Inverse Problems, Design and Optimization Symposium
Rio de Janeiro, Brazil, 2004

AN APPROACH TO FUNCTIONAL BRAIN MAPPING USING AN INVERSE SOLUTION BASED ON THE PRINCIPAL COMPONENT TRANSFORM

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ABSTRACT

The algorithm developed in this study integrates a frequency analysis of key frequency bands (Alpha, Beta, Delta, and Theta) with an inverse solution using the principal component analysis (PCA) to validate brain functional mappings associated with the characterization effects of an Auditory/Comprehension task, consistent with earlier findings involving the Wernicke and Broca's brain areas in relation to language comprehension. Spectral arrays and topographic maps are used for both listening and answering phases. The areas most responsible for the language comprehension were reverse-detected by means of an innovative search algorithm that iteratively relocates electrodes based on the direction of increasing PCA outcomes. The inverse PCA reveals that eigenvectors associated with the largest eigenvalues produce an interesting activity pattern directly attributable to those characteristic behaviors found in the different frequency bands. The clinical electroencephalogram (EEG) data involved 9 subjects at Miami Children's Hospital using the Electrical Source Imaging system with 256 electrodes.

INTRODUCTION

The study focuses primarily on exploring the human brain mechanisms responsible for auditory language comprehension and response functions. The purpose of this study is also to examine some of the EEG and the subjective effects of these tasks alone and in combination with the so mentioned band-frequency brain waves. Conceivably, as the EEG and subjective effects of these tasks become better understood, their use as a helpful tool in mapping the different functions of the brain will become more effective. This study also presents a new approach of interpretation on the EEG activity. This method is based in the analysis of the standard deviation of the principal components of predetermined groups of electrodes that represent different areas of the brain. In others words, for each of these groups, the eigenvalues were calculated and the standard deviation of this set of eigenvalues was considered with the purpose of ascertaining the level of standard deviation among these different groups. The anticipated outcome is that the highest standard deviation would point to the area on the brain with more correlation. The EEG of each subject was recorded during the Auditory/Comprehension test. The original EEG signals were divided into the auditory/comprehension phase of the test and its response time, in order to differentiate between the auditory phase and the response phase. The fluctuations of changes in the frequency spectrum are displayed for both tasks. By means of complex digital analysis, an evaluation of spectral arrays is shown in comprehensive color topographic maps illustrating the resulting brain activities in order to establish relationships between brain waves at different cortex locations. Methods such as the one proposed in this study may provide a picture of the dynamic neural processes underlying the allocation of attention during the performance of auditory and response tasks.

A new algorithm was thus developed to find specific patterns of dynamic brain behavior during monitoring of these processes. The algorithm developed in addition to producing detailed head topography maps showing the frequency changes that take place, also compares EEG signals of any new subject to be potentially included in the experimental study in order to evaluate similar/dissimilar behaviors. Auditory/comprehension and answering tasks as measured by the above mentioned brain waves activities identify specific involvement of each cerebral hemisphere. Each brain lobe (frontal, temporal, parietal, and occipital) is associated with different human functions [1, 2]. Therefore, it is important to know the involvement of the two brain hemispheres (Left and Right) as well as the involvement of each region of the brain during an auditory/comprehension test.

METHODS

Data Acquisition

EEG data was recorded using the ESI-256 recording system, under expert clinical supervision. The main modules of the system consist of 8 SynAmps (synchronous amplifiers). Software support consists of the Acquire program. The host computer executing this program controls the data acquisition of the SynAmp. This program performs all the acquisition process, including the display and storage of data. The EEG data collected was done is continuous mode using a 500 Hz sampling frequency for all subjects. The total number of electrodes used was 41 following the Modified Combinatorial Nomenclature (MCN) montage [3]. The EEG recording time for each subject was no more than 10 minutes. The subjects that took part in the experiment had standard requirements placed on them prior to the test. Each subject was laid down in a bed and a brief explanation about the test was given before starting with the procedure. The test administered to the subject is a standard auditory test used in behavioral medicine. The subject has to complete 34 sentences. It was required from the subject to have his/her eyes closed and to maintain the maximum possible relaxation in order to reduce the effect of artifacts in the EEG signal. Thirty to forty seconds of normal brain activity of the relaxed subject is recorded with the eyes closed in order to have a normal EEG behavior to be used as baseline behavior for comparative purposes. Once the EEG data was collected for all the subjects, the data was digitized in order to perform the second off-line digital signal processing on the EEG data.

Algorithm Development Process

EEG data recorded from all the channels was initially preprocessed through the ESI-256 in order to eliminate common EEG artifacts together with the background noise. The algorithm is designed to contend with 7 files, which consist of the baseline file and 6 auditory/answering files for each subject. The program reads the files and creates a matrix with 41 columns, where each column of a given matrix represents a digitized data recorded from a single electrode. The vertical axis thus represents all electrodes used in the experiment, and the horizontal axis displays the EEG data recorded at 500 Hz sampling frequency. A Fast Fourier Transform (FFT) is performed in these sections of the EEG data to determine the power content of the frequency bands in order to perform spectrum analysis. The resulting waveforms are displayed as a brain map, which will show the power distribution within each frequency band. In this case the FFT is applied to six different auditory/comprehension and answering blocks of the EEG signals (these signals are obtained from the same subject, and during the same task, either listening or answering).

The algorithm integrated the following important processing steps that led to the desired results:

- Removing the DC offset of the EEG signals by subtracting the average behavior for each electrode;
- Filtering unwanted noise of the EEG signals by applying Daubechies family of wavelet functions;
- Applying the Fast Fourier Transform in order to perform spectrum analysis;
- Averaging the 6 epochs of EEG, during auditory and response tasks in frequency and time domains;
- Subtracting the baseline of a subject from the averaged EEG signal of the auditory and answering blocks in frequency and time domains;
- Applying two algorithms on the available data. The first algorithm is a region search approach that uses the standard deviation of the eigenvalues of different regions as fitness function. It locates regions in the hope that they will coincide with the doctors' assessments with respect to as which regions are more active for each different task. The second algorithm was developed to test new subjects based on the power of the frequency bands of their EEG and to establish a comparison with known patterns.

Search Algorithm. The first search algorithm based its fitness function on regional EEG. The process consisted on finding the region whose EEG's eigenvalues have the highest standard deviation. Best candidate regions where usually integrated by consecutive electrodes, as depicted in Fig. 1. Table 1 shows the region definitions used in this study.

Table 1: Standard region definitions and corresponding electrodes

Group Number	Group Name	Electrodes within the Group
1	Frontal Left (FL)	FP_1, AF_7, F_7, FT_7, AF_3, F_3, FC_3
2	Frontal Right (FR)	FP_2, AF_8, F_8, FT_8, AF_4, F_4, FC_4
3	Temporal Left (TL)	FT_7, T_7, TP_7
4	Temporal Right (TR)	FT_8, T_8, TP_8
5	Parietal Left (PL)	TP_7, P_7, PO_7, CP_3, P_3, PO_3
6	Parietal Right (PR)	TP_8, P_8, PO_8, CP_4, P_4, PO_4
7	Occipital Left (OL)	PO_7, PO_3, O_1
8	Occipital Right (OR)	PO_8, PO_4, O_2
9	Central (C)	FC_3, C_3, CP_3, FC_Z, C_Z, CP_Z, FC_4, C_4, CP_4

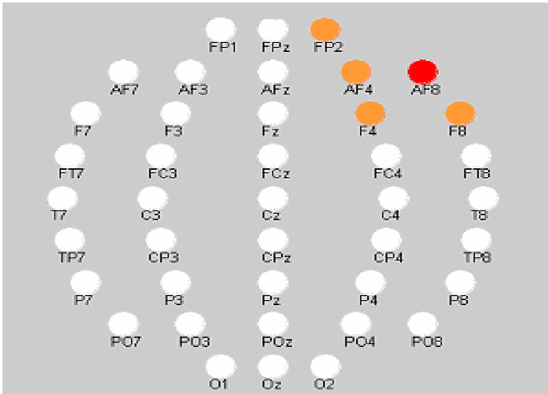

Figure 1: Nomenclature of the electrode placement.

Initially, the EEG was stored as an N*M matrix X, where N is the number of samples and M the number of electrodes analyzed.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1M} \\ x_{21} & x_{22} & \cdots & x_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ x_{N1} & x_{N2} & \cdots & x_{NM} \end{bmatrix}$$

Each matrix element x_{ij} denotes the discrete measurement taken from electrode j at time (sample) i. From this matrix, a matrix subset was constructed for each region that was created. The PCA analysis [4, 5] was then performed on those sub matrixes by calculating the elements of the covariance matrix C of each input matrix X (refer to equation (1)).

$$C_{ij} = \frac{1}{N-1} \sum_{k=1}^{N} (X_{ik} - \overline{X_i})(X_{jk} - \overline{X_j}) \qquad (1)$$

where $\overline{X}_i$ and $\overline{X}_j$ represent the means of the measurements of channels i and j. The PCA analysis was then performed based on the regional covariance matrixes.

The main steps for iteratively finding the regions can be described as follows:

1. Initialization:
   Set functional to 0
   Select a number of electrodes between 3 and 9
   Apply PCA analysis to the initial region and compute its functional
   Initialize motion operator M(e) on each electrode *e* (Right, Down, Left, Up) (Example: M(e)=[1,0,0,0] moves electrode *e* to the electrode location closest to its right).

2. Electrode relocation:
   Set RegionWasMoved to false
   For each electrode *e* do the following steps:
   - Apply previous motion operator to the electrode *e*
   - Evaluate functional of the new created region
   - If functional is not higher, then restore electrode to previous location and right-shift its motion operator, otherwise set RegionWasMoved to true

3. Iteration:
   Repeat Step 1 until RegionWasMoved becomes false – Optimum region is found, conforming the highest standard deviation of the eigenvalues of the PCA.

As it can be observed from the pseudo-code, the less electrodes used in the search, the more accurate solutions can be obtained, i.e., the centroid of the area covered by the electrodes is going to be closer to the area that develops the highest activity during the auditory comprehension task. The optimum regions obtained with the search algorithm after using the standard deviation of the eigenvalues as the fitness function coincided with the doctors' assessments. This corroboration was a fundamental outcome of the study.

Subject Evaluation Algorithm. As a supplementary approach to improve the developed application, an algorithm for future subject evaluation was designed for evaluating the regions according to the power of the frequency bands. This step was performed by calculating the relative mean power and absolute mean voltage for each electrode in time domain and in the frequency bands (Alpha, Beta 1, Beta 2, Delta, and Theta) of the different regions (Fig. 1), as shown in Equations (2.a) and (2.b).

$$\overline{P_r} = \sum_{i=1}^{N} x_i^2 \,/\, \sum_{j=1}^{N} y_j^2 \qquad (2.a)$$

$$\overline{V} = \frac{1}{N} \sum_{w=i}^{w=j} X_{(w)} \qquad (2.b)$$

with $i = f_{c1} \frac{N}{2} \cdot 2 \cdot f_s$ and $j = f_{c2} \frac{N}{2} \cdot 2 \cdot f_s$.

In equation (2), N is the total number of samples, X represents the voltage values for a specific band and Y represents the voltage values for all the bands; f_{c1} and f_{c2} are the cut off frequencies, f_s is the sampling frequency and $X_{(w)}$ is the vector containing the real values of the Fourier Transform. In this approach, two thresholds T_1 and T_2 of 1 and 2 standard deviation(s) respectively were applied in the positive and negative directions with respect to the absolute mean voltage of the signal in order to consider only those values V within the following ranges: [$+T_1 < V < +T_2$], [$V > T_2$], [$-T_1 < V < -T_2$], and [$V < -T_2$].

After creating specific data arrays for all subjects containing the number of active electrodes in each hemisphere and for each frequency band; a database was created to be used as a reference against to which each new subject should be compared. The criterion used for the selection of the case most similar to the test subject was the minimum energy difference criterion. The measure of similarity E_{pi} between the observed behavior of a subject *p* and a behavior stored in a record *i* of the database is computed as shown in Equation (3):

$$E_{pi} = \sqrt{(F_p - F_i)^2 + (T_p - T_i)^2 + (P_p - P_i)^2 + (C_p - C_i)^2 + (O_p - O_i)^2} \qquad (3)$$

where R_p and R_i represent the number of electrodes that were found active in region R of the subject and of the recordset, respectively. The regions used in this step were identified as F (Frontal), T (Temporal), P (Parietal), C (Central), and O (Occipital) respectively. This procedure was done with the five different frequency bands and for each hemisphere.

In this part of the application, topographical representations were performed for different testing subjects using a color-coding scheme in order to enhance locations in the brain that reflect increasing and decreasing changes.

RESULTS

The results reveal that there were substantial but characterizing differences in hemispheric activation at the frontal, temporal, parietal, central, and occipital sites. Equation (4) was used to calculate the asymmetry ratio, which relates the left hemisphere to the right hemisphere.

$$K = (R-L) / (R+L) \qquad (4)$$

with K being the asymmetry ratio, R is the number of electrodes active in the right hemisphere and L is the number of electrodes active in the left hemisphere. If the ratio is negative, that means that the left hemisphere was more active than the right and vice versa if the ratio is positive. Tables 2 and 3 reflect the asymmetry values for each frequency band and for both tasks (auditory vs. answer).

Table 2: Asymmetry Ratio (Auditory/Comprehension Task)

Bands	**Alpha**	**Beta1**	**Beta 2**	**Delta**	**Theta**
Positive	0.17	-0.25	0.238	0	0
Negative	-0.09	0	-0.091	0.71	-0.053

Table 3: Asymmetry Ratio (Answering Task)

Bands	**Alpha**	**Beta1**	**Beta2**	**Delta**	**Theta**
Positive	0.11	0.25	-0.33	0	0
Negative	-0.09	-0.14	-0.23	0.846	-0.27

Illustrative examples of the results obtained in this clinical study are as shown in Figure 1 and 2. The dots represent the positions of the electrodes used in this study and the color bar on the right side represents the voltage values. Note that there is a similar behavioral pattern of brain activity in all the subjects illustrated.

In terms of the PCA, Tables 4 and 5 show the values of the standard deviation of the set of eigenvalues resultant of the different regions. Note that the highest standard deviations are located in the frontal and temporal regions respectively.

Table 4: Standard deviation of the eigenvalues of the different regions during listening task for the 9 subjects.

Subj. #	FL	FR	TL	TR	PL	PR	OL	OR	C
1	593.2	527.0	146.3	222.0	308.0	471.5	361.6	491.5	529.9
2	364.2	720.9	45.8	148.6	85.4	116.4	87.9	115.1	173.9
3	919.8	384.8	80.6	95.0	94.3	163.3	106.8	151.0	293.8
4	184.3	800.1	26.9	47.5	171.3	180.3	212.8	172.8	146.0
5	397.4	429.0	51.6	42.8	77.2	55.0	51.5	39.5	155.3
6	406.2	200.5	105.2	62.5	152.2	108.8	121.4	124.2	175.4
7	2.3e+3	1.2e+3	197.9	146.9	74.9	85.4	49.5	58.5	184.3
8	2.1e+3	2.0e+3	130.9	200.3	139.7	268.1	114.6	240.0	349.0
9	332.2	718.4	87.5	142.3	252.9	220.4	231.8	198.6	297.9

Table 5: Standard deviation of the eigenvalues of the different regions during answering task for the 9 subjects.

Subj. #	FL	FR	TL	TR	PL	PR	OL	OR	C
1	2.7e+3	2.3e+3	486.9	648.2	542.8	755.6	511.0	603.3	1.2e+3
2	618.8	1.2e+3	115.8	223.0	188.4	252.8	169.9	240.5	341.2
3	1.5e+3	1.1e+3	112.9	157.8	134.1	222.9	120.6	172.0	471.6
4	1.2e+3	3.1e+3	90.8	177.8	269.7	246.6	296.3	193.4	282.7
5	1.1e+3	943.5	118.7	295.6	137.0	300.4	95.3	177.1	333.1
6	569.3	349.1	174.1	224.3	161.0	144.8	126.2	157.4	207.0
7	1.4e+4	9.1e+3	1.9e+3	1.4e+3	318.6	307.1	154.5	131.2	614.4
8	2.4e+3	2.9e+3	220.8	372.8	227.6	421.5	177.6	337.54	475.0
9	1.7e+3	3.2e+3	212.7	223.4	286.8	195.4	236.0	174.1	495.2

DISCUSSION

From these results, it is noted that during the auditory/comprehension task, changes in the beta frequency, which is involved with mental activity, is more predominant in the left hemisphere. This corroborates the premise that the left hemisphere is associated with more logical thoughts patterns and analytical approaches to problem solving [1]. Changes in the delta band, the slowest frequency that is associated with less concentration, is predominant in the right hemisphere. The right hemisphere dominance is associated more with relatively less skill in articulations of thoughts. Theta frequency activity is evidently increased in the frontal region of the brain during the auditory-comprehension task. This concurred with previous research that claims that theta activity is increased during internal focus [2]. Evident changes of alpha activity are observed in the parietal and frontal regions of the brain. These results are in agreement with previous studies that claim that EEG alpha rhythm in response to manipulations of task practice shows activity in the frontal and parietal regions [6]. During the answering task, it looks like the frontal region is the more active. Since Broca's area is located in the frontal lobe and it is associated with the production of language, the positive changes of most of the frequency bands are concentrated in the frontal cortex [7, 8]. With respect to the decreasing changes, alpha activity seems to localize its activity in the temporal and parietal lobes of both hemispheres, even though the activity is more oriented to the left hemisphere than the right. It was established that the major activity of the brain during the processes of listening and answering was noted in the temporal and frontal lobes. It is therefore appropriate to conclude that the integration of the two methods will constitute a unified method for assessing EEG activity during a listening/answering session that is conform to earlier findings suggesting involvement of the Broca's and Wernicke's areas.

Tables 6 and 7 presents the general analysis of the increasing and decreasing frequency changes with respect to the mean during the auditory/comprehension and response phases: (L&R stands for Left and Right).

Table 6: Final Analysis (Auditory Phase)

Auditory	Positive	Negative
Alpha	Right frontal	Temporal and parietal L&R (more to the left)
Beta 1	Right frontal and occipital	Temporal and parietal and some frontal to the L&R hemispheres
Beta 2	Occipital L&R, partially parietal	Temporal left
Delta	Bilateral frontal (oriented to left hemisphere)	Not much activity. Some rare activity in the temporal and central Right lobes
Theta	Bilateral frontal (L&R hemisphere)	Temporal and parietal left

Table 7: Final analysis (Response phase)

Answer	Positive	Negative
Alpha	Right frontal	Temporal and parietal L&R (more to the left)
Beta 1	Right frontal	Temporal and parietal in both hemispheres (more to the left)
Beta 2	Occipital and parietal left	Central left
Delta	Bilateral frontal (more oriented to right hemisphere)	Not much activity. Rare activity in central right lobes
Theta	Bilateral frontal	Almost no activity

CONCLUSION

The aim of this study was to identify those frequencies and regions in the brain that best characterize brain activity associated with an auditory/comprehension test. The objectives were to: (a) Analyze the differences that exist between auditory/comprehension tasks vs. answering phase; (b) Visualize through color-coding maps the different activities of the cerebral hemispheres (right vs. left); (c) Contrast the EEG signals of any new subject included in the experimental study in order to evaluate similar/dissimilar behaviors. All of these objectives were addressed through the analysis of the changes in activity introduced for the different frequency bands; and (d) Analyze the standard deviation of the principal components of predetermined groups of electrodes that represent different areas of the brain.

The results obtained reveal the following significant findings: (a) The left hemisphere was more involved with the auditory/comprehension task; (b) The frontal and temporal lobes were more involved in the Auditory and Answering tasks, recalling that Wernicke's area is located where the parietal lobe meets the temporal lobe and Broca's area is located in the frontal lobe; and (3) The highest standard deviation of the eigenvalues is located in the frontal and parietal areas of the brain in direct confirmation of the Wernicke and Broca areas.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation Grants EIA-9906600 and HRD- 0317692, and the Office of Naval Research Grant N00014-99-1-0952, as well as the NSF Graduate Research Fellowship in support of Ms. Mercedes Cabrerizo. The support of Miami Children's Hospital is greatly appreciated.

REFERENCES

[1] B. Greenstein and A. Greenstein, Color Atlas of Neuroscience, Neuroanatomy and Neurophysiology, Thieme Stuttgart New York, 2000.
[2] F. H. Martini, Fundamentals of Anatomy & Physiology, Fifth Edition, Prentice Hall, New Jersey 07458, 2001.
[3] Gevins, A., Remonds, A., Handbook of Electroencephalography and Clinical Neurophysiology, 1, 1987.
[4] R. C. Gonzalez, R. E. Woods, Digital Image Processing, Addison-Wesley Publishing Company Inc., 1993.
[5] R. O. Duda, P. E. Hart, D. G. Stork, Pattern Classification, John Wiley & Sons Inc., 2001.
[6] G.J.C. Lokhorst. "The First Theory About Hemispheric Specialization: Fresh Light On An Old Codex", Journal of the History of Medicine and Allied Sciences, Vol. 51 No. 3, pp. 293-312, 1996.
[7] Inouye, Ishihara, and Shinosaki, "Mathematically Derived Frequency Correlates in Cerebral Function: Theoretical and Clinical Implications for Neurofeedback Training", Journal of Neurotherapy, Vol. 1, No. 2, pp. 1-15, 1995.
[8] A. Gevins, Smith, "Neurophysiological Measures of Working Memory and Individual Differences in Cognitive Ability and Cognitive Style", Cerebral Cortex, Vol. 10, pp. 829-839, 2000.

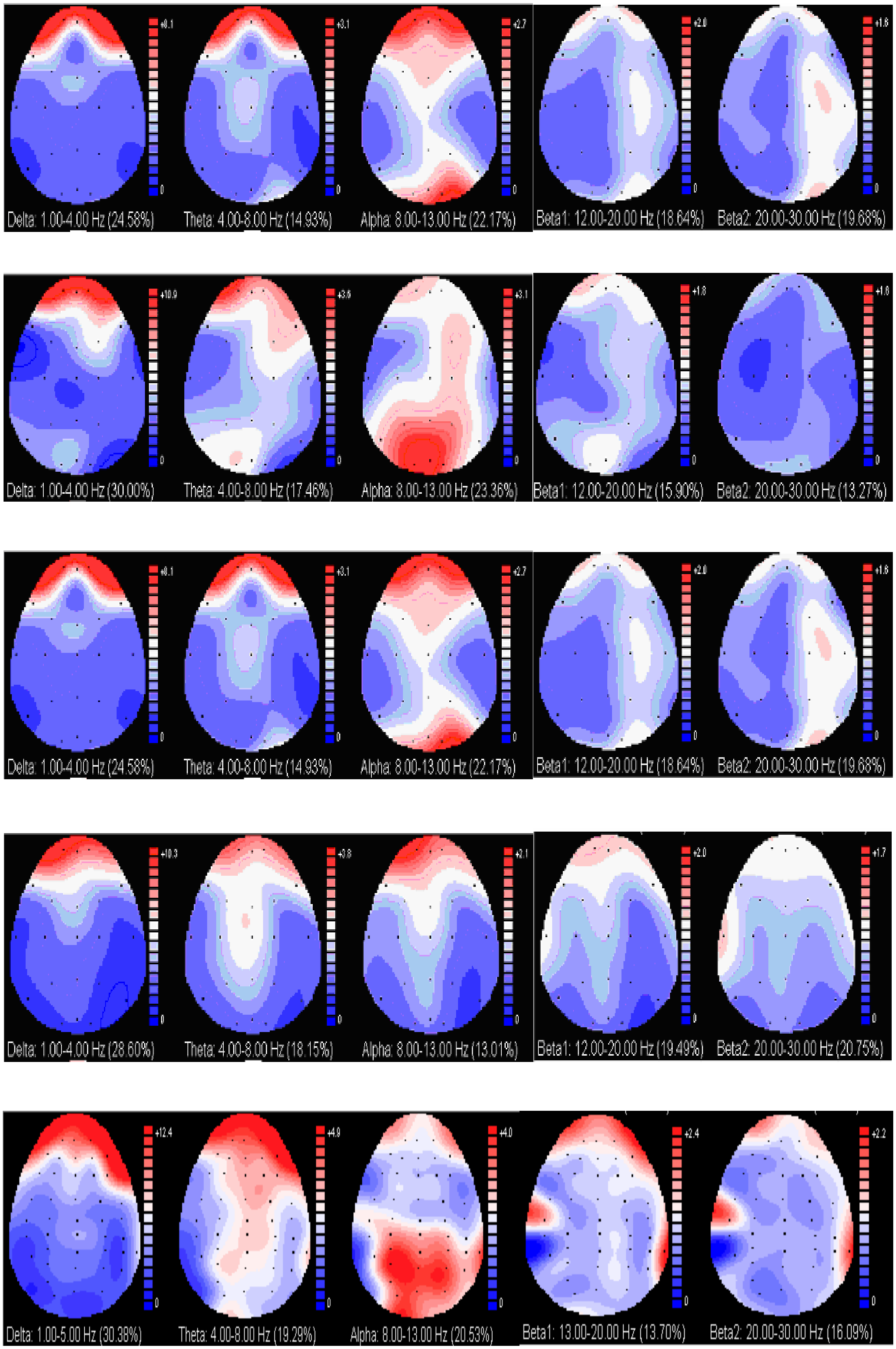

Figure 1: Illustrative frequency **a**ctivities in the 9 subjects during auditory/comprehension task.

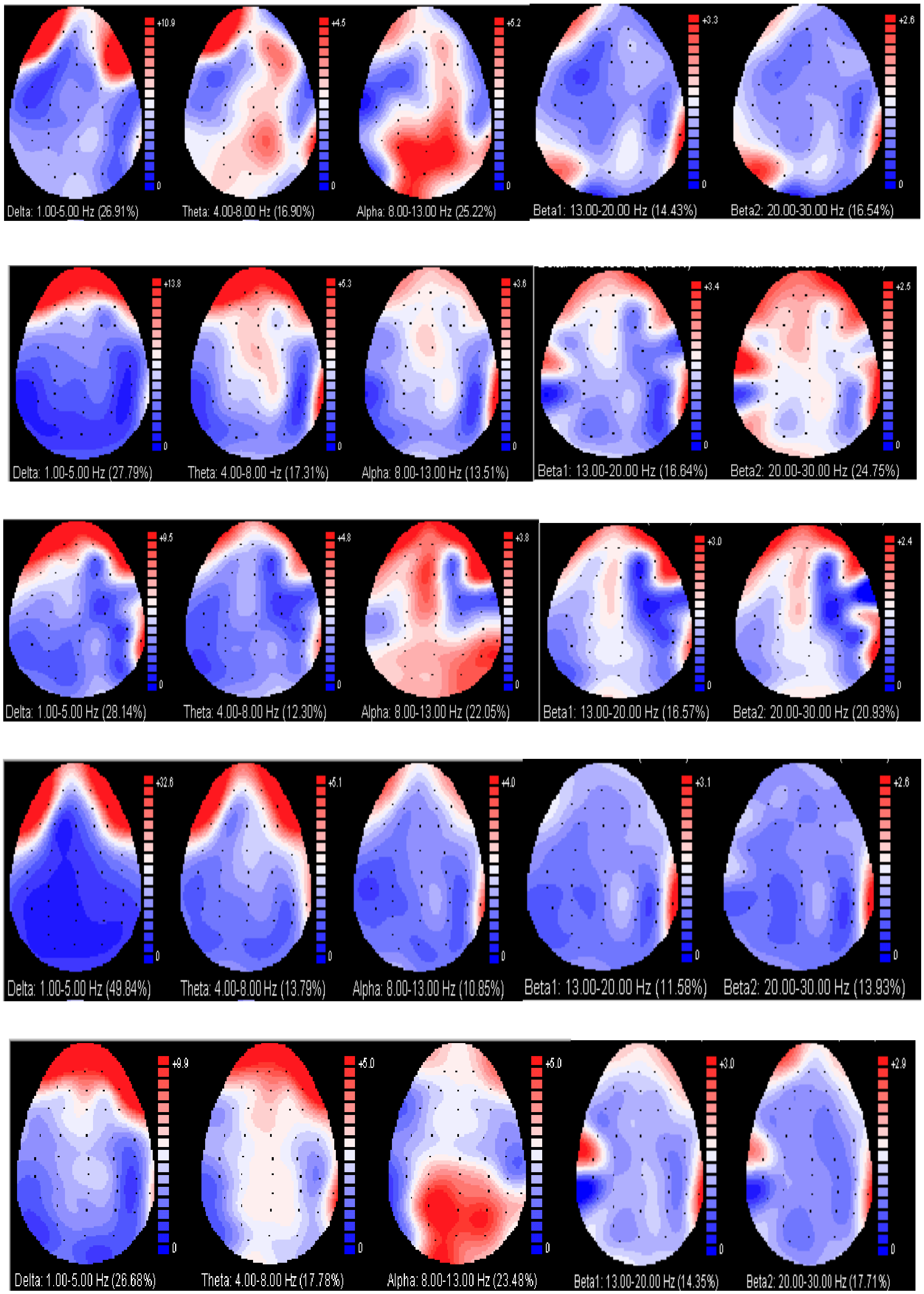

Figure 2: Illustrative frequency **a**ctivities in the 9 subjects during answer task.