Brain Topogr (2010) 23:199–204
DOI 10.1007/s10548-009-0119-0

ORIGINAL PAPER

Gender Differences in Brain Functional Organization During Verbal and Spatial Cognitive Challenges

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Received: 28 August 2009 / Accepted: 6 November 2009 / Published online: 27 November 2009

Abstract This is a quantitative EEG study of gender-related differences in brain function. It is novel in that to elicit gender differences, it was necessary to apply a spatial filter to the EEGs that was effective for suppressing components common to different cognitive states. The study involved estimates of both the source-current power density in the brain and the complex coherence between different regions in the brain, the latter probably unique in EEG source analysis. Gender effects are shown in terms of differences in both lateralized source power and complex coherence in response to verbal and spatial cognitive challenges. The results provide evidence that verbal and spatial challenges are more lateralized in males than in females, that females are more verbal than males, that males are more spatial than females, that females verbalize more interpretively than males and that males verbalize more consequentially than females.

Keywords Normal brain function · Gender differences · EEG source analysis · Source power and coherence

This is one of several papers published together in Brain Topography on the "Special Topic: Cortical Network Analysis with EEG/MEG".

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Introduction

The methods of quantitative EEG have been applied in studies of the functional organization of the brain for over 35 years (Galin and Ornstein 1972). Many of these studies have implicated the left cerebral hemisphere in verbal cognitive challenges and the right hemisphere in spatial, holistic challenges. More recently, fMRI has been used to demonstrate gender differences in language lateralization with females showing a greater bilateralization than males (Vikingstad et al. 2000). We report here the results of a study of the EEG source configurations present during verbal and spatial cognitive activation in groups of young male and female subjects. Only the alpha band (8–13 Hz) is considered since it is now accepted that this band of frequencies is strongly reflective of normal cognitive function. The study is novel in that the EEG is analyzed at the level of the underlying source currents in terms of both power density and complex coherence between different brain regions. The results provide evidence that verbal and spatial challenges are more lateralized in males than in females, that females are more verbal than males, that males are more spatial than females, that females verbalize more interpretively than males and that males verbalize more consequentially than females.

Materials and Methods

Data was recorded from a total of 80 normal female and 65 normal male right-handed subjects. The mean age of the females was 27.2 (s.d. = 8.1) and the males 25.6 (s.d. = 8.4) years. All potential subjects were administered a pretest interview. Any who responded in the affirmative to having any history of neurological disease, birth complications, head trauma, psychiatric illness or substance abuse were excluded from the study.

EEGs were recorded from the subjects during two passive conditions, eyes closed (EC) and eyes open (EO), and during two active cognitive conditions, Word Finding (WF) and Dot Localization (DL). At least 3 min of recording was obtained from each subject. During the passive conditions, the subjects were told to relax, to think of nothing in particular and, during EO, to fixate on a point across the room. The tasks producing the cognitive challenges were developed by Miller et al. 1995 to be psychometrically matched in terms of difficulty, item-scale correlations and internal consistency. The test questions were presented to the subjects as slides projected from the rear of the recording chamber. Once having formulated an answer to a question, the subjects were asked to press a button to indicate that they were about to verbalize a response. By using the recording of the button signal, the EEGs were separated into cognitive and motor phases. Only the cognitive phases were analyzed. To ensure compliance, only those EEGs corresponding to correct responses to the test questions were utilized.

EEG recordings were obtained using 43-lead electrodes at standard electrode positions described in the American Electroencephalography Society Guidelines. All leads were referenced to the left ear and the impedance at each electrode was adjusted to be below 5 KΩ. All channels were digitized to 12-bits and sampled at a rate of 256 s^{-1}.

The digitized EEG records were visually edited off-line to select from each subject 20 nonoverlapping 1-s data segments corresponding to correct responses to the tasks. Segments that contained voltage spikes, large eye movements, or muscle activity were not selected for analysis. Rejection of segments resulted in 80, 79, 44 and 63 female and 65, 65, 43 and 50 male subjects being able to contribute 20-segment EEGs during the EC, EO, WF and DL conditions, respectively. Only those subjects who were able to contribute the 20 segments were admitted into the study.

Spectral Analysis

The Fast Fourier Transform (FFT) was applied to each row of the data matrix formed by the 43 EEG channels (as rows) and 256 time samples (as columns) in each 1 s segment. With 256 samples in each segment, the frequency resolution of the FFT along the columns of each transformed data matrix $\mathbf{V}(f)$ was 1 Hz spanning the range of frequencies from 0 to 255 Hz. Only the alpha band (8–13 Hz) was investigated in this study and therefore only the columns 9–14 in $\mathbf{V}(f)$ corresponding to these frequencies were selected.

The selected columns from the transformed data matrices were characterized in terms of their cross-spectra. The cross-spectral matrix $\Sigma(\alpha)$ was formed as:

$$\Sigma(\alpha) = \mathbf{V}(\alpha)\ \mathbf{V}^{T}(\alpha) \tag{1}$$

where $\mathbf{V}(\alpha)$ represents the alpha columns from $\mathbf{V}(f)$ to T is the complex conjugate transpose. An average 43 × 43 complex-valued cross-spectral matrix over the 20 segments obtained from each subject was then calculated for each of the EC, EO, WF and DL conditions. Each average matrix was then normalized by dividing all of its elements by its trace (the sum of its diagonal elements).

Estimation of the Cortical Source-Current Cross-Spectral Matrix

The source current cross-spectral matrix was estimated for each subject using a realistic head model obtained from the Montreal Neurological Institute (MNI). The model contains 4,079,350 cubic elements and was segmented into five tissue compartments, scalp, skull, CSF, gray matter, and other brain tissue. The elements contained in each tissue compartment were assumed to be isotropic with conductivities assigned according to Haueisen et al. 1997. The solution space consists of 51197 source locations distributed as a sheet in the gray matter compartment of the head model. Three mutually orthogonal current dipoles were placed at each source location. The lead-field matrix for the head model was obtained using a variation of the preconditioned conjugate-gradient method (Neilson et al. 2005).

The estimate of the cortical source-current cross-spectral matrix for each subject, $\mathbf{S}_i^2(\alpha)$, was obtained from:

$$\mathbf{S}_i^2(\alpha) = \mathbf{G}\ \mathbf{F}^{T}\ \bar{\Sigma}_i(\alpha)\ \mathbf{F}\ \mathbf{G}^{T} \tag{2}$$

where $\bar{\Sigma}_i(\alpha)$ is an individual subject's average cross-spectral matrix in some cognitive state, $\mathbf{G}$ is the Borgiotti-Kaplan BEAMFORMER solution to the EEG inverse problem (Sekihara 2001) and $\mathbf{F}$ is a spatial filter designed to suppress those spatial components in $\bar{\Sigma}_i(\alpha)$ that are common when two cognitive states are compared. The diagonal elements of $\mathbf{S}_i^2(\alpha)$ are the classical source-current power densities corresponding to each location in the solution space while the off-diagonal elements are the complex cross-spectra between the source-current densities at all possible locations. $\mathbf{F}$ is a 43 × 43 matrix, $\mathbf{G}$ is a matrix with 3 × 51197 rows and 43 columns and $\mathbf{S}_i^2(\alpha)$ is a square complex-symmetric (Hermitian) matrix with 3 × 51197 rows and 3 × 51197 columns.

The matrix $\mathbf{F}$ in Eq. 2 was included prior to the BEAMFORMER transformation to eliminate the components in the EEGs that were common to two cognitive states. It is derived from the simultaneous diagonalization of the average cross-spectral matrices across each subject group in each of two cognitive states. That is:

$$\Sigma_1(\alpha) = \mathbf{C} \ \ \mathbf{\Psi}_1 \ \mathbf{C}^{\mathrm{T}} \quad \text{and} \quad \Sigma_2(\alpha) = \mathbf{C} \ \ \mathbf{\Psi}_2 \ \mathbf{C}^{\mathrm{T}} \qquad (3)$$

where **C** is the matrix of alpha-band spatial patterns common to the two groups in two cognitive states, $\mathbf{\Psi}_1$ and $\mathbf{\Psi}_2$ are diagonal matrices containing the eigenvalues corresponding to each of the spatial patterns and $\Sigma_1(\alpha)$ and $\Sigma_2(\alpha)$are the average alpha-band cross spectral matrices obtained over all of the subjects in each of two cognitive states. **C** is determined from $\mathbf{C} = \left(\mathbf{P}^{-1}\right)^{\mathrm{T}}$where the matrix **P** contains the eigenvectors of either $\Sigma_1^{-1}(\alpha)\ \Sigma_2(\alpha)$ or $\Sigma_2^{-1}(\alpha)\ \Sigma_1(\alpha)$ both being the same. The columns of **C** were scaled such that $\mathbf{\Psi}_1 + \mathbf{\Psi}_2 = \mathbf{I}$, the identity matrix. After scaling, the eigenvalues in $\mathbf{\Psi}_1$ are sorted from largest to smallest along with the corresponding columns in **C**. As a result of these two operations, the first column (spatial pattern) in **C** accounts, in the first subject group, for the largest variance in the first cognitive state and the smallest variance in the second cognitive state. Similarly, the last column in **C** accounts, in the second subject group, for the largest variance in the second cognitive state (as given by the corresponding eigenvalue in $\mathbf{\Psi}_2$) and for the smallest variance in the first cognitive state (Koles et al. 2001). Only the first and last common spatial patterns in **C** were used to derive the spatial filter **F** where $\mathbf{F} = \mathbf{P}_R \ \ (\mathbf{C}_R)^{\mathrm{T}}$ and where $(\mathbf{C}_R)^{\mathrm{T}}$ represents the transpose of the first and last columns of **C** and $\mathbf{P}_R$ the first and last columns of $\left(\mathbf{C}^{\mathrm{T}}\right)^{-1}$. It should be noted that $(\mathbf{C}_R)^{\mathrm{T}}$ is of dimensions 2 rows by 43 columns and $\mathbf{P}_R$ is of dimensions 43 rows by 2 columns resulting in **F** having 43 rows and 43 columns. It is also noteworthy that if all the columns of **C** and **P** are retained then $\mathbf{F} = \mathbf{I}$.

Statistical Comparisons

To elicit possible differences in the cortical source power distribution in the subjects between two cognitive states, multiple statistical t tests were performed on the source powers estimated across all of the subjects at all of the locations in the source space. The total power at each location in each subject was obtained by summing the estimates of the three orthogonal source components at each location in the source space. The method used involves randomly assigning the subjects to the two cognitive states and tabulating the value of t_{max} across the entire source space (Holmes et al. 1996). The distribution of the values of t_{max} obtained after 5000 randomizations was used to determine the probability of significant differences when the subjects were assigned to their correct cognitive states. This method has the advantage of not relying heavily on the actual distribution of the source powers while simultaneously reducing the probability of obtaining false-positive results. The t_{max} distribution was used to determine the critical value of t, t_c, such that if $t > t_c$ the probability that there is no significant difference (two sided) between the sources powers in the two cognitive states is less than the chosen value of 0.01 ($P < 0.01$). The results of the statistical comparisons were summarized by displaying the statistically significant t scores on a 3D rendering of the cerebral cortex of the head model.

Results

Figure 1 shows the four views (Left, Right, Back, Front) of the cortical regions of the head model where the source-current power density is significantly greater during the EC condition than in the EO condition (red hues) and where the source-current power density is significantly greater during the EO than the EC condition (blue hues) in the *female group*. As expected, the power density is greater in the EC condition in the parietal-occipital regions of the cortex.

Figure 2 shows the cortical regions where the source-current power density is significantly greater during the WF active condition than in the EO passive condition (red hues) and where the source-current power density is significantly greater during the EO than in the WF condition (blue hues) also in the *female group*. The distribution of significantly different power densities is generally reversed from that seen in Fig. 1 in that there is greater source-current power during EO in parietal-occipital regions of the cortex than in WF.

Figure 3 shows the cortical regions where the source-current power density is significantly greater during the WF active condition than in the DL active condition (red hues) and where the source-current power density is significantly greater during the DL than in the WF condition (blue hues) in the *female group*. There is now an asymmetry in distribution of power densities where generally the right hemisphere appears to be more involved in the tasks than the left. In terms of the accepted inverse relationship between alpha-band power density and functional activity (alpha suppression), increased DL power is interpreted as increased verbal function while increased WF power is interpreted as increased spatial function. No significant differences in these maps could be elicited with $\mathbf{F} = \mathbf{I}$ the identity matrix (that is, without spatial filtering).

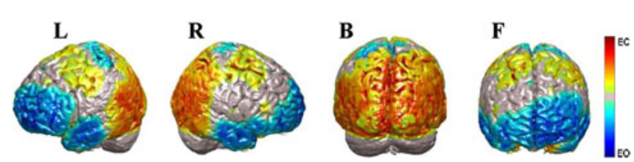

Fig. 1 Statistical t maps ($t > t_c$) of the cortical regions were the source current density is significantly different ($P < 0.01$) between the eyes closed (EC *red* hues) and eyes open (EO *blue* hues) resting conditions in the *female group*

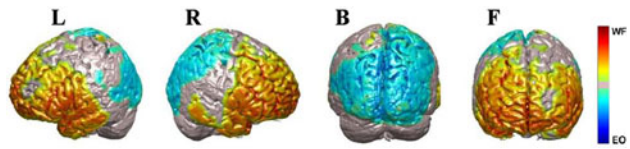

Fig. 2 Statistical t maps ($t > t_c$) of the cortical regions were the source current density is significantly different ($P < 0.01$) between the word finding (WF *red* hues) and eyes open (EO *blue* hues) conditions in the *female group*

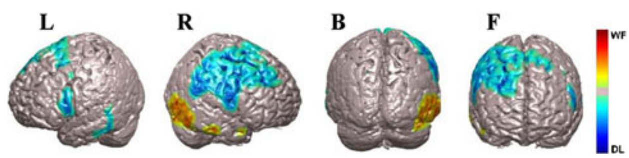

Fig. 3 Statistical t maps ($t > t_c$) of the cortical regions were the source current density is significantly different ($P < 0.01$) between the word finding (WF *red* hues) and dot localization (DL *blue* hues) conditions in the *female group*

Figure 4 shows the cortical regions where the source-current power density is significantly greater during the WF active condition than in the DL active condition (red hues) and where the source-current power density is significantly greater during the DL than in the WF condition (blue hues) in the *male group*. There is a stronger asymmetry in the distribution of power densities where generally, there is greater source power in right hemisphere during the WF task and greater source power in the left hemisphere during the DL task. No significant differences could be elicited with $\mathbf{F} = \mathbf{I}$.

Figure 5 shows two cortical patches (labeled x and y) on the left hemisphere between which estimates of the complex coherence of the source currents were obtained for each subject and for each cognitive state. The pre-frontal location contains 289 elementary dipole sources and the temporal location 284 sources. Homologous patches were also located on the right hemisphere. It was assumed that if these two brain regions are involved in an active cognitive challenge, a change in the coherence between the patches from that which occurs in the passive state will be observed. The complex coherence between the patches for each subject and for each cognitive state is calculated

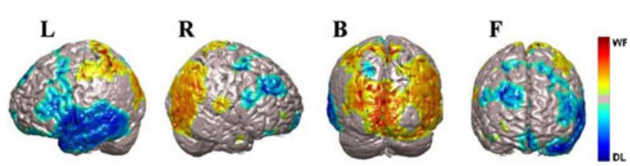

Fig. 4 Statistical t maps ($t > t_c$) of the cortical regions were the source current density is significantly different ($P < 0.01$) between the word finding (WF *red* hues) and dot localization (DL *blue* hues) conditions in the *male group*

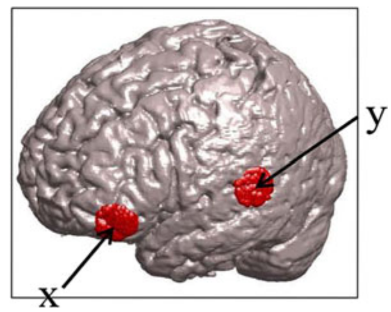

Fig. 5 Cortical patches x and y located on the *left inferior* frontal gyrus and on the *left superior* temporal gyrus between which the coherence is estimated during the various cognitive conditions

according to Eq. 4 by averaging the values of the off-diagonal and diagonal elements of the source current density matrix $\mathbf{S}_i^2(\alpha)$ over the patches.

$$\mathbf{C}_{xy}(\alpha) = \bar{\mathbf{S}}_{xy}(\alpha) \Big/ \sqrt{\bar{\mathbf{S}}_{xx}(\alpha)\,\bar{\mathbf{S}}_{yy}(\alpha)} \qquad (4)$$

where $\mathbf{C}_{xy}(\alpha)$ is the complex coherence between the patches, $\bar{\mathbf{S}}_{xy}(\alpha)$ is average the cross spectrum between all the sources in the two patches, $\bar{\mathbf{S}}_{xx}(\alpha)$ is the average source power in patch x and $\bar{\mathbf{S}}_{yy}(\alpha)$ is the average source power in patch y. By averaging over the patches, minimally biased and consistent estimates of the complex coherence between the cortical patches were obtained.

Figure 6 shows the complex coherence (in complex Cartesian coordinates) between the cortical patches in Fig. 5 for each of 39 *female subjects* performing the WF cognitive task and for each of 75 female subjects during the

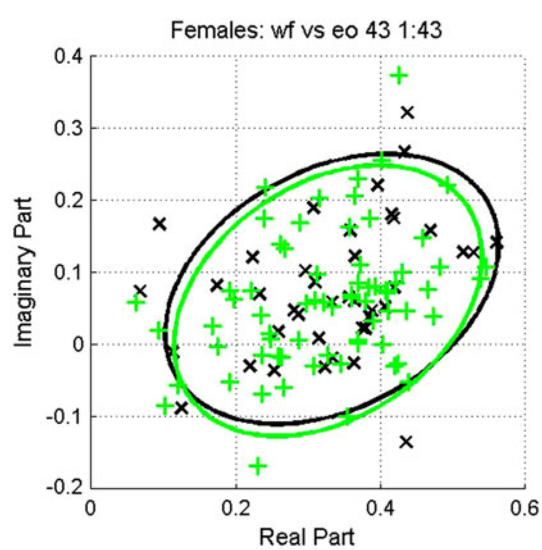

Fig. 6 Complex coherence values between the patches in Fig. 5 obtained for each of the members of the female group during WF (*black symbols*) and EO (*green symbols*) without spatial filtering (F = I)

EO passive condition with no spatial filtering (**F** = **I**). The black symbols (and enclosing ellipse) are the values for WF while the green symbols (and enclosing ellipse) are the values for EO. The ellipses enclose each of the distributions at two standard deviations from the complex mean. The figure suggests that, with no spatial filtering, there is no significant difference in the coherences between the two cognitive conditions.

Figure 7 shows the distribution of complex coherence values between the patches for the *female group* during the WF and DL cognitive challenges compared to the EO passive condition with common spatial patterns filtering (**F** ≠ **I**). The blue/red combination shows the right hemispheric coherence while the black/green combination shows the left hemispheric coherence. In each case, red and green indicate the EO condition. In each comparison, the spatial filter **F** was derived from the two common spatial patterns between the WF–EO and DL–EO conditions, respectively. The numbers in the rectangles beside each comparison indicate an overlap factor between the ellipses. The values of this factor range between 0 and 1 with a lower value indicating a smaller the overlap between the ellipses. The figure indicates that there is a shift in the distribution of coherencies from the passive condition in both active conditions and that this occurs in both hemispheres. In addition, the overlap between WF and EO is less in the left hemisphere than the right (0.68 vs. 0.88) and the overlap between DL and EO is less in the right hemisphere than the left (0.55 vs. 0.59).

Figure 8 shows the distribution of complex coherence values for the *male group* during the WF and DL cognitive challenges compared to the EO passive condition. In each comparison, the **F** filter is derived from the two spatial patterns common to the WF–EO and DL–EO conditions, respectively. The figure indicates that the overlap between WF and EO is less in the left hemisphere than the right

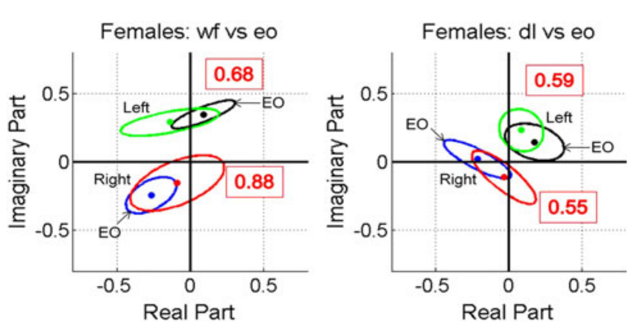

Fig. 7 *Ellipses* illustrating the distribution of complex coherence values for the members of the *female group* with the spatial filter derived from only the first and last common spatial patterns in each of the WF–EO and DL–EO comparisons. *Blue* and *black ellipses* indicate the EO condition while *red* and *green ellipses* indicate the active condition in each of the WF and DL cases (*left* and *right* panels, respectively)

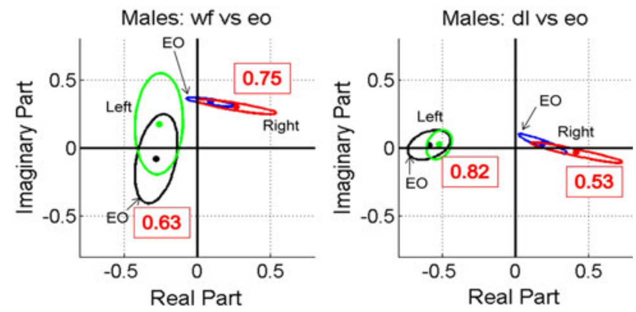

Fig. 8 *Ellipses* illustrating the distribution of complex coherence values for the members of the *male group* with the spatial filter derived from only the first and last common spatial patterns in each of the WF–EO and DL–EO comparisons. *Blue* and *black ellipses* indicate the EO condition while *red* and *green ellipses* indicate the active condition in each of the WF and DL cases (*left* and *right* panels, respectively)

(0.63 vs. 0.75) and the overlap between DL and EO is less in the right hemisphere than the left (0.53 vs. 0.82). This pattern is similar to that observed in the female group. However, it is also observed that, during WF–EO, there is a larger difference in overlap factors between the hemispheres in the female group than in the male group and, during DL–EO, there is a larger difference in overlap factors between the hemispheres in the male group than in the female group.

Figure 9 shows the connections between those cortical patches on the left hemispheres of the female and male groups where the overlap factors were less in the WF–EO comparison than in the DL–EO comparison. The assumption was that these regions of the cortex were most strongly involved in the verbal challenge. The seven patches shown were chosen arbitrarily with the intention of covering the hemisphere but including Broca's and Wernike's Areas. In the female group, 11/21 of the possible connections between the seven patches showed the effect while in the male group, 8/21 of the possible connections showed the effect. The figure suggests that, in the female group, there appears to be a change in connectivity between Broca's Area and Wernike's Area during verbal cognition while in

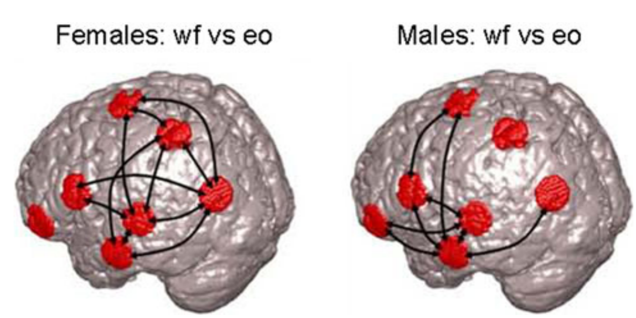

Fig. 9 Cortical patches in the *left hemisphere* where the overlap factor between the WF–EO comparison was less than that between the DL–EO comparison in the female and male groups

the male group there is a change in connectivity between Broca's Area and the prefrontal lobe during verbal cognition.

An analysis of the homologous patches in right hemisphere showed that, in the female group, the overlap factors were less in the DL–EO comparison than in the WF–EO comparison in 9/21 of the possible connections and in 11/21 of the possible connections in the male group. In terms of the number of connected patches, these ratios are opposite to that observed in the left hemisphere.

Discussion and Conclusions

The results obtained from an analysis of the alpha-band source-current power densities and complex cortical coherences underlying the EEG are suggestive of gender differences in how the respective brains deal with verbal and spatial cognitive challenges. Interpretation of the results is based on the assumptions that active cognitive functions result in the suppression of alpha activity everywhere in the brain and that active cognitive functions are reflected by changes in the connectivity between brain regions. This study has focused on the sources of the EEG at the cortical level by using estimates of both the source-current power density at individual cortical locations and the complex coherence between cortical regions. To elicit gender differences, it was necessary to apply a common spatial patterns filter to the EEGs presumably because patterns in the EEG common to the two cognitive challenges were sufficient to cloud differences in functional organization. It would appear to us that the application of the common spatial patterns filter in EEG source analysis involving populations is a novel aspect of this work. In addition, we are not aware of any previous studies that have utilized complex coherence to study changes in cortical connectivity.

The gender differences suggested by the results are that the verbal and spatial cognitive functions are more lateralized in males than in females, that females are more verbal than males, that males are more spatial than females, that females verbalize more interpretively than males and that males verbalize more consequentially than females. The main evidence for greater lateralization in males is the source current power differences shown in Figs. 3 and 4. Figure 3 perhaps indicates as well that not only is verbal cognition bilateral in the female group but that it might actually more heavily involve the right hemisphere than the left. Lateralization in males is also evident from Figs. 7 and 8 where the changes in the complex coherence are stronger in the left hemisphere during WF and in the right hemisphere during DL while these changes are not as strong in females. Some evidence for females being more verbal and males being more spatial comes is suggested by the coherence connection ratios in that more of the left hemisphere is involved in the verbal challenge in females and more of the right hemisphere is involved in the spatial challenge in males. The suggestion that females verbalize more interpretively than males and males more consequentially than females comes from the changes in cortical connectivity shown in Fig. 9 where Wernike's area appears to be more involved in the verbal challenge in females and the left prefrontal lobe more involved in the males.

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