the linked ears reference would not apply because his objection was based upon the provision of a low-resistive shunt across the head when the two earlobes are physically linked. However, the process of mathematically averaging the activity from the two earlobes may itself attenuate the magnitude of asymmetry, thus leading to the less consistent pattern of results for data based on this reference. In the future, it would be valuable to compare data referenced to the ipsilateral earlobe with the average of the two ears.

A question that might be raised about our data concerns the removal of eye movement artifacts. The EEG data were carefully visually edited to remove all epochs associated with any detectable eye movement or blink, based on the EOG recordings. However, it is conceivable that some EEG activity associated with very small eye movements not visually detectable in the EOG was included in the analyses. Because we did not digitize the EOG in this study, we could not use an automated EOG correction algorithm. However, it should be noted that the power spectrum of EOG eye movement activity is primarily in the sub-delta and delta bands and negligible for frequencies in the alpha range and above (Gasser, Sroka, & Möcks, 1985). Gasser et al. (1985) found that for posterior scalp sites (which resulted in the most consistent findings in the present study), significant transfer of eye movement activity to the EEG was present in frequencies up to 4 Hz. In the anterior sites, significant transfer occurred in frequencies up to 6 Hz. Our most consistent asymmetry effects were in the alpha band. Based upon the findings of Gasser et al. (1985), power in this band, particularly in posterior scalp sites, should be relatively unaffected by eye movements. Moreover, this group has reported that eye movement correction has no effect on asymmetry. Asymmetries that were present prior to correction remain after correction (Gasser, Sroka, & Möcks, 1986). It is therefore very unlikely that small eye movements undetectable in the EOG record that may have remained after editing influenced our measures of task-dependent EEG asymmetry.

Summary and Conclusions

The findings from this study indicate that robust differences in asymmetrical brain physiology are produced by psychometrically well-matched verbal and spatial tasks during epochs unconfounded by response requirements. The measure of asymmetry that was most highly correlated with task performance was parietal alpha derived from vertex-referenced recordings. When task-dependent shifts in asymmetry were found in other bands, the direction of the effect was always such that relatively less power was found in the hemisphere putatively most engaged in task processing.

Aside from the specific findings we obtained, the methodology used in this study illustrates an important strategy in studies of relations between brain function and cognition. With the use of reliable measures of task performance, different physiological indices can be compared with respect to their association with these behavioral measures. Such an approach has the potential of contributing to a better understanding of the underlying functional significance of different indices of brain activity.

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Announcements

NIDA Seeks Proposals Evaluating Long-Term Drug Effects

The National Institute on Drug Abuse is soliciting research proposals evaluating the effects of long-term, illicit drug abuse on subsequent behavior and physiology following discontinuation. Subjects should be drug abstinent when tested. Relevant evaluations could be laboratory performance as well as physiological measurements, e.g., electroencephalogram, evoked potentials, heart rate, GSR, blood pressure, or tremor.

Additional information can be obtained from Dr. John Spencer, National Institute on Drug Abuse, 5600 Fishers Lane, Room 10 A-46, Rockville, MD 20857 (301/443-1263).

Postdoctoral Position Available at the National Institutes of Health, PHS

The Section of Clinical Brain Research in the Laboratory of Clinical Studies at the National Institute on Alcohol Abuse and Alcoholism (NIAAA) has an opening for a 2–3 years postdoctoral fellowship. The successful candidate is expected to be a psychophysiologist who is familiar with techniques for measuring skilled performance and eye movements in humans, as well as electrophysiological measures of autonomic and central nervous system functions. Ongoing studies involve adult and child normal volunteers and patients with organic brain syndromes associated with alcoholism. Needed is an individual capable of participating in an interdisciplinary group, who is well-versed in the techniques of brain imaging, electrophysiology, pharmacology, and behavior. Demonstrated experience in computer programming is also desirable.

Candidates must be U.S. citizens and have completed their doctorate training with no more than 3 years postdoctoral experience. Stipends begin at $25,000 but may be adjusted depending on the candidate's postdoctoral experience. Appointment would be as an intramural research training associate.

The laboratory is located at the National Institutes of Health in Bethesda, Maryland just north of Washington, DC. To apply, please send an explanatory letter including a statement of scientific interest, and a resume and the names of three references to: Michael J. Eckardt, Laboratory of Clinical Studies, NIAAA, NIH Building 10, Room 3C-102, 9000 Rockville Pike, Bethesda, MD 20892 (301/496-5353). NIAAA is an equal opportunity employer.