Interpreting EEG functional brain activity

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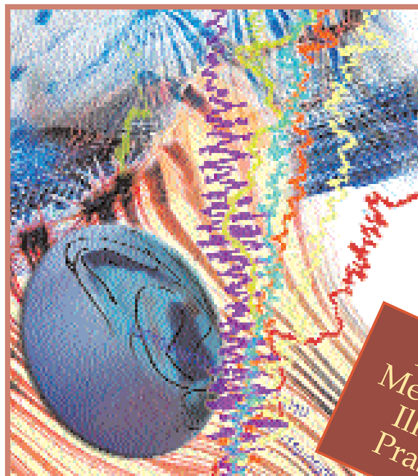

One critical issue in the pre-surgical evaluation of brain operations is mapping regions that control speech and language functions (Fig. A). The goal is to preserve these regions during surgery. Mapping done by electrically stimulating the cortex subdurally (under the skull on the cortical surface of the brain) with implanted electrodes is highly effective. However, this procedure also introduces a high risk for cortical tissue injury, and should be used only for extreme cases. Mapping the brain with non-invasive techniques such as EEG recordings (done through externally placed electrodes on the scalp) is possible. We believe that the results produced could be effective and useful; yet, they would not present any risk to the patient. It is this last assertion that this study is trying to attain.

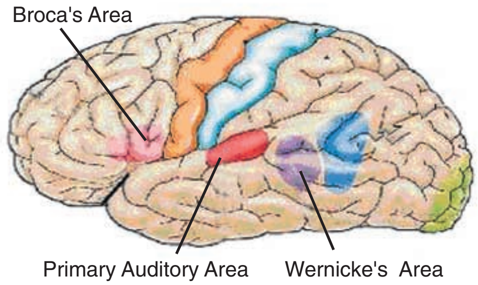

Fig. A Human Cortexes

Figure B shows how auditory inputs travel from the ear to the auditory cortex and from the cortex to the auditory association cortex. From the association areas, the signals are projected to Wernicke's area, where comprehension is carried out. The information is then projected to Broca's area, where speech is generated. This information is sent to the frontal cortex and the pre-motor areas for processing prior to being sent to the motor cortex, where the words are produced. Knowledge of these pathways is relevant in order to better understand the functional maps of brain activities.

Earlier studies have determined that Alpha (8-13 Hz) waves occur whenever the person is alert, but not actively processing information. Beta1 activity is defined as 13-20Hz and Beta2 activity as 20-30Hz. (The Beta wave was subdivided in the study to look for possible differences between low Beta and high Beta frequencies.) Beta waves in general are considered fast (high frequencies or high oscillation) and are the dominant rhythm in those who are alert and are listening and thinking (processing information), among other activities. The lowest wave frequencies are Delta (1-4Hz), and they occur in deep sleep. Theta waves (4-8Hz), on the other hand, are classified as slow waves (low frequencies or low oscillation), and are found to be strong during internal focus and during meditation. Figures C and D show these four waves' frequency bands.

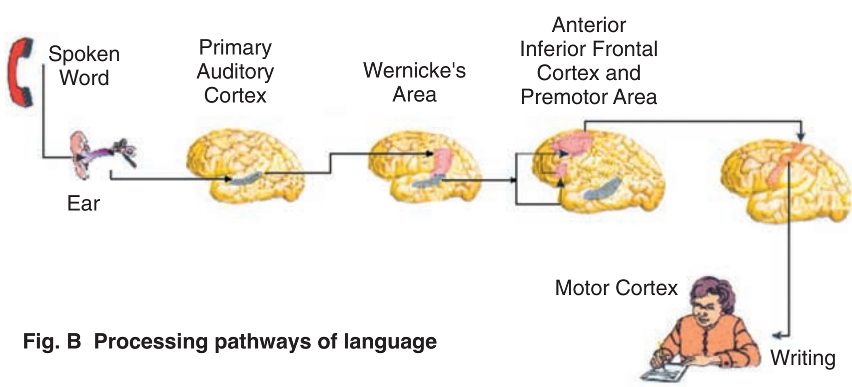

Fig. B Processing pathways of language

Auditory/comprehension and answering tasks as measured by these four main brain waves activities identify specific involvement of each cerebral hemisphere. Each brain lobe (frontal, temporal, parietal and occipital) is associated with a different human function. In general, the frontal lobe is concerned with reasoning, parts of speech and movement, emotions, and problem-solving; the temporal lobe is concerned with hearing and memory; the parietal lobe is concerned with perception of stimuli such as touch and pain and the occipital lobe is concerned with vision. 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.

This study primarily explored the human brain mechanisms/patterns responsible for auditory language comprehension and answering functions in a non-invasive manner. 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. The study involved 15 subjects (age 23-42) with 12 males and 3 females. The subjects were chosen randomly, sex and age were not issues.

The study also examined some effects of the EEG that are produced through the auditory/comprehension tasks given, and through responses provided by the subjects. They were looked at alone and in combination with the four main brain waves.

The EEG was recorded for each subject during the Auditory/Comprehension test from 41 scalp sites. The electrodes were placed according to the Modified Combinatorial Nomenclature (MCN). EEG montages are designed to be symmetrical about the midline in order to obtain information from the left and right hemisphere relating to amplitude and difference of the phases. The 10-20 system is the most commonly used montage. The "10" and "20" refer to the 10% and 20% inter-electrode distance. This system could be expanded to use more electrodes in order to obtain more information from specific areas of the scalp and to improve EEG spatial resolution. Taking this into consideration, the American Clinical

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Neurophysiology Society (ACNS) has developed a more extensive placement scheme using modified combinatorial nomenclature (MCN). With the use of this scheme, which is illustrated in Fig. E, more recording electrodes are used. This yields a higher spatial resolution and improved signal quality. In this specific study, only the electrodes shown in blue were used).

The original EEG signals were divided 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. Using a complex digital analysis, an evaluation of spectral arrays is shown in comprehensive, colorful, topographic maps. They illustrate the resulting brain activities in order to establish statistical relationships between brain waves at different cortex locations. By this means, we may gain insight about the fast shifting functional networks that are formed between the cortical regions. In other words, methods such as proposed here may show the dynamic neural processes underlying the allocation of attention during auditory and response tasks.

A new algorithm was developed to find any specific patterns of dynamic brain behavior during monitoring of these processes. The goal is to interpret and characterize the EEG activity during auditory/comprehension tests. The algorithm produces detailed head topography maps that show the frequency changes that take place. The algorithm also compares EEG signals of any new patient possibly included in the experimental study in order to evaluate similar/dissimilar behaviors against those already in the database.

Data acquisition methods

EEG data was recorded using the ESI-256 recording system under expert clinical supervision. Figure 1 illustrates the high-resolution recordings of EEG activity performed at the scalp level. The main modules of the system consist of 8 SynAmps (synchronous amplifiers), which are connected to a head-box. As illustrated in Fig. 2, each head-box inputs up to 32 channels. The first SynAmp stage is in the head box. Support consists of the "Acquire" software program. The host computer executing this program controls the data acquisition of the SynAmp. This program performs all the acquisition processes, including the display and storage of the data recorded.

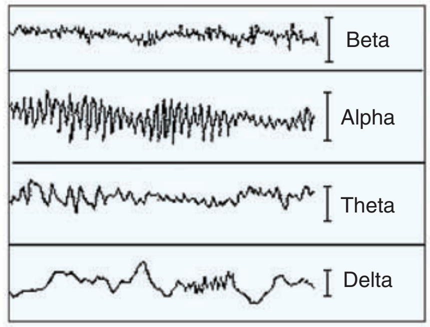

Fig. C Frequency Bands

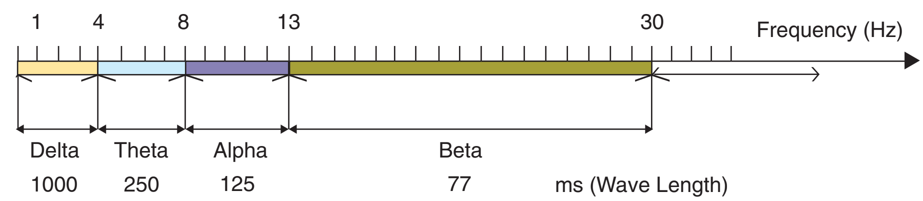

Fig. D Boundaries of commonly used frequency bands

The EEG data was collected in a continuous mode using a 500 Hz sampling frequency for all the subjects. The total number of electrodes used was 41 following the MCN montage. This is a total of 500x41 data points collected per second per subject. The EEG recording time for each subject was no more than 10 minutes. Even so, the continuous file generated took a large amount of memory. The gain of the amplifiers was set to 100.

The cut-off frequencies for the filters used were 0.15 Hz for the High pass and 100 Hz for the low pass. This range allowed us to eliminate unwanted frequency components and, at the same time, fit our data to the spectrum ranges most common when analyzing EEG signals.

The subjects who took part in the experiment had standard requirements placed on them prior to the test. Each subject laid in a bed with 41 electrodes connected to the scalp. An explanation about the test was given to the subject before starting the procedure. For the test, the subject listened to 34 sentences and had to complete each one. The auditory/comprehension test is a standard test used in behavioral medicine. A test example is: Water looks blue and grass looks ________. (Answer: green)

Also, the subject had to have his or her eyes closed and maintain the maximum possible relaxation to reduce the effect of artifacts such as eye blinks and body movement in the EEG signal. Thirty to forty seconds of normal brain activity of the subject relaxed (with eyes closed) was recorded. This was used as a baseline for normal EEG behavior for comparative purposes.

Once the EEG data was collected for all the subjects, the software provided with the Scan 4.1 converted it to ASCII files. This conversion allowed a further off-line processing of the data. A program was written in Matlab 6.1 in order to perform the second off-line digital signal processing on the EEG data.

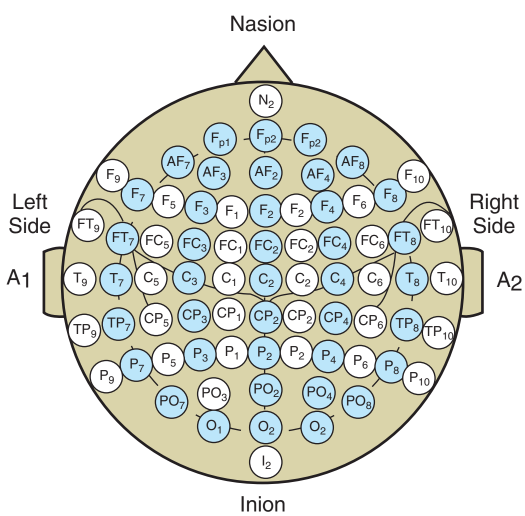

Fig. E Modified Combinatorial Nomenclature

Algorithm development process

A new algorithm was developed to help process the data for this study. EEG data coming from all the channels was meticulously observed. Preprocesses were implemented in order to eliminate common EEG artifacts together with the background noise. The software program developed analyzed seven files: the baseline file and the six longest

Fig. 1 The ESI-256 System with its 8 SynAmp amplifiers with host computer and display monitor

auditory/answering files. Since there were 34 questions in the test, the length of the questions varied so we selected the longest ones in order to perform a

Fig. 2 8 x 32 electrode head-boxes

more accurate analysis of the EEG frequencies at the moment of the listening and answering phases. Figures 3 and 4

Table 1 Asymmetry Ratio (Auditory Task Cumulative Values)					
Bands	Alpha	Beta 1	Beta 2	Delta	Theta
Positive	0.17	- 0.25	0.238	0	0
Negative	- 0.09	0	- 0.091	0.71	- 0.053

display typical examples of the listening and answering EEG data for all the electrodes. The y-axis represents all the

Table 2 Asymmetry Ratio (Answer Task Cumulative Values)					
Bands	Alpha	Beta 1	Beta 2	Delta	Theta
Positive	0.11	0.25	- 0.33	0	0
Negative	- 0.09	- 0.14	- 0.23	0.846	- 0.27

electrodes used, and the horizontal axis displays the EEG data recorded at the 500 Hz sampling frequency.

The program reads the files and creates a matrix with 41 columns. Each column for a given matrix represents digitized data recorded from a single electrode. A Fourier Transform (FT) is performed on 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 to show the power distribution within each frequency band.

In this case, the FT 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.) For each subject, 34 recordings were considered, out of which six were used for analysis. The six signals chosen were void of eye blinks and body movement. Functional mappings of the brain must be made accurate; therefore, this EEG preselection process is only done to enhance the representation and not to distort the results. Once the signals were carefully chosen, a conversion to ASCII files was performed for compatibility in the processing.

The algorithm integrated the following processing steps that led to the desired results: 1) Removing the DC offset of the original EEG signals by subtracting the average behavior for each electrode;

2) Getting rid of the unwanted noise of the original EEG signals by applying a wavelet transform (using Daubechies family of wavelet functions). When data is decomposed using wavelets, some filters act as averaging filters (approximation coefficients) and others produce details. If the details are small, they might be omitted without substantially affecting the main features of the EEG data;

3) Applying the Fast Fourier Transform (FFT) on sections (obtained from the same subject and during the same task) of the EEG data that was previously fitted to a power of 2 number of points needed for the FFT. When the digitized EEG data is transformed from an array of voltage values in the time domain to the frequency values in the frequency domain by applying the Fourier Transform, the formula is based in an array of a length of a power of 2 ($N=2^n$). This move is done to facilitate the implementation of the Fast Fourier Transform (FFT). This is a mathematical constraint that yields a faster time in executing the FFT. The procedure was repeated for each electrode in order to perform the spectrum analysis;

4) Getting the average of the six epochs of EEG, during the auditory and response tasks in the frequency domain for the same test administered six times;

5) Subtracting the baseline of a patient from the averaged EEG signal of the auditory and answering blocks in frequency domain;

6) Performing the calculation of the relative mean power and the absolute mean voltage for each frequency band (Alpha, Beta 1, Beta 2, Delta, and Theta), refer to Equations (1) and (2).

$$\overline{P_r} = \frac{\frac{1}{N}\sum x_{(i)}^2}{\frac{1}{N}\sum y_{(i)}^2} \qquad (1)$$

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

Where i and j are defined as follows:

$$i = f_{c1}\frac{N}{2}\cdot 2\cdot f_s$$

and

$$j = f_{c2}\frac{N}{2}\cdot 2\cdot f_s$$

With N being in the two equations the total number of samples, $\overline{P_r}$, in the first equation, is the relative mean power; x represents the voltage values for a specific band, and the y values represent the voltage values for all the bands. In the second equation, $\overline{V}$ is the mean voltage and 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;

7) Calculating two thresholds of 1 and 2 standard deviation(s) (T_1 and T_2) in the positive and negative directions with respect to the absolute mean voltage of the signal in order to consider only those values within the following ranges: [$+T_1$ $+T_2$] and [$> T_2$] and [$-T_1$ $-T_2$] and [$< -T_2$];

8) Creating specific data arrays that contain the number of active electrodes in each hemisphere for each frequency band mentioned earlier;

9) Applying the minimum energy difference criterion to these arrays in order

to attain similarities/dissimilarities between different subjects. Equation (3) was used to calculate the energy difference between any unknown subject and all the existence subjects from the database.

$$E = \sqrt{(F - U_1)^2 + (T - U_2)^2 + (P - U_3)^2 + (C - U_4)^2 + (0 - U_5)^2} \qquad (3)$$

Where, E is the minimum energy value, U is the quantity of the unknown patient and F, T, P, C, and 0 define the number of electrodes that are active in the Frontal, Temporal, Parietal, Central, and Occipital regions respectively. This procedure is done with the five different frequency bands and for each hemisphere (left & right). A complete analysis for each band such as alpha, beta 1, beta 2, delta, and theta will be provided in order to cope with the changing fluctuations of the different frequency components;

10) Performing topographical representations using a color-coding scheme in order to enhance locations in the brain that reflect increasing and decreasing changes. Results obtained in this clinical study come in support of the algorithm developed in this study. Figure 5 shows an example of the distribution of activity in the scalp of alpha, delta and theta bands during an auditory/comprehension task. The dots represent the positions of the electrodes used in this study and the color bar on the right side represents the voltage values.

Results

The final results reveal that there were substantially 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.

$$K = \frac{(R - L)}{(R + L)} \qquad (4)$$

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. If the ratio is positive, then the right hemisphere is more active.

Tables 1 and 2 reflect the asymmetry values for each frequency band and for both tasks (auditory vs. answer). The results show the distribution of activity depending on the frequency under analysis. For instance, there seems to be a slight increase in alpha-activity in the right hemisphere with respect to the mean during the auditory/comprehension process, even though alpha activity is evident in the left hemisphere. Activity in both hemispheres depends on the person and the alertness level at that specific moment. Nevertheless, for decreases with respect to the mean, even though the activity is distributed bilaterally in the brain, there exists a little more activity in the left hemisphere. Delta and theta frequency bands have a bilateral distribution of increasing changes of activity in both hemispheres.

In observing the topographical maps, during the auditory/comprehension task it seems there are changes from the baseline activity in the beta1 frequency, which is involved with mental activity, that are more predominant in the left hemisphere. This corroborates with the premise that the left hemisphere is associated with more logical thought patterns and analytical approaches to problem solving. Changes in delta waves, associated with less concentration, are predominant in the right hemisphere. The right hemisphere dominance is associated with being relatively less skilled in the articulations of thoughts. (The left hemisphere is involved with processing of language and the right hemisphere is involved with the processing of nonverbal stimuli.)

Theta frequency activity is evidently increased in the frontal region of the brain during the auditory-comprehension task. This concurred with previous research that claimed that theta activity is increased during internal focus. 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 claimed that EEG alpha rhythm in response to manipulations of task practice and load shows activity in the frontal and parietal regions. (When the subject is trying to listen to a statement, a load is applied to the brain because it is trying to understand the task inferred by that statement.)

During the answering task, the frontal region appears to be the more active one. Since Broca's area (which is associated with the production of language) is located in the frontal lobe, the positive changes of most of the frequency bands are concentrated in the frontal cortex. In addition, there are some changes in activity also in the posterior and central regions for beta frequency.

With respect to the decreasing changes, alpha activity seems to localize

Table 3 Final Analysis (Auditory Task)

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

Table 4 Final Analysis (Answering Task)

Answering	Positive	Negative
Alpha	Right frontal	Temporal and parietal Left and Right (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. Some rare activity in the central right lobes
Theta	Bilateral frontal	Almost no activity

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. Based on the asymmetry ratio, we can conclude that the increasing and decreasing changes with respect to the mean during the auditory/comprehension and response phases are located in the cerebral cortex as shown in Tables 3 & 4.

The final results, based on the minimum energy difference criterion values, were provided for every frequency band of the unknown subject with respect to the ones already in the database. The minimum distance and the numbers that specify the subjects in the database show which behaviors were similar and are displayed along with a topographical mapping of the unknown subject. That is, when the program is executed, it creates two arrays of activity for the right and left hemispheres. The vectors represent how many electrodes are active, either in the increasing or decreasing order, in each region and for each hemisphere. As a result, four vectors are created for each subject: for left and right hemispheres and for negative and positive changes resulting in left positive, left negative, right positive, and right negative. Each of the four vectors is composed of the following five elements [F T P C O], where F means frontal , T means temporal, P means parietal, C means central, and O means occipital. Finally, the minimum energy criterion is calculated based on the following formula:

$$E = \sqrt{(F-U1)^2 + (T-U2)^2 + (P-U3)^2 + (C-U4)^2 + (O-U5)^2}$$

or

$$\sum (D-U)^2 \tag{5}$$

Where E is the minimum energy value, U is the unknown array, which is equal to the following: U = *[UF UT UP UC UO]*. Each value represents the quantity of active electrodes for each region of unknown patient and *F, T, P, C, O* define the distinct regions analyzed.

This procedure was done with the five different frequency bands. A complete analysis for each band such as alpha, beta 1, beta 2, delta, and theta were provided. The reason was to cope with the changing fluctuations of the different waveforms and to analyze a specific behavior of any new subject with respect to the behaviors already presented in all the subjects in the database.

Discussion/conclusions

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:

1) Analyze the differences that exist between auditory/comprehension tasks vs. answering phase,

2) Visualize through color-coding maps the different activities of the cerebral hemispheres (right vs. left), and

3) 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.

The statistical analysis of the results obtained reveals the following outcomes:

1) There were differences of regions activation in all the frequency bands between the left and right hemispheres;

2) There were differences in the activation of brain regions (frontal, temporal, parietal, central, and occipital); and

3) There were no relevant differences in the alpha, delta, and theta bands between the two tasks.

With this study, we confirmed that patterns of brain activity in different regions exist that related the different behavior of all the frequency bands in a similar way for all the subjects. Mapping the brain with non-invasive techniques should therefore produce results that are effective and yet do not present any risk to the patient.

The patients were very relaxed before and after the test. Conditions were set for the subjects to be very comfortable. They laid in a hospital bed in a comfortable position and in dark room void of any external stimulus (free of sound and visual distractions). Furthermore, they have their eyes closed.

What were the limitations of the study? EEG activity is complex and intricate in nature. Therefore, every effort should be made to minimize the effects of artifacts that may skew the interpretation results. That is why the constraints in the experimental set up are stringent under a well-controlled environment. Also, only a small number of people were tested. These are patients were available for testing at Miami Children's Hospital under strict clinical supervision. At this stage of the study, gender and age were not issues. What was important in this first phase of the study was to show the brain activity and topography related to the auditory/comprehension and speech tasks. The algorithm developed is trying to interpret the most

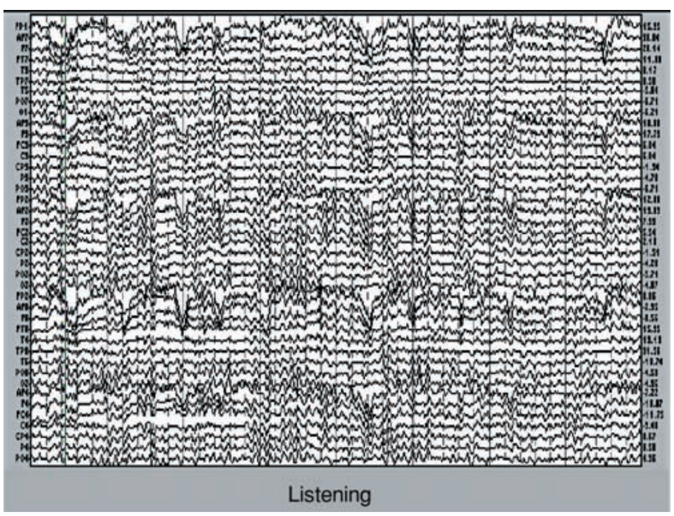

Fig 3 Block of EEG data recording during the listening phase

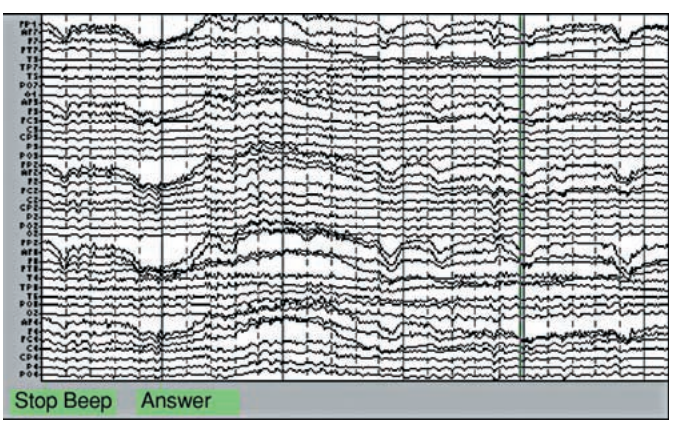

Fig. 4 Block of EEG data recording during the answering phase

important frequency waves (Delta, Theta, Alpha, and Beta) that characterize the brain. The analysis is based on these specific frequency ranges in order to interpret the changes that occur during an auditory/comprehension task.

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Read more about it

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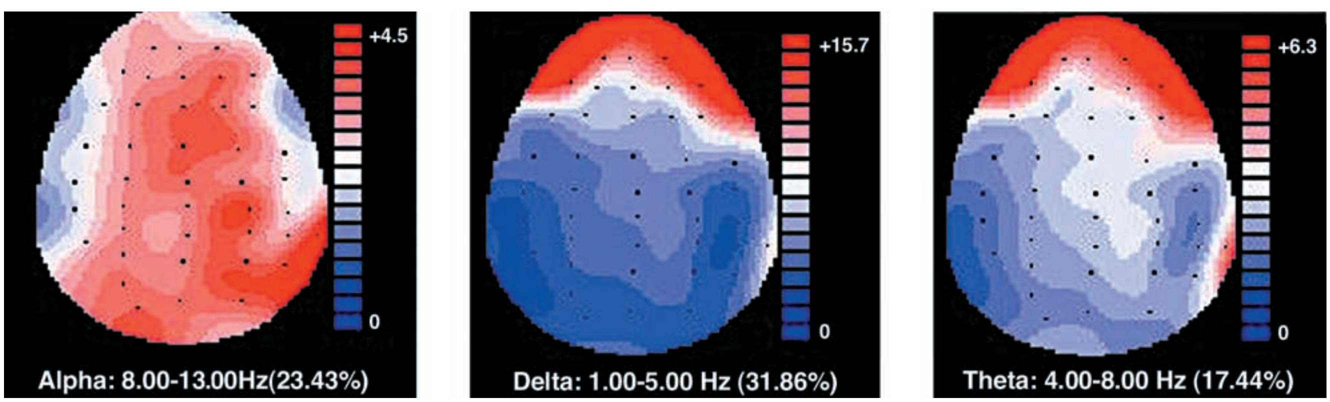

Fig. 5 Activity distribution (auditory/comprehension task)

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The study capsulized

The EEG data was collected at Miami Children's Hospital using the Electrical Source Imaging with up to 256 electrodes (ESI-256 system). The EEG of each subject was recorded during the Auditory/Comprehension test using 41 key locations of the possible 256 according to the Modified Combinatorial Nomenclature (MCN). The fluctuations of changes in the frequency spectrum were topographically displayed to observe descriptive functional mappings of the brain. An evaluation of spectral arrays was thus performed based on comprehensive color topographic maps of the various induced brain activities. This representation allows us to highlight how different subjects react under similar auditory/comprehension tests, in order to assess the similarity/dissimilarity of brain functional patterns, and to potentially detect the presence of any associated neurological disorders. This study confirms that all frequency bands can be used to characterize under distinct events the activation associated with a well-established auditory/comprehension test.—*MA, MC, IY & PJ*