

Grzegorz Marcin Wójcik

3 Selected methods of quantitative analysis in electroencephalography

3.1 Introduction

Electroencephalography (EEG) has been known for about 100 years and covers the techniques used for detecting and recording the electrical activity of the brain cortex. It is hard to state who invented the EEG; however, most often three researchers are mentioned in the literature: Richard Caton, Hans Berger, and Adolf Abraham Beck [1, 2].

Richard Caton (1842–1926) was a physician, a physiologist, and Lord Mayor of Liverpool, where he moved from Edinburgh in the late sixties of the nineteenth century and lived there until the end of his life. Caton used galvanometer to detect the electrical activity of the rabbit's, dog's, and monkey's brains. He put the electrodes directly on the surface of the cortex or on the skull, which can be treated as the beginning of EEG [1–3].

Caton's research was noted by Hans Berger (1873–1941): “Caton has already published experiments on the brains of dogs and apes in which bare unipolar electrodes were placed either on the cerebral cortex or on the skull surface. The currents were measured by a sensitive galvanometer. There were found distinct variations in current which increased during sleep and with the onset of death strengthened. After death they became weaker and then completely disappeared” [1, 4]. Initially, this German psychiatrist studied mathematics, and after the accident in the cavalry, where he was drafted for 1 year, he resigned of becoming an astronomer and finally became a medical doctor at the University of Jena. He was the first to observe the alpha waves (see Fig. 3.1), originally called Berger rhythms, and is recognized as the father of EEG by many historians of neuroscience. He suffered from clinical depression and committed suicide by hanging himself in his clinic in 1941 [1].

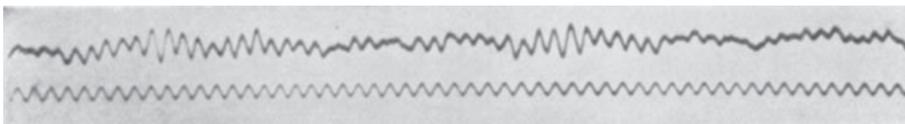


Fig. 3.1: Recording of alpha waves from the Berger's works in 1929 [4].

Adolph Abraham Beck (1863–1942) was a Polish professor of physiology at Jagiellonian University in Cracow where he studied medicine and attracted great attention in Western Europe by publishing in 1890–1891 [5, 6]. Since that time, he has been

regarded as one of the pioneers of EEG. Unfortunately, he also committed suicide during the war (1942) in Janowska concentration camp in Lwów.

EEG is a noninvasive, relatively cheap and effective method in the diagnosis of epilepsy, widely applied in clinics and other medical institutions for years. However, in the last two decades, its renaissance was observed as some new algorithms were proposed making it possible to model the cortex electrical activity in time and space, sometimes with possibility of looking deeper into the brain subcortical structures.

This chapter presents the fundamental methods of quantitative EEG (qEEG) with its typical applications accompanied by useful software review and some tips and tricks that may improve the quality of the undertaken research.

3.2 EEG technology and resting state

The electrical activity of the brain cortex is recorded using a set of electrodes and amplifiers. Amplifiers transmit the registered activity most often to the computer where the signal is recorded on the hard disk. The recorded signal can be then cleaned, preprocessed, and postprocessed without the necessity of the patient's presence in the lab.

Before discussing technology, it is necessary to understand how long and hard way the signal must go through before it can be recorded. The cortex is composed of tens of billions of neural cells called neurons. Each neuron has its base potential equal to approximately -70 mV and reaching $+40$ mV during excitations. It must be remembered that the current in the brain has ionic character, as the potential on neural cells is a result of potassium, sodium, and chloride ions dynamics across the membrane. Considering the typical shape of the head and the size of the brain that is a bit smaller than the size of the head, one can imagine the size of the cortex that covers the subcortical areas of the brain. Next, when electrodes are placed on the head, the signal registered by one electrode is assumed to come from millions of neurons. To be registered, the electrical potential must be probed deeply through the hair, some dirt and fat on the scalp, the scalp itself, the skull, some blood, meninges, and cerebrospinal fluid. The appropriate contact (impedance) between scalp, metal electrodes, and electrolyte must also be taken into consideration, and these are the electrodes where the electron current appears for the first time and in fact they are converters of ionic current to the electron current. That is why amplifiers used in EEG are the most expensive parts of the whole system. Amplifiers usually used in clinical practice consist of 16–24 electrodes. There are also amplifiers with a smaller number of electrodes, sometimes even two-electrode amplifiers, used for game industry or simple experiments [7], including neurofeedback techniques [8] or brain-computer interfaces. The most advanced EEG labs are equipped with the so-called dense array amplifiers with 256 [9] or very rarely 512 operating electrodes. To provide appropriate impedance between the electrode and the scalp, different substances are used to moisture the electrode—from the gel-based substances to electrolyte solution filling

up the sponge in the electrode socket. The best EEG labs are also equipped with eye trackers that allow eliminating eye blink artifacts or saccadic eye movements and photogrammetry stations owing to which it is possible to place particular electrodes on the later-generated model of the brain.

The simplest EEG experiment is called the resting state. During the experiment, the subject is sitting, often with closed eyes, doing nothing, not moving. The activity of the brain is then registered for several minutes, and the laboratory staff can then observe the changes of activity during the resting state. It is the resting state where, for example, epilepsy can be observed. As a result, we obtain the table of numbers, like a typical spreadsheet, with the number of columns equal the number of electrodes and one additional column in which the time is registered. The number of rows in the table depends on the probing frequency and the length of the experiment. The best amplifiers allow to record the signal with a 1,000-Hz probing frequency. The frequency usually is set to 250 Hz, which means that 250 rows are added to the table for each second of the experiment. This makes the EEG far ahead of all competitors, including fMRI, in the temporal resolution category.

In Fig. 3.2, the Laboratory of EEG in the Chair of Neuroinformatics and Biomedical Engineering (CoNaBI),¹ Maria Curie-Skłodowska University in Lublin, Poland,



Fig. 3.2: Laboratory of EEG in the Chair of Neuroinformatics and Biomedical Engineering (CoNaBI).

¹ Chair of Neuroinformatics and Biomedical Engineering, Maria Curie-Skłodowska University in Lublin, ul. Akademicka 9, 20-033 Lublin, Poland. E-mail: gmwojcik@live.umcs.lublin.pl.

is presented. It is equipped with the dense array amplifier able to record the brain electrical activity with 500-Hz frequency through 256 channel HydroCel GSN 130 Geodesic Sensor Nets.

The laboratory is a complete and compatible system provided by electrical geodesic systems (EGI).² In addition, the geodesic photogrammetry system (GPS) was used, which makes a model of subject brain based on its calculated size, proportion, and shape, owing to 11 cameras placed in its corners, and then puts all computed activity results on this model with very good accuracy. The amplifier works with the Net Station 4.5.4 software, GPS under the control of the Net Local 1.00.00, and Geo-Source 2.0. Gaze calibration, eye blinks, and saccades elimination are obtained, owing to the application of eye tracking system operated by SmartEye 5.9.7. The event-related potential (ERP) experiments are designed in the PST e-Prime 2.0.8.90 environment.

3.3 EEG rhythms and power spectrum

However, current EEG is not only looking at the wormlike plots of the registered potentials. The real power of technology manifests itself when cortical activity is treated in a quantitative way. Probably the oldest quantitative method of EEG is the application of Fourier transforms to the signal. The power spectrum allows to find the dominant rhythms, sometimes called EEG bands, as it becomes possible to see how much amount of sine waves with particular frequencies contribute to the whole signal. A nice metaphor comes to my mind as an example—the neurons in the brain cortex tend to play music like crickets in the meadow, and they play synchronically. Thus, the rhythm observed in the cortex is characteristic of its large part, not only for the single electrode.

There are six most important EEG rhythms: δ , delta band (less than 4 Hz) often observed in babies; θ , theta (4–7 Hz)—greater in young children; α , alpha (8–15 Hz)—associated with relaxation, closed eyes, and meditation; β , beta (16–31 Hz)—in stress or active thinking; γ , gamma (more than 31 Hz)—when short-term memory is engaged and during cross stimulation; sometimes μ , mu (8–12 Hz)—in motor neurons in the resting state [10].

The question that should be asked right now is about the length of the signal that should be taken to the Fourier transforms. Obviously, there is not much sense in finding the dominant frequency in the whole signal, lasting, for example, for an hour as this may change in time. The answer depends on the conducted experiment. Sometimes just a few seconds is enough, and in another case, this may be one minute. One thing is certain—spectral analysis is still useful in the quantitative research of cortical electrical activity.

² Electrical Geodesic Systems, Inc., 500 East 4th Ave. Suite 200, Eugene, OR 97401, USA.

3.4 Event-related potentials

Another method with the fundamental applications in qEEG is the observation of ERPs. Quite often, when we tell someone who is not familiar with neuroscience about the EEG, the question whether it is possible to see the manifestation of a luxury car or a beautiful woman in the cortical activity is asked. Unfortunately, it is not possible to notice this in a single EEG trial. However, if such stimuli were shown more than once, it would probably be possible to get a hold of something. Such an approach to the experiment is called ERP [11]. Some events evoke some reactions in the brain, and when the whole process is treated statistically, there will appear measurable curves, indicating characteristic response to the stimuli.

Probably the most famous ERP experiment is the so-called P300. During the experimental trial, the subjects are asked to press buttons whenever they can see a cross on the computer screen. There are only two objects that can be shown on the black screen of the computer: a white circle (80% of stimuli) and a white cross (20% of stimuli). The circles are called standards, whereas the crosses are called targets. All symbols are shown 400 times in total. The subject expects to see the cross each time the stimulus is shown. He or she hunts for targets. Unfortunately, in 80% of cases, the subject is disappointed. However, when the target stimulus appears—the button is pressed. Actually, they do not need to press anything. We can tell what they see based only on their cortical activity owing to the ERP appearing in their brains. To get the ERP, the signal must be averaged in some set time intervals, for example, 200 ms before the stimulus and 400 ms after that. The averaged signal looks completely different from the typical EEG recording, but the extrema of the function show the appearance of the stimuli and cortical reaction to such stimulation. Note that this must be repeated many times because only the noise will be observed in single recording.

There is a variety of different ERPs appearing on different parts on the scalp, depending on the stimuli. Thus, there are visual ERPs, auditory ERPs, language-related responses, decision making–related responses, or even ERPs appearing during face recognition [11]. Numerous books have been written about the ERP, among the most worth reading is by Luck [11]. One thing is certain—it is hard to imagine current experimental psychology using EEG without ERP. We have some experience in doing ERPs in patients with psychiatric disorders, and such an approach may be useful in finding psychiatric disorder biomarkers in the EEG signal, making psychiatry more “quantitative” and experimental [12, 13].

3.5 Dipole source modeling

It has been already pointed out that in the category of temporal resolution, the EEG is much better than any other technique, especially fMRI. However, when considering

the spatial resolution, it is relatively poor. That is why some algorithms have been proposed to solve this problem, and they are generally called source localization methods. Owing to them, it is possible to put EEG-based and calculated activity of a particular region of the brain on the brain model and get the resolution similar to that obtained from the computed tomography (CT). This is very important as for the first time in this chapter, the set of time series with the number of elements equal to the number of electrodes will not be discussed, but the topographic map of the brain cortex placed on the brain model and calculated from the data present in that time series will be considered.

The origin of the dipoles in the brain is strictly connected with the anatomical structure of the cortex. The electrical activity that can be registered using the EEG amplifiers comes mainly from the so-called pyramidal cells. The current flows perpendicular to the surface of the cortex because such is the alignment of the neural columns, and the electrical current coming from the dendritic trees almost totally cancels as their orientation is rotational and parallel to the cortex. Intercortical current vectors sum linearly, and the areas of about 3 cm can be very effectively modeled by a single electrical dipole. The more electrodes, the better spatial resolution is obtained. It should be remembered that the potential we measure does not come directly from the neurons that are the closest to the electrode [10, 14].

To generate the brain model with dipoles responsible for the EEG activity measured on the scalp, one must solve the inverse problem using the Laplace and the Poisson electric field equations. However, there is no space in this book to discuss it in detail. Moreover, the good news is that there are a lot of software solutions that allow treating the collected EEG signal so that the dipole source modeling (DSM) is conducted without the knowledge of highly complicated methods of applied mathematics and theoretical physics. Then the dipoles calculated from the EEG signal can be put on the standard model of the brain or when the lab is well equipped—on the real model of the subject's brain generated by means of the photogrammetry station. A lot of research in neurophysiology has been carried out using the DSM technique as the dynamics of the dipoles can shed some light on the problem impossible to be noticed when looking only at pure EEG [10, 14].

3.6 Source localization LORETA/sLORETA

One of the best-known algorithms originating from the idea of source localization is the low-resolution brain electromagnetic tomography (LORETA) and its standardized version sLORETA. Proposed by Pasqual-Marqui in 2006, it is characterized by many modifications that can be useful in some special cases of analysis [15, 16]. Based on the EEG inversed problem, these methods allow to calculate and then visualize the activity of the whole brain in the three-dimensional model consisting of voxels put on

the Talairach atlas. In contrast to the DSM, we do not get the current dipoles but the map of the points of interests with calculated activity in nanoamperes and the time in which that activity occurred. We have experience in applying sLORETA for the analysis of the EEG signals in both healthy and disordered subjects in the ERP experiments [12, 13]. This method allowed us to indicate the most active Brodmann areas (BAs) on the brain cortex and in some subcortical areas like amygdala. Our findings come along with those findings of some MRI/fMRI experiments, which in some way prove the effectiveness of such an approach [12, 13].

Remembering that the electric current is defined as the electric charge flow in time, it is possible to integrate the current over time and obtain the mean electric charge flowing through the particular brain area. In the study of Wojcik et al. [12], we defined such a new measure adding some value to qEEG as it may be important whether the increased activity of the selected area lasted in time or not.

The expression of each BA through which the electric current is flowing is as follows:

$$I(\text{BA}, t, \tau, |\psi\rangle) = \frac{\partial q(\text{BA}, t, \tau, |\psi\rangle)}{\partial t}, \quad (1)$$

where $q(\text{BA}, t, \tau, |\psi\rangle)$ indicates the electric current accumulated in a given period of time with the stimulation in τ . It is sure to depend on a group of psychophysiological parameters whose representation is the vector $|\psi\rangle$. ι (Iota), which is a new observable, can be termed as the electric charge flowing through the BA obtained by the following integral:

$$\forall \text{BA} : \iota = q(\text{BA}, t, \tau, |\psi\rangle) = \int_{\tau+t_2}^{\tau+t_1} I(\text{BA}, t, \tau, |\psi\rangle) dt, \quad (2)$$

in the range from t_1 before and t_2 after the stimulation in τ [12].

It is crucial to note that there are still common beliefs that it is impossible to record the EEG activity from the subcortical areas, but these are wrong beliefs. Indeed, subcortical structures produce smaller scalp EEG signals. This is due to the fact that they are farther from the head surface than the cortical structures. To make matters worse, subcortical neurons can have a closed-field geometry that further weakens the observed distant fields and subcortical structures are surrounded by the cortical mantle [17]. Thus, measurements of activity in deep brain structures can be potentially explained by a surrogate distribution of currents on the cortex. That is why it can be very difficult to measure subcortical activity when cortical activity takes place at the same time [17]. However, owing to the source localization and algorithms like sLORETA—this subcortical activity can be simulated with very good accuracy, which is extensively used to understand the activity patterns appearing on the cortex while performing cognitive tasks. This can lead, as we hope, to finding some biomarkers, for example, in decision-making processes or selected psychiatric disorders on which our research is focused [12, 13].

3.7 Principal component analysis

In the zoo of quantitative methods used in EEG, the statistical methods seem to be very interesting. One of them is principal component analysis (PCA), which is used in many areas that are far away from neuroscience. PCA applies orthogonal transformations expressed by matrix operations to reduce the amount of data. Among other reasons, the PCA is often chosen to shorten the time of computations without loss of crucial information present in the system [10, 18].

During the EEG procedure, a huge data set A is obtained, and the main idea of the PCA method is to reduce the dimension of such a multidimensional data set A of variables depending on each other [10]. This can be achieved by transforming data set A into another data set B with uncorrelated elements called principal components. The elements of data set B are not correlated and often orthogonal. In data set B , the data are arranged in such a way so that the first few sum up to most of the variation present in data set A [10]. In other words, the PCA method allows to reduce the amount of information in the EEG signal by removing some less important components originating from artifacts or another noise and keeping the most important components responsible for the dynamics of the whole system.

In the aspect of ERP experiments, this method is responsible for the decomposition of the ERP curve into the component-related curves that sum up to the original one.

In the applied computational neuroscience, owing to the PCA methods, it was possible to find useful topographies and effects of interest in a wide range of experiments and neurophysiological research [10, 18].

3.8 Independent component analysis

Imagine an orchestra assembling of no more than 256 musicians playing different instruments in the concert hall. Now imagine 256 microphones recording the concert. The position of the microphones does not change during the recording time. After the concert, one obtains 256 recordings in 256 sound files. They are very similar, though quite different. The difference depends, for example, on the distance of a particular microphone from the given instrument. Try to find the position of each instrument of the orchestra in the concert hall and separate the music it plays to put it in a new sound file. In addition, the sum of all the separated sound files should give the whole concert.

Such a metaphor exemplifies the other useful qEEG method called independent component analysis (ICA). The assumption of that method is to separate the EEG signal in such a way so that it is possible to express it as a sum of temporarily independent and spatially fixed components. Contrary to the PCA, these components do not have to be orthogonal [10, 19].

Similar to the PCA, the EEG signal is treated as the huge data set. In the signal registered by one electrode, there can be many artifacts, and the influence of different brain regions placed under other electrodes can be observed. This means that one electrode does not necessarily record strictly the activity of the group of millions of neurons placed exactly under that but under ideal conditions from the whole brain.

If one wants to remove the artifacts from the signal, he should definitely try to use the ICA. ICA application also makes it possible to topographically place the origin of cortical activity registered by the electrode.

The ICA is regarded to be a blind source separation (BSS)-type algorithm. It is based on the theory of central limit according to which when the random variable is characterized by a normal distribution (recording of a single electrode), it is regarded to be a “mixture” of independent random variables (in this case, signals that are independent). The sources making up the recoded signal are assumed to be statistically independent of each other, which is the algorithm base. This results in the negative aspect of the algorithm as the effect of ICA is the minimalization of the Gaussian distribution as far as the values are disseminated. Thus, a distribution close to normal of more than one primary signal gives an ambiguous result [10, 19].

The algorithm has an unknown number of steps and is both time and power consuming. The length of computation depends on the length of the signal. The main disadvantage of the ICA is that even if it is possible to separate independent component signal frequency, it is not possible to calculate their amplitude, which is typical of BSS algorithms.

The EEG manufacturers do not often add ICA to their software solutions. That is why in many cases, the ICA must be implemented by the researcher to satisfy his or her needs and expectations.

We have experience in ICA programming. As it was mentioned above, the computations are time consuming. We proposed some methods of the ICA parallelization and tested them on different architectures [20–22]. To get satisfactory results, one ought to consider decomposition on the supercomputers or apply at least the CUDA methodology.

3.9 Software reviews

3.9.1 OpenSesame

During the design phase of each experiment, it is obligatory to choose the software that will be used to present the stimuli to the subject. There is a wide range of software solutions for the ERP experiment design; among others, the OpenSesame³ is

³ OpenSesame: <https://osdoc.cogsci.nl>.

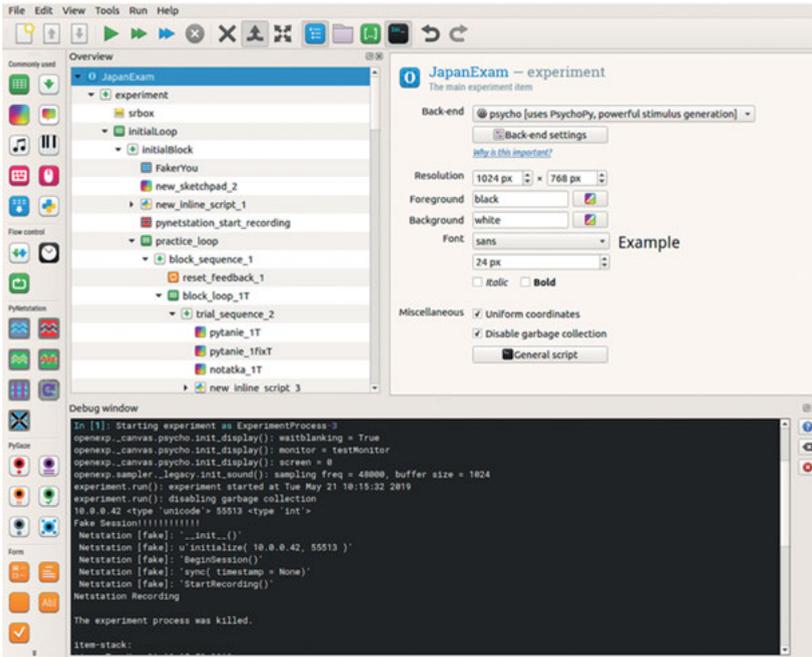


Fig. 3.3: OpenSesame interface. It allows the user to design experiments in many stimulation ways as sound or visual. Experiment can be controlled and run using the power Python scripting language. The signal can be tagged during the experiment, which makes it suitable for future postprocessing.

often chosen by experimentalists owing to its elastic interface, making it possible to present a wide range of stimuli and tag the recorded signal in the required way. It is free, available for the most popular platforms (Linux, MacOS, Windows, and even Android—only runtime), and compatible with most devices that can be found in the EEG labs like amplifiers and other EEG equipment, eye tracking systems, and response pads. The greatest power of the OpenSesame manifests itself due to the Python interface. One can design experiments with flexibility and practically an infinite range of solutions available in the Python programming language. The interface of the OpenSesame is presented in Fig. 3.3. In the case of problems, the user is also supported by the community forum, which can be useful for the researchers beginning the EEG adventure.

3.9.2 Net Station

When the experiment is designed, it must be conducted in the EEG laboratory, and signal recording is the most important phase of the experiment. There are so many possible obstacles that may make the proper recording impossible. Unfortunately,

there is no space in this chapter to mention all of them. Obviously, the electromagnetic noise is the most common. Not always is it possible to use Faraday's cage due to the fact that it is huge and quite expensive. However, researchers must try to find the most electromagnetically friendly room and often the time of the day in the reality of the building in which the laboratory is situated. There may also be problems originating from the long hair of the subjects or the gender as women tend to have periodically changing electric activity of the brain. When all conditions are satisfied, and the impedance between the scalp and the electrodes is appropriate, one can start the signal recording.

The software used to record the signal and integrate it with the stimuli systems is usually provided by the amplifier manufacturer. However, it can also be developed from the scratch in which we have some experience [7, 8]. The software used in our EGI system is Net Station.⁴ With its hundreds of functionalities, it allows to design the experiments from the very low-level stage, such as selecting the cable connections of all devices used in the experiment, through the multichannel recording with up to 1,000-Hz probing frequency, to the artifact elimination, such as saccadic eye movements or eye blinks. The recorded signal can be preprocessed by the Net Station and postprocessed later, and the data can be exported to many most common data formats to be transformed in any way.

The interface of Net Station is presented in Fig. 3.4. The other amplifiers are equipped with different software. It is no use to describe all of them. However, there is

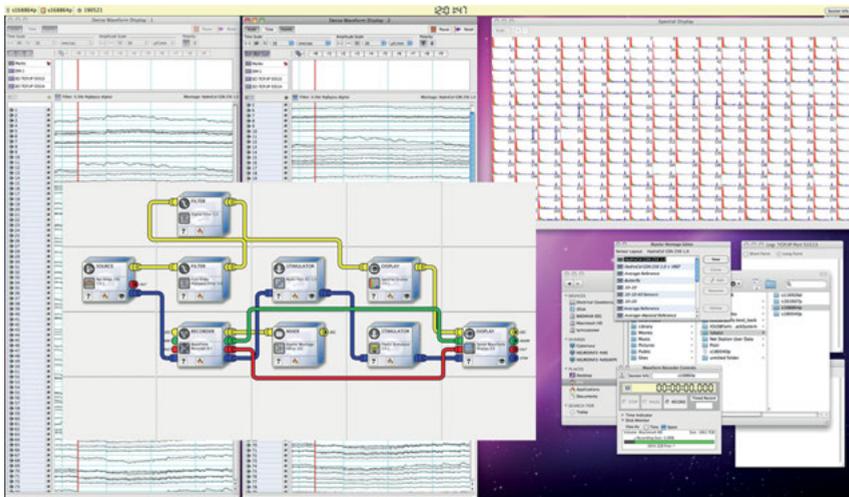


Fig. 3.4: The interface of the Net Station experiment control system. One can observe the raw signal windows as well as the online Fourier analysis (in the background). It is also possible to design particular modules and connections to prepare the most appropriate experiment setup.

⁴ Net Station Software for Clinical Use: <https://www.egi.com/clinical-division/net-station>.

always a typical scheme of the EEG recording: impedance checking, artifact elimination, cleaning the signal in the pre- and postprocessing phases, and exporting to the next steps of analysis.

3.9.3 GeoSource

Having the signal recorded, one can think about doing, for example, the source localization. The GeoSource⁵ software was developed by EGI and is an option in the EGI laboratory system. It can solve the EEG inverse problem, and it calculates sources of the currents flowing through the medium, in this case through the subject's head. With the LORETA and sLORETA algorithms, one can generate the visualization of the activity propagation either in the head volume (including subcortical structures) or on the cortex of the so-called flat map with particular BA being highlighted during the activation.

Thus, it is possible to export to the data set the time of the occurrence of a given activation and the electric current in nanoamperes flowing throughout the

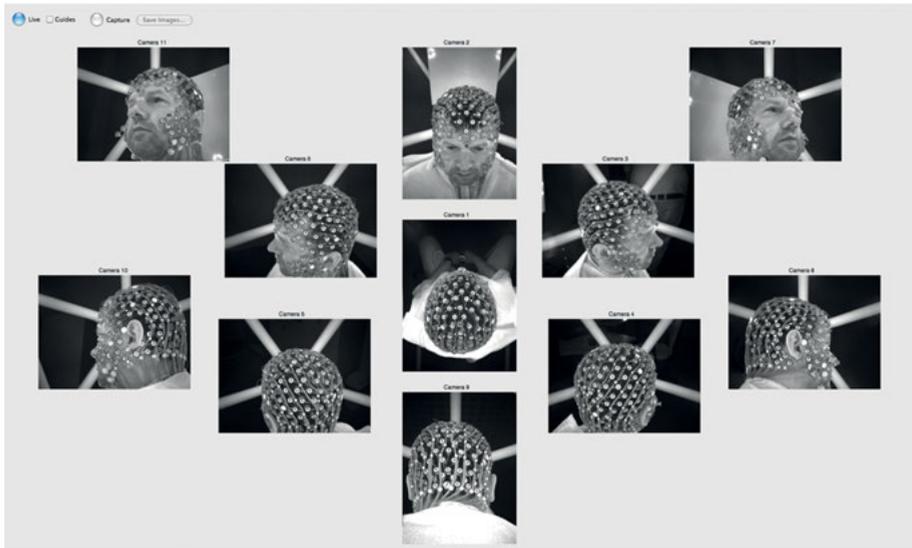


Fig. 3.5: Photos taken by 11 cameras of the photogrammetry station with Net Local software supporting GeoSource. When the subject leaves the laboratory, the assistant marks the black reference electrodes so that the GeoSource software could use the model of the subject's brain.

⁵ GeoSource 3 electrical source imaging packages: <https://www.egi.com/research-division/electrical-source-imaging/geosource>.

selected BA. To place the activity on the brain model with perfect accuracy, the lab should be equipped with a photogrammetry station. After selecting the referential electrodes in the photos taken by cameras placed in the photogrammetry gantry's corners, it is possible to generate the perfect model of the subject's head and, as mentioned above, to create a visualization of dipole propagation with the spatial resolution characteristic for the CT. Fig. 3.5 presents the photos taken by the photogrammetry station. The visualization mentioned above will be presented later in this chapter.

3.9.4 EEG lab

What happens if there is no access to the lab manufactured by EGI and accompanied by the Net Station and GeoSource software? It turns out that most of the cleaning, pre-processing, and postprocessing operations as well as the source localization can be conducted in the available free-of-charge and open source MATLAB toolbox. Similar to the closed and expensive solutions, the EEGLAB⁶ [23] offers its own graphical user interface, multiformat data import, lots of plotting functions, semiautomated artifact removal, source modeling for both forward and inverse problems, ICA implementation, and the possibility to add external plug-ins. Visualizations generated in the EEGLAB toolbox are characteristic because of the rainbow-colored small head cross sections appearing in lots of papers in the last decades. The typical EEGLAB output is presented in Fig. 3.6.

3.9.5 Brainstorm

As far as the open source software is concerned, the best solution for neuroimaging and data visualization is offered by the Brainstorm⁷ [24]. Not only the EEG signal can be totally processed by the Brainstorm but also other technologies, including MEG, MRI, and invasive experiment using animals. There is a very long list of amplifiers offered by practically all EEG equipment manufacturers that are supported by Brainstorm, and all leading brain atlases are compatible with 2D/3D models that can be generated in this environment. All the qEEG methods described in this chapter are supported, and most of the technical solutions used in the filtering or cleaning procedures are implemented at least as good as in the Net Station. It must be noted that using Brainstorm, it is possible to map the cortical electric activity recorded using EEG on the anatomical brain model generated by voxels obtained in MRI scan and including ultra-high-field frequency 7T scanners. Visualizations generated using

⁶ EEGLab: <https://scn.ucsd.edu/eeglab/>.

⁷ Brainstorm: <https://neuroimage.usc.edu/brainstorm/>.

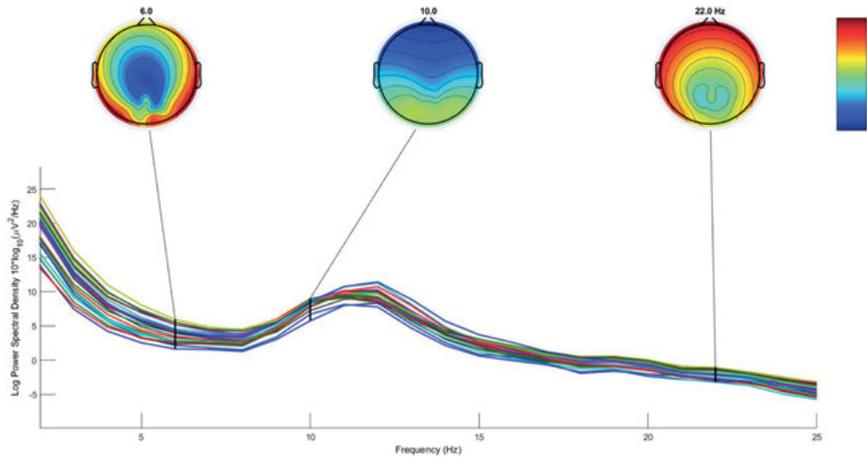


Fig. 3.6: Typical plots generated in the EEGLAB. Except for the rainbow cortical activity visualizations, one can observe the logarithm of power spectrum activity in the space of EEG in the frequency range from 0.1 to 25 Hz, generated using signal from the 26 most significant electrodes in some P300 experiment. (Courtesy of Andrzej Kawiak, MSc, Eng, CoNaBI)

Brainstorm are always very spectacular, and two examples are presented in Figs. 3.7 and 3.8.

3.10 Example of the Iowa Gambling Task experiment

Finally, we would like to present the example of the ERP experiment conducted in our laboratory, by showing its most important phases step by step. For example, we chose the Iowa Gambling Task (IGT).

Antoine Bechara, Antonio Damasio, Hanna Damasio, and Steven Anderson were the ones who brought the IGT into practice. Since that time, this activity has been one of the best liked by the subjects taking part in numerous experiments dealing with experimental psychology [25]. Based on the investigations, which were carried out for the first time at the Iowa University, the IGT was meant to control the decision-making process mechanisms applied in the card game with the reward-punishment orientation.

The rules of the game consist in choosing the deck symbol of one card out of four with 100 trials. The aim is to earn the most possible virtual money beginning with zero by the people taking part in it. Each set of four cards (or symbols) contains some good cards to be rewarded as well as some bad ones to be punished. However, not knowing which card is good and which one is bad, the participant must make a decision on the game course. The first impression is that all cards are good. However, the reward proves to be much higher when choosing two (of four) cards that seem to be better.

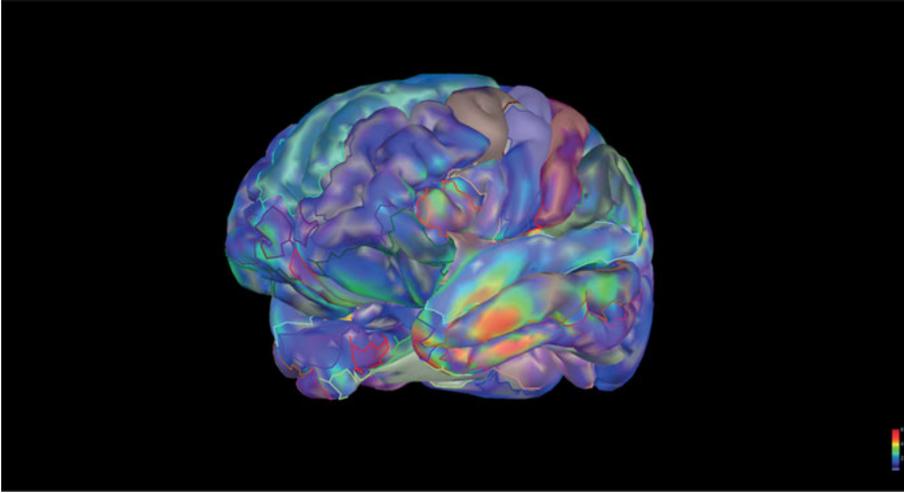


Fig. 3.7: Author's brain cortex visualization generated in Brainstorm. A 15-minute long meditation resting state is averaged and then presented. (Courtesy of Andrzej Kawiak, MSc, Eng, (CoNaBI))

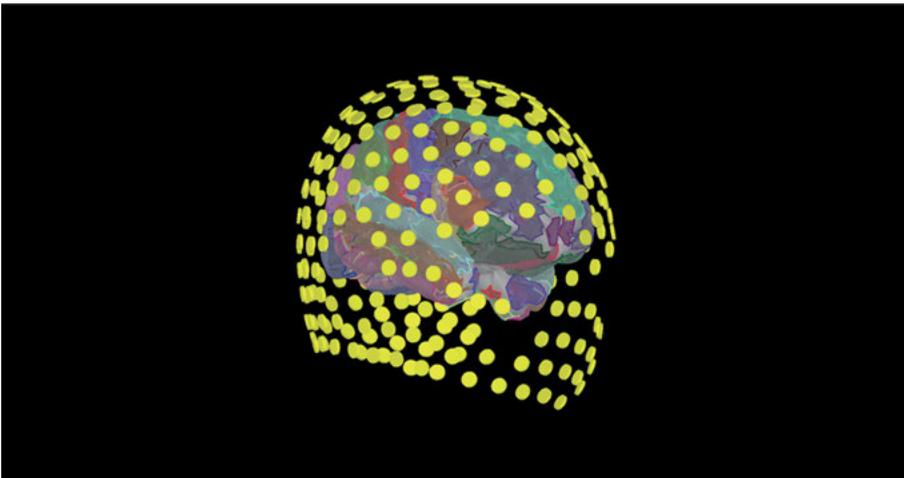


Fig. 3.8: Author's brain cortical activity with electrode position visualization generated in Brainstorm. During visualization, one can make any rotations of the model and check the activity of selected brain regions according to one of several most popular anatomical atlases of brain. (Courtesy of Andrzej Kawiak, MSc, Eng, (CoNaBI))

By choosing the better cards too many times, one is finally severely punished. However, the choice of the worse cards is mildly punished and, at the end of the game, results in better financial achievements in comparison with the other event. Fig. 3.9 shows the typical computer screen based on which decisions are made by participants.

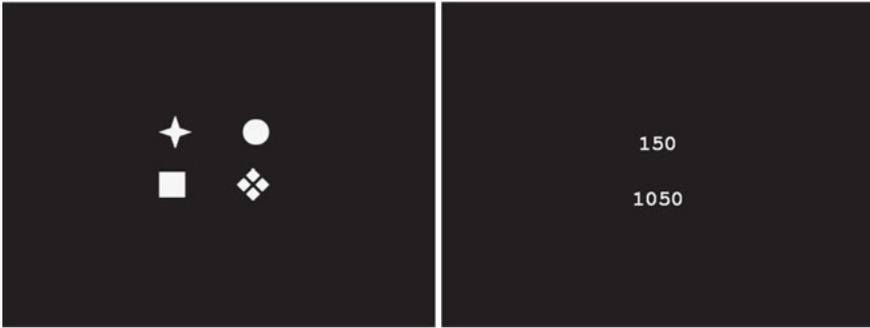


Fig. 3.9: Iowa Gambling Task typical screen shown to participant (in the left). He or she must choose one of four figures to receive awards and avoid punishments. Reward and total score are shown on the screen like that the right.

The case considered is when the subject signed the agreement to participate in the research and the EEG cap was placed on his head, which usually takes about 20 minutes. The cap consists of 256 electrodes, a moisture with an electrolyte that is kept in the bucket. Next, the impedance between the electrodes and the subject's scalp must be checked. The amplifier returns the information about the impedance, and if there are still some electrodes that do not contact the scalp properly, the electrolyte can be added to them without the necessity of taking the cap off. The abovementioned 100-trial series takes the subject about 15 minutes. Then the signal is recorded in the main laboratory computer system. After the signal recording, the subject is asked to get to the gantry of the photogrammetry station where the photos of his head in the EEG cap are taken (see Fig. 3.5). This is the last procedure applied to the subject in the lab. The preprocessing of the signal usually takes 2 hours. The laboratory worker must ensure that the signal is clean, without artifacts, and properly recorded. In the postprocessing phase, the additional several scripts must be applied to the signal. The names of the preprocessing and postprocessing scripts are similar in most software solutions and as follow the following: filtration, segmentation, artifact detection, manual signal cleaning, bad channel replacement, averaging, montage operations, and baseline correction. Each script, about which one can read in any software documentation, is responsible for the tasks that finally will enable the qEEG analysis. It should be remembered that to conduct good photogrammetry, the model of the brain must be generated by the Net Local software attached to the GPS system, and it is characteristic of that system, so there is no point in describing it in detail.

The fragment of the raw EEG signal is presented in Fig. 3.10. One obtains 256 time series, each for one amplifier channel. Fig. 3.11 presents the power spectrum analysis for the selected channels. One can find the dominant frequencies in this selected time of the experiment. The DSM propagation appearing in the averaged signal is

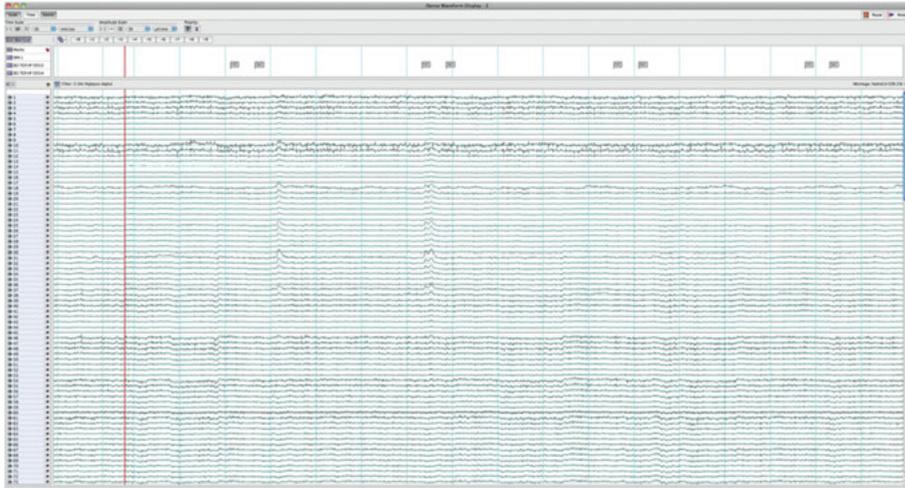


Fig. 3.10: Raw signal visible on the laboratory computer screen during the experiment. There is one plot for each of the 256 electrodes, varying in time. Although it is still far from drawing any conclusions on the basis of such a screen, it is possible to assess whether the signal is noisy or good.

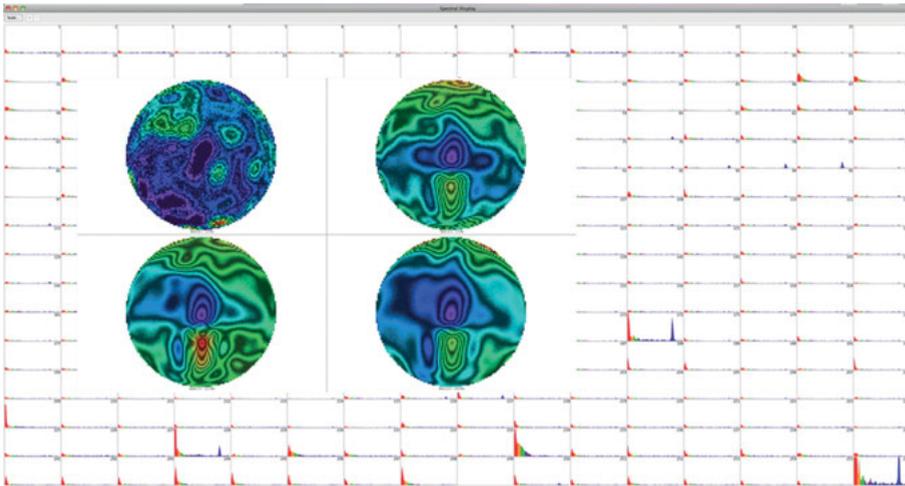


Fig. 3.11: During the experiment, it is possible to observe the Fourier analysis of the signal registered by particular electrodes. It is possible to save these data into separate data sets for further analysis.

presented in Fig. 3.12. The example of the frame from the sLORETA analysis conducted in the GeoSource is shown in subject's responses in Fig. 3.13.

It looks nice in the figures, but the raw signal takes several hundred gigabytes. To process one subject in the IGT, the researcher usually spends 12 hours. To arrange a

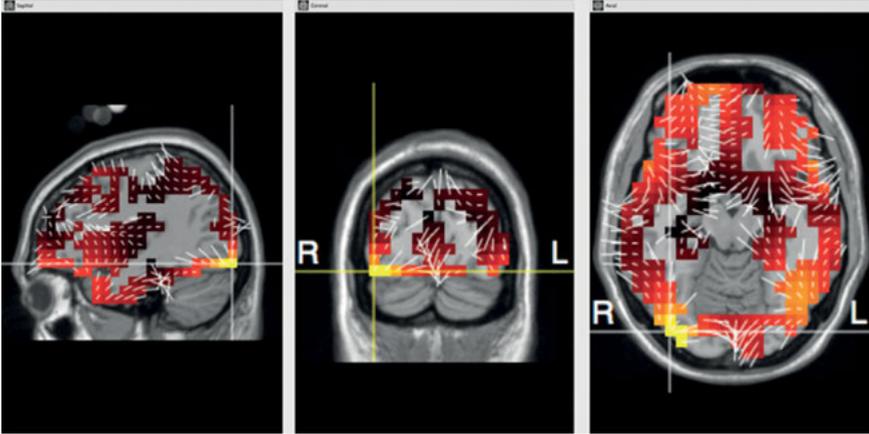


Fig. 3.12: Dipole propagation visualized in the GeoSource software in the discussed IGT experiment. The simulated activity is put on the brain model with CT-like resolution, and then it can be played as a movie.

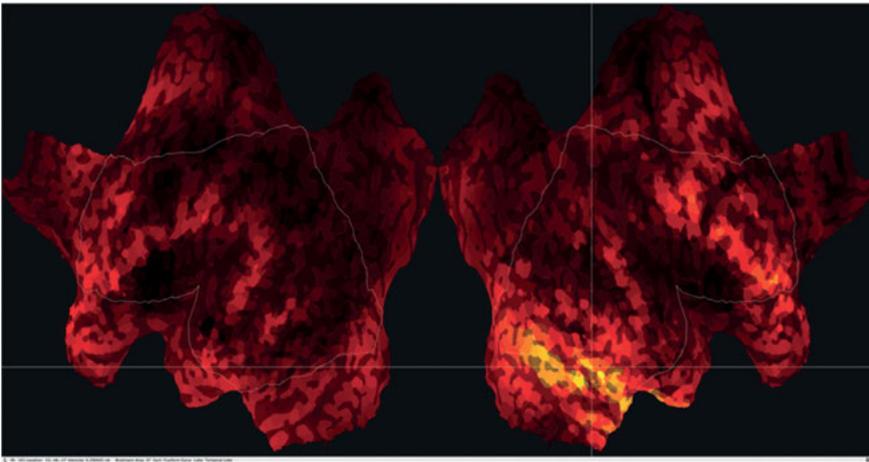


Fig. 3.13: Source localization calculated and later visualized using the GeoSource in the discussed IGT experiment. The simulated activity is presented in the so-called flat map of brain cortex with left (L in the left) and right (R in the right) hemispheres. Below one can read the activity of Brodmann area 11 and the intensity of 0.073880 nA, and Brodmann area 37 and the intensity of 0.290445 nA.

real experiment, we should consider at least 30 good recordings. Sometimes it is necessary to also build the control group. The EEG is an experimental science. In many cases, the signal of even 20% of participants cannot be processed properly. That is why we should consider larger cohorts than those mentioned above. Only having such a job done is it possible to prepare first scientific reports or papers.

3.11 Where do we go from here?

This chapter briefly describes, in our opinion, the most popular methods of quantitative analysis. One who has no experience in the EEG would ask the question, where should I go from here? There is no one clear answer. First of all, the readers who have access to the EEG laboratory and are eager to start doing the EEG ought to think of the experiment they intend to conduct. The decision whether to do the resting states or ERPs is fundamental. For sure, from both types, one gets hundreds of gigabytes of data. These data must be processed. All methods originating from the data science will be useful here. Thus, if the data science is involved in the EEG research, building appropriate hardware for the Big Data infrastructure should be taken into account. In the wide range of data science methods, the statistics and machine learning tools often play the key role. To support the researcher's workshop, it would be in demand to get some knowledge of the Python, Matlab, and R programming languages as well as some cloud architectures for the support. In each stage of research, the quality of the collected data and their security should be kept in mind as everything we record is very sensitive and legally protected. There are not many scientific areas in which so high interdisciplinary character, including IT, programming, data science, experimental psychology, and medicine, is manifested. Definitely, as the part of biomedical engineering area [26, 27], EEG and qEEG belong to that elite and interdisciplinary group [26, 27]. Probably that is why this is so fascinating.

3.12 References

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