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Baseline Asymmetries in Brain Electrical Activity Predict Dichotic Listening Performance

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Forty-four right-handed participants were assessed on 2 occasions 6 weeks apart on electrophysiological measures of activation asymmetry derived from spectral estimates of electroencephalogram (EEG) alpha power in homologous scalp electrodes. Approximately 4 months following the final EEG assessment, participants were administered a dichotic listening CV-syllables task. Overall, participants exhibited a highly significant right-ear advantage. Differences among individuals in ear asymmetry were predicted by the earlier recorded electrophysiological data. Participants with greater activation in left-sided posterior temporal and parietal regions showed a larger right-ear advantage. In addition, a larger right-ear advantage was predicted by right-sided prefrontal activation. These data indicate that some of the variance in dichotic listening performance can be explained by dispositional activation asymmetries and is associated with a complex pattern of posterior and anterior activation asymmetries.

A number of investigators of brain asymmetry have distinguished between hemispheric specialization and hemispheric activation (e.g., Davidson, 1988; Levy, 1983). *Hemispheric specialization* refers to differences between the two cerebral hemispheres in the proficiency with which each performs a particular task. If one hemisphere excels at task performance compared with another, then it is said to be more "specialized" for the task in question. In contrast, *hemispheric activation* refers to the degree to which each hemisphere displays physiological or behavioral signs of arousal. In the present article, this concept is operationalized as differences in the brain electrical activity recorded from each hemisphere.

Individual differences in each of these two domains of brain asymmetry have been noted. For example, there exist differences between right- and non-right-handed individuals in hemispheric specialization for cognitive function (e.g., Peters, 1995). There also are tonic differences in the magnitude and direction of activation asymmetry. Using behavioral measures to make inferences about activation asymmetry, Levy and her colleagues (Levy, Heller, Banich, & Burton, 1983) have reported that individuals differ in the extent to which one hemisphere is tonically more activated than the other and these differences predict patterns of performance on certain types of cognitive tasks. The notion that there are individual differences in activation asymmetry is important because it implies that variations across individuals in performance on certain lateralized tasks may reflect lawful differences in tonic patterns of activation asymmetry.

When more direct biological measures were used to make inferences about individual differences in activation asymmetry, it became clear that this was not a unitary construct (see Davidson, 1988; Tomarken, Davidson, Wheeler, & Kinney, 1992, for reviews). Rather, pronounced differences in the direction and magnitude of activation asymmetry exist along the rostral-caudal plane. Behavioral measures of activation asymmetry do not provide any direct information on the cerebral location of the activation differences that are reflected in task performance.

Dichotic listening performance has often been used to make inferences about hemispheric specialization (see Hugdahl, 1988, for overview). If an individual shows a right-ear advantage for verbal material on this task, the inference is then made that the left hemisphere is indeed more specialized for processing verbal material (Bryden, 1988; Kimura, 1961). However, it is also clear that although the majority of individuals show a clear right advantage on this task, some do not, even if the sample is restricted to exclusively right-handed participants who are expected to show left hemisphere specialization for processing of verbal information. Moreover, among those who show a right-ear advantage, the magnitude of this ear asymmetry varies considerably (Hugdahl, 1995). Several studies indicate that the test–retest reliability of dichotic ear asymmetry scores is good, with reliability estimates reported between .70 and .90 (Bakker, Van der Flught, & Claushuis, 1978; Harper & Kraft, 1986). The variation in magnitude of the stability estimates stems from differences in the index scores used, the nature of the stimuli, the age of subjects, and the interval between test occasions (see Hugdahl, 1995, for review).

Measures derived from scalp-recorded brain electrical activity have been demonstrated to provide reliable indices of asymmetric activation in different scalp regions. For example,

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Ehrlichman and Wiener (1979) reported that alpha power asymmetry in parieto-temporal sites was stable over time ($r = .74$ over a 3-week interval). Davidson and his colleagues (Tomarken et al., 1992) recently reported on the test–retest stability and internal consistency reliability of electroencephalogram (EEG) measures of activation asymmetry derived from aggregated eyes open and eyes closed resting conditions (presented in eight 1-min trials, with four of each type) in different scalp regions over a 3-week interval. Intraclass correlations for measures of alpha power asymmetry ranged from .66 to .77 for different scalp regions. Measures of internal consistency reliability across the eight 1-min trials ranged from .83 to .92. In a series of recent studies, Davidson and colleagues have reported that individual differences in EEG measures of asymmetry from anterior temporal and prefrontal scalp sites predict important features of emotional reactivity and affective style (see Davidson, 1992, 1995, for reviews).

The purpose of the present study was to determine whether baseline measures of electrophysiological asymmetry recorded in a manner identical to previous studies from the Davidson laboratory (see Tomarken et al., 1992, for a detailed description) predict performance on a standard dichotic listening (DL) task consisting of the simultaneous presentation of consonant–vowel (CV) pairs. In the present study, two EEG assessments were obtained 6 weeks apart. The dichotic task was presented approximately 4 months following the last EEG assessment. It was hypothesized that activation asymmetries in posterior temporal areas would predict performance on the dichotic task such that participants with greater relative left-sided posterior temporal activation would show a larger right-ear advantage on the dichotic task. The relation between asymmetries in more anterior regions and dichotic performance was also examined because a growing body of evidence indicates that there may be reciprocal relations between anterior and posterior patterns of cortical activation. For example, Knight (1991) reported that sensory evoked potentials recorded from posterior scalp regions are enhanced in patients with frontal lobe damage. Davidson, Schaffer, and Saron (1985) reported that during a face-processing task, EEG asymmetries recorded from frontal and parietal scalp sites (at the same points in time) were inversely correlated. A similar pattern of data derived from xenon measures of regional cerebral blood flow have also been reported (Wood, Flowers, & Naylor, 1991). Therefore, it was expected that if anterior asymmetries were related to dichotic performance, they would show a pattern of association that was opposite to that observed for posterior scalp regions.

Method

Participants

We recruited 44 right-handed undergraduates (19 women) between the ages of 18 and 35 years ($M = 19.2$ years) from the introductory psychology subject pool at the University of Wisconsin—Madison. Only right-handed participants (10 right-handed items out of a total of 13 assessed with the Chapmans' Handedness Inventory; Chapman & Chapman, 1987) were selected to reduce the heterogeneity of our sample with respect to hemispheric specialization.

Procedure

Participants took part in a total of three experimental sessions. The initial two sessions were held 6 weeks apart and consisted of an electrophysiological assessment that was identical on both of these occasions. EEG data acquisition and reduction procedures that have been described in a number of recent publications were utilized (Tomarken, Davidson, Wheeler, & Doss, 1992; Tomarken, Davidson, Wheeler, & Kinney, 1992). All participants were tested individually. After electrodes were applied for the recording of EEG, participants were told that all of the instructions necessary for the session would appear on the video monitor in front of them, that they should remain relaxed but alert, and that they would be asked to refrain from eye movements. After the experimenter left the room, instructions informed participants that (a) there would be eight 1-min resting baselines; (b) four baselines would be conducted with eyes open, four with eyes closed; and (c) during the baselines they should try to minimize eyeblinks and movements but not be so concerned about doing so that they were distracted.

Two randomly assigned, counterbalanced orders were used for the eyes-open (O) and eyes-closed (C) trials of the resting baselines (O-C-C-O-C-O-O-C and C-O-O-C-O-C-C-O). Participants heard one tone denoting the start of each trial and two tones 60 s later to signal that the trial was over. After the first two baselines, all participants were reminded to stay relaxed and keep their eyes still. The remaining six baselines were presented consecutively without interruption. The experimenter then returned to remove the electrodes.

Participants returned to the laboratory for the second experimental session approximately 6 weeks after Session 1. The allowable interval between sessions was 39–45 days, with the vast majority returning 42 days after the first session. The procedures for this session were identical to those described in Session 1.

EEG Recording and Quantification

EEG was recorded with a lycra stretchable cap (Electro-Cap, Eaton, OH) positioned on the head according to known anatomical landmarks. During each session, EEG was recorded from the following left and right homologous scalp locations in the 10/20 system: midfrontal (F3 and F4), lateral frontal (F7 and F8), frontal poles (Fp1 and Fp2), anterior temporal (T3 and T4), central (C3 and C4), posterior temporal (T5 and T6), parietal (P3 and P4). In addition, 6 homologous electrode pairs (12 electrodes) were positioned at locations between the standard ones (FpF1, FpF2, FC3, FC4, FT7, FT8, CP3, CP4, CP5, CP6, PO3, PO4). Several midline electrodes were also included. During recording, all sites were referenced to linked ears (A1 and A2). All electrode impedances were under 5,000 ohms, and the impedances of homologous sites were within 1,000 ohms of each other. In both sessions, two channels of eye movements (electrooculogram; EOG) were recorded to facilitate artifact scoring of EEG. Horizontal EOG was recorded from the external canthi of each eye; vertical EOG was recorded from the supra-orbit and suborbit of one (randomly selected) eye. EEG was amplified with a Grass Model 12 Neurodata System, Quincy, MA) with Model 12A5 preamplifiers (bandpass = 1 and 300 Hz) and passed through anti-aliasing low-pass filters (MF6 Chip) set at 200 Hz (48 dB per octave roll-off). EEG was digitized at 500 Hz on a personal computer.

The EEG and EOG signals were visually scored, and those portions of the data containing eye movements, muscle movements, or other sources of artifact were deleted. When an artifact occurred on a given channel, data from all channels were removed. All artifact-free chunks that were 1.02 s in duration were extracted through a Hamming window, and chunks overlapped by 50%. A fast Fourier transform (FFT) was then used to derive estimates of spectral power (in microvolts squared) in different frequency bands. Power density (in $\mu V^2/Hz$) was computed by summing power values within each band and then dividing by the band width. Based on an extensive corpus of previous findings that indicated that the majority of the variance in the awake EEG is accounted for by changes in alpha power (8–13 Hz; see Davidson, Chapman, Chapman, & Henriques, 1990), only data from this band are presented in this article.

To compute a measure of activation asymmetry from the eyes-open and eyes-closed resting trials for each participant, we adopted the computational strategy reported in recent articles (e.g., Tomarken, Davidson, Wheeler, & Kinney, 1992). First, an average of power density across four eyes-open baselines, weighted by the number of 1.02-s chunks of artifact-free data, was taken. The same procedure was applied to the eyes-closed data. When a participant had fewer than 10 s of artifact-free data for a given baseline, that baseline was dropped from further computations. When the weighted average of either eyes-open or eyes-closed baselines resulted in fewer than 40 s total of artifact-free data, that session's data were dropped from further analyses. Based on this criterion, no participant was dropped from the analyses. Next, a simple average across the two-eye conditions was computed. The total average duration of artifact-free EEG was 184.4 s and ranged between 90.9 s and 319.5 s. Finally, to normalize the data, we log transformed all power density values. When asymmetry data are reported, asymmetry is computed as the difference between mean log power density in a right hemisphere lead and mean log power density in a left hemisphere lead (i.e., log right minus log left power density). To derive an asymmetry score for a particular region for each participant, we computed the simple average of power density asymmetry for that region across Sessions 1 and 2. All participants met the minimum criteria for sufficient artifact-free data.

Dichotic Procedure

Participants returned to the laboratory for a third testing session that was held an average of 4 months (range = 2–6 months) following the second EEG assessment. During this session, the dichotic task was administered. The dichotic stimuli consisted of the six stop-consonants paired with the vowel *a* to form six consonant–vowel syllables: *ba, da, ga, pa, ta,* and *ka.* The tape was designed so that the CVs were simultaneously presented to each ear. The syllables were paired with each other for all possible combinations, yielding 36 dichotic pairs (6 trials in which the same CV was presented to each ear, and 30 trials in which two different CVs were presented to each ear). Trials during which the same CVs were presented to both ears were used only as test trials and were not included in the statistical analysis. The dichotic tape consisted of three lists of 36 stimuli; thus the total number of trials was 108, with the homonymic pairs (same CV to each ear).

The tape was prepared on a Model PDP 11/45 computer and was played to participants on a portable cassette player through stereo headphones (Sony Model MDR-V6). Dichotic listening with CV-stimuli have yielded test–retest reliabilities of between .70 and .90 (see Hugdahl, 1995, for review). Andersson and Hugdahl (1987) found that 83% of subjects maintained their ear advantage over a 1-year period. All participants were administered five practice trials to ensure that they understood the nature of the task. Half of the participants (randomly assigned) began the task with the left headphone on their left ear and half with the right headphone over their left ear. Between each trial block of 36 trials, headphones were reversed. The output of each headphone was calibrated prior to each session to produce a sound level of 75 dB. Participants were instructed to give a single response on each trial. If they heard more than one stimulus, they were told to select the one they heard the best or the first. The experimenter, who was seated behind the participant, recorded the participant's response on each trial. To determine ear asymmetry for each trial block, we scored the 30 dichotic trials separately for the right and left ear.

Results

Dichotic performance was examined first to ascertain that a right-ear advantage was observed across subjects and to ensure that the data were comparable to other samples. A dichotic laterality quotient (DQ) was derived. It was computed as total right-ear correct responses minus total left-ear correct responses divided by the sum of total right- and left-ear correct responses (R − L/R + L). This index expresses the performance difference between the two ears. For the sample of 44 participants, the DQ was .26, indicating that there was a 26% difference between performance in the right versus left ear. A t test comparing the DQ values to the null hypothesis of no difference between the ears revealed a highly significant right-ear advantage, $t(43) = 7.76$, $p < .0001$. Despite the finding of a strong overall right-ear advantage, there was also great variation among subjects, as others have found. DQ scores ranged from −.11 to .86. There was no significant difference between men and women on the DQ, $t(42) = 0.32$, $p > .7$.

Relations between the EEG asymmetry metric and dichotic performance were next examined. Higher numbers on the EEG asymmetry metric denote greater relative left-sided activation. Therefore, positive correlations between EEG asymmetry and dichotic performance indicate that more left-sided EEG activation predicts greater right-ear advantage on the dichotic task. As we hypothesized, the most significant predictor of dichotic performance among the posterior scalp electrodes was activation asymmetry in the posterior temporal region (T5/T6), $r(43) = .30, p < .05$; see Figure 1).[1] Activation asymmetries in other posterior scalp regions were correlated with dichotic performance in the same direction: parietal (P3/P4), $r = .29, p < .06$; occipitoparietal (PO3/PO4), $r = .25$; centroparietal (CP5/CP6), $r = .24$. This general pattern of correlation indicates that subjects with greater relative left-sided posterior activation have a larger right-ear advantage when tested 4 months later.

Relations between asymmetries in more anterior scalp sites and dichotic performance were also examined. Prefrontal asymmetry (FpF1/FpF2) was significantly correlated with dichotic performance, albeit in a direction opposite to that found for the posterior scalp sites ($r = -.33$, $p < .03$; see Figure 2). The direction of this correlation indicates that participants with more left-sided prefrontal activation had less of a right-ear advantage. The pattern of correlation for other anterior sites was in the same direction, though nonsignificant (F3/F4, $r = -.22$; F7/F8, $r = -.18$; Fp1/Fp2, $r = -.18$). These inverse correlations with dichotic performance are particularly striking in light of the fact that in this sample, posterior and anterior asymmetries were essentially unrelated. Thus, asymmetry in the posterior temporal region (T5/T6) was correlated ($r = -.04$) with asymmetry in the prefrontal region (FpF1/FpF2). The difference in correlation between the DQ scores

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[1] Unless otherwise noted, the degree of freedom for all analyses was 43.

and posterior temporal versus prefrontal asymmetry was significant, $t(43) = 3.26$, $p < .01$, by t test for significance of the difference between dependent *r*s.

Using hierarchical regression, we entered posterior temporal asymmetry and prefrontal asymmetry as predictors of DQ. The two variables together accounted for 18.3% of the variance in the DQ, $F(2, 41) = 4.59$, $p < .02$. With the Laplacian-transformed data, the two variables together accounted for 25.1% of the variance, $F(2, 33) = 5.52$, $p < .01$.[2]

To better understand which hemisphere contributes more to the correlations described above, we implemented a procedure described in an article from Davidson's laboratory (Wheeler, Davidson, & Tomarken, 1993) that enables the examination of power at an individual electrode site after the variance associated with whole head power (which is a joint function of skull thickness and global activation) and power at the homologous electrode are statistically removed with a regression procedure. Figure 3 presents these data in the form of a topographic map that expresses the correlations between the residualized power measures at each site (interpolated across the scalp) and the DQ. Colors in the purple end of the continuum indicate that increases in activation (as reflected in decreased alpha power) are associated with a greater right-ear advantage. As can be seen from this figure, increased left-sided posterior activation is associated with a larger right-ear advantage, and decreased (indicated by orange) left-sided anterior activation is associated with a larger right-ear advantage. Residualized alpha power in the left posterior temporal site (T5) predicts DQ ($r = -.30$, $p < .05$), such that greater activation (i.e., less alpha power) is associated with a greater right-ear advantage. Activity at the homologous right hemisphere (T6) is uncorrelated with DQ ($p > .25$). Left-sided parietal activation also predicts greater right-ear advantages on the dichotic task ($r = -.38$, $p = .01$, between residualized P3 alpha power and DQ), whereas right-sided parietal activity is unrelated to dichotic performance ($r = .19$, $p > .20$). The difference between the correlations for the left and right hemisphere parietal activation measure is significant, $t(42) = 2.13$, $p < .05$. In the prefrontal region (FpF1/FpF2), decreased left-sided activation predicts a greater right-ear advantage ($r = .40$, $p < .01$), whereas increased right-sided activa-

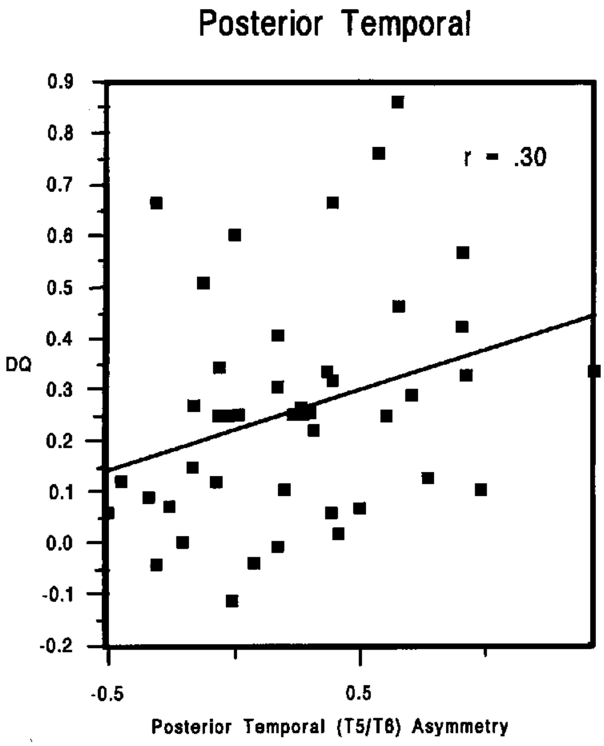

Figure 1. Scatter plot of relation between the dichotic quotient (DQ; R − L/R + L correct responses) and posterior temporal EEG alpha power asymmetry (log T6-log T5 alpha power). Higher numbers on the dichotic index reflect greater relative right-ear performance, and higher numbers on the EEG asymmetry score reflect greater relative left-sided activation.

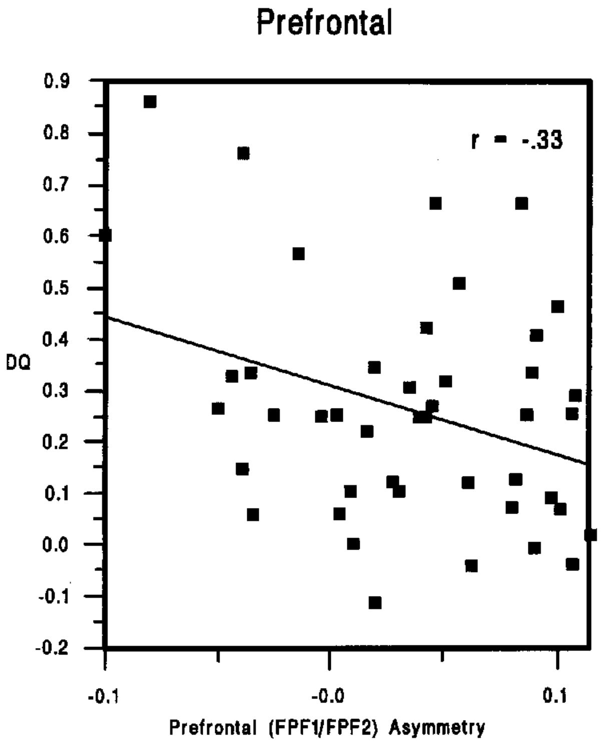

Figure 2. Scatter plot of relation between the dichotic quotient (DQ) and prefrontal EEG alpha power asymmetry (log FpF2-log FpF1 alpha power).

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[2] The EEG data were also rederived to both a Cz vertex reference and a Laplacian-transformed derivation. The pattern of findings with each of these two other references was identical to the linked ears findings. For Cz, the correlation between posterior temporal asymmetry and the DQ was .32, and the correlation between prefrontal asymmetry and the DQ was −.17. For the Laplacian, the correlation between posterior temporal asymmetry and the DQ was .30, and the correlation between prefrontal asymmetry and the DQ was −.38. Because previous findings from Davidson's laboratory on relations between baseline EEG asymmetry and other behavioral and biological variables is based on linked ears (e.g., Kang et al., 1991; Tomarken et al., 1992b), only data from this reference are reported.

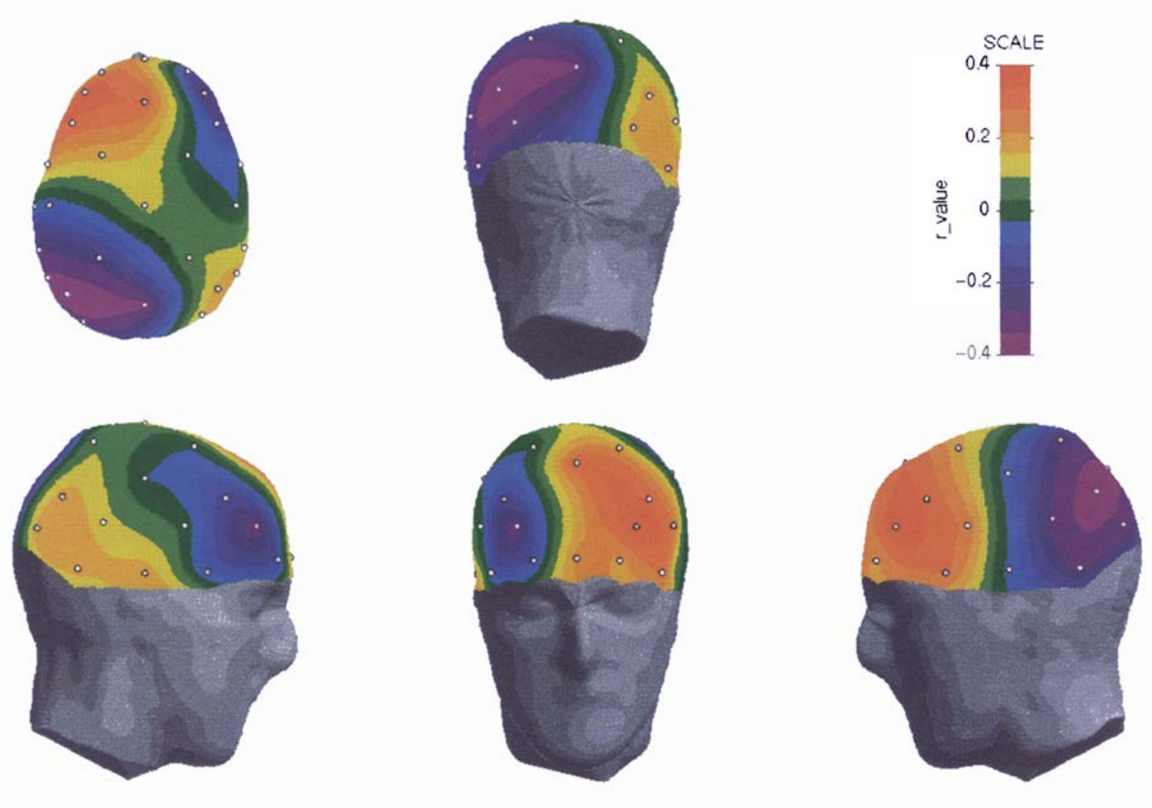

Figure 3. Correlation map between residualized alpha power and dichotic quotient (DQ; R − L/R + L correct responses). Purple regions indicate that decreased alpha power (i.e., increased activation) is associated with higher DQ, whereas the orange end of the spectrum indicates that increased alpha power (i.e., decreased activation) is associated with a higher DQ. Note that left-sided posterior activation is associated with a greater right-ear advantage, whereas right-sided anterior activation is associated with a greater right ear advantage.

tion predicts a greater right-ear advantage ($r = -.31, p < .05$). Because of the significant inverse relation between activation in FpF1 and FpF2, the difference between these correlations was not significant.

Discussion

The findings from this study indicate that measures of spectral power asymmetry obtained 4 months prior to the administration of a standard dichotic CV task predict the magnitude of right-ear advantage on this task. These are the first data to establish that direct measures of brain function predict individual differences in performance on a dichotic task and thus offer general support for the notion that there are individual differences in dispositional asymmetric activation that have cognitive consequences.

The pattern of data indicated that individuals with more left-sided activation in the temporo-parietal region had a larger right-ear advantage. Activation levels in the homologous right hemisphere regions were not significantly associated with dichotic performance. Of particular interest in our data was the fact that activation asymmetry in the prefrontal region also predicted dichotic performance, albeit in the opposite direction. Decreased activation in the left prefrontal region and increased activation in the right prefrontal were each associated with a greater right-ear advantage. This is all the more remarkable because asymmetry in the prefrontal and parieto-temporal regions was uncorrelated.

These findings suggest that auditory lateralization is probably not related to a single mechanism (cf. Jaencke, Steinmetz & Volkmann, 1992). It further underscores the specificity of activation asymmetries along the rostral-caudal plane. Low correlations among measures that putatively reflect hemispheric specialization (e.g., dichotic listening and divided visual half-field techniques) are not surprising in light of this specificity.

A second important implication of these data is that they provide another validation of the dichotic listening technique as a measure of hemispheric function. Participants with larger right-ear advantages have more left-sided posterior temporal-parietal activation and less left-sided prefrontal activation. These findings indicate that in addition to searching for the temporal lobe basis of dichotic performance (e.g., Hudghal, 1995), future studies might also examine dichotic performance in patients with unilateral frontal lobe lesions. In the future, it will also be useful to examine relations between dichotic performance and other measures of temporal and prefrontal region functioning.

These findings imply that the neural mechanisms reflected in dichotic performance are complex and include both posterior and anterior components. Moreover, because the anterior and posterior measures of activation asymmetry were related to dichotic performance in opposite directions, these findings argue for considerable caution in interpreting a right-ear advantage on a verbal dichotic task as reflecting a simple left-hemisphere processing advantage.

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