Electroencephalographic detection of synesthesia

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Abstract − In this paper the research on a person declaring synesthetic abilities will be presented. According to the current state of knowledge synesthesia activates additional cortical fields in the brain which can be found in the EEG. The research was conducted using an EGI-EEG system (Electrical Geodesic Inc., Eugene, Oregon, USA) with the GeoSource software. GeoSource is a tool that implements the algorithms LAURA, LORETA and sLORETA. Using these algorithms for EEG analysis we can determine where in the brain the source of activity is. The authors will try to answer the question whether the use of these tools can prove the occurrence of synesthesia.

1 Introduction

The human brain is a complex network of connections in which communication takes place through the conduction of electrical and chemical impulses along dendrites and axons. As a result, on the surface of the brain the activity that we are able to measure using electroencephalograph is formed. This device measures the potential difference between points under two electrodes placed on the scalp, then we take into account measuring of voltage. The resulting record is called electroencephalogram. This is a completely non-invasive way of monitoring brain activity in order to determine what brain is doing at the moment. Then electroencephalogram is defined as the potential difference between two points in time function [1]. EEG signal is generated by the synchronous activity of the inhibitory and stimulating postsynaptic potentials, with the participation of large groups of cortical pyramidal cells [2]. By analyzing the EEG signal the person's current mental state can be determined, one can also distinguish correct from incorrect recording (which is often useful in the diagnosis), as well as

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determine which parts of the brain communicate with each other at certain mental activities. This is a vast field of research for neuroinformatics. Neuroinformatics is a scientific area where neuroscience combines with computers and often numerical solutions are most appropriate tools for analysis of psychological phenomena [**3, 4, 5, 6**]. Looking into brain electrical activity may be meaningful for people suffering from a range of disabilities [**7, 8**].

In this article, in particular, we deal with the phenomenon of synesthesia. Synesthesia is an extremely rare phenomenon where mixing of sensations is induced by stimuli going through different senses. People diagnosed with synesthesia can for example see sounds and taste colours. Initially, these impressions were attributed to the imagination [**9**], but after analyzing the distribution of cortical centers in the brain it is supposed to have an neuroanatomical analysis.

Cortical fields responsible for completely different functions may be in its close distance in the brain [**10, 11, 12, 13**]. As a rule, they do not interact with each other, but in about 2 % – 4 % of human population it can lead to communication between them. Then the brain performs certain tasks involving its centers, which should not take part in it [**14**].

While estimating type of synesthesia, it is customary to put the stimulus of sensations before the induced one. As an example, synesthesia at which we hear a sound and associate it with colour is called phoneme-colour synesthesia and sense of taste due to visual sensations gives grapheme-taste synesthesia.

In this paper the grapheme-colour synesthesia type has been deeply probed. Specifically, it is a crossmodal binding of vision and visual representation of ordinal words (weekdays), which is probably the most common type of synesthesia. Therefore, when analyzing the results, our attention will be attached to the 19 Brodmann area, which is credited with the location of the V4 area. It is believed that this is where the analysis of shapes and colours is conducted [**15**].

1.1 Review and research basis

The fusion of sensations called synesthesia was first scientifically documented in 1812 [**16**].

The conditions in which synesthetic abilities develop have notbeen fully studied yet. Synesthesia often discloses as a result of brain damage. It is also thought that the presence of synesthesia is genetic [**14**].

There is no right way to detect synesthesia. There are psychological methods of checking elements that may indicate synesthesia and distinguish it from other phenomena such as visual imaginery. These are the automaticity (synesthetic impression occurs independently of the will), consistency (specific stimulus always evokes the same synesthetic reactions over time), projection (synesthete does not imagine synesthetic experience) and reliability (impression is not associated with memory, like the smell of

childhood). It is also said that the synesthete approaches the factors causing synes-
thesia emotionally. Most of psychological methods examine one of these items, so they
can not be considered fully reliable [**17**].

The most common test for detection of synesthesia is a Test Battery and it can be
done everywhere in front of a screen. The principle of the test is based on checking
coinsistency. If we deal with the type of grapheme-colour synesthesia, the tested person
has available colour palette from which he/she chooses the colour corresponding to the
grapheme. This must be repeated three times for each grapheme at different time-
intervals [**18**]. But it has a lot of drawbacks and limitations. First of all, the subject
usually performs the test independently without any supervision. Besides, synesthete
may not associate the grapheme with one particular colour, but see something such as
a gradient or irregular texture.

Another type of test is querying of experience for the individual stimulants and
repeat the test after a long time. In the case of people with synesthesia, the answers
will be the same. There is also a method that checks for automaticity. Subject sees
before him a set of letters or numbers in the same colours (for example, 2 and 5),
and indicates distinctive scheme among them (for example, the twos are arranged in
a triangle). Synesthete will find this model more quickly, because different letters and
numbers will be in different colours [**17**].

Most of the methods are based on a similar or modified rule.

There are also many articles that document the detection of synesthesia by EEG,
specifically indicating the activity of certain cortical areas, which theoretically should
not take part in the stimulation of grapheme and sound [**19, 20, 21, 22**]. EEG may
be a reliable way of detecting synesthesia. Psychological tests can always be ques-
tioned, while recorded brain waves can not. We hope to confront this thesis based on
the available high-quality electroencephalographic tools and software that implements
sLORETA algorithm.

1.2   Objective

The study on the type of person declaring grapheme-colour synesthesia has been
carried out. In the context of this paper the authors will try to answer the question
whether with the 256-channel EGI Geodesic machine with the GeoSource software
(sLORETA) it is possible to identify the point at which we deal with the synesthetic
impression and in which parts of the brain its source is.

2   Area of studies

The study was carried out on high-end hardware of EGI Geodesic Inc.

EGI Geodesics System includes (besides an amplifier with signals from all channels)
NetStation 4.5.4 (a software package from EGI for register, review and analysis of EEG
signal), E-Prime for NetStation (a software for designing experiments), two machines:
one with NetStation and one for running experiments, a computer with eye-tracking

system SmartEye, sensor nets (EGI's HydroCel Geodesic Sensor Nets with 256 channels) and Geodesic Photogrammetry System – GPS (for improving location of sensors) [**23**].

In addition, the laboratory is equipped with the Geosource 2.0 software for mapping to a computer model the measured sources of the brain activity to a computer model. It implements 3 algorithms: LORETA (LOw REsolution electromagnetic Tomography), sLORETA (Standardized LOw REsolution electromagnetic Tomography) and LAURA (Local AUtoRegressive Average). All three algorithms are based on the assumption that there are always activated neighboring neurons. As a result of the adoption of the above assumption there are obtained blurry images of the electric charge distribution within the skull [**24**]. During the EEG analysis for this experiment the sLORETA algorithm was chosen. sLORETA is a method that computes images of electric neuronal activity from EEG and MEG. With the right conditions sLORETA localises a source activity quite accurately. However, it has very low spatial resolution, and spatial resolution decreases with depth [**25**].

According to Pascual-Marqui: "There are N_E instantaneous extracranial measurements. There are N_V voxels in the brain. [...] At each voxel there is a point source, which may be a vector with three unknown components (i.e., the three dipole moments), or a scalar (unknown dipole amplitude, known orientation). The cases considered here correspond to $N_V >> N_E$" [**25**].

There are three cases that sLORETA estimates the localization of source activity:

- EEG with unknown current density vector
- EEG with known current density vector orientation and unknown amplitude (cortical surface is completely known, voxels are distributed along the cortical surface, the dipoles at each voxel have known orientation)
- MEG

The main equation of algorithm is:

$\Phi = KJ + c1$,

where Φ is a vector with electric potentials measured at N_E electrodes, J is a current density, where J is a N_V - element set of voxels (each voxel contains three unknown dipole moments), K is a matrix N_E x N_V. Each element of the matrix indicates the electric potential of each voxel, $c1$ is a constant.

To improve localization of source activity, the algorithm employs the current density estimate given by the minimum norm solution. Then it uses standardization typical of sLORETA.

3   Methods

3.1   Data acquisition

EEG data were recorded using a 256-channel Geodesic Sensor Net. Data were sampled at 1000 Hz and recorded using NetStation 4.5.4 (EGI Software: EGI, Eugene,

OR). Impedances were kept below 100 kΩ at the beginning of the session. All channels were referenced to Cz during recording and later rereferenced to an average reference.

A 26-year-old right-handed man (later called S.) has been tested. S. declared synesthetic abilities in the field of viewing days of the week in colours. S. has passed Test Battery.

Before the experiment S. was queried about colours, which he sees on individual days of the week. He used the colour palette. This test was repeated after one year, while S. gave exactly the same answers.

On the basis of that interview an experiment was designed using the ERP software EPrime 2.0. The experiment consisted of watching stimulus in the form of colour and chromatic names of days of the week. The stimulus was composed of a day of the week and the task of the subject was looking at the grapheme. The names of the days of the week were presented as white letters on a black background (A-type grapheme) or in colours. The colours of some stimuli corresponded to those days, which synesthete gave during the initial interview (B-type grapheme). The rest of the stimuli were in random colours, different from those specified by synesthete (C-type grapheme). Additionally, in some stimuli colours given by synesthete were assigned to other days of the week (D-type grapheme). The were 10 samples of each type.

3.2 Data analysis

An FIR 0.1–30 Hz bandpass filter was applied. Data were stimulus-locked to the onset of the test stimulus. Segments were based on 100 ms pre-stimulus to 700 ms post-stimulus. For each segment the channel was considered bad if the fast average amplitude exceeded 200 μV or eye blink was detected (more than 140 μV) or eye movement occured (more than 55 μV). The rest of ocular artifacts were marked using the SmartEye. Bad channels were replaced through interpolation of neighbouring electrodes [26].

The data were further examined whether the algorithm did not omit any bad segment or trial. Finally, segments were excluded if they contained more than 10 bad channels or eye artefacts.

EEG source imaging was performed using the standardized low resolution brain electromagnetic tomography (sLORETA) method [25], as implemented in the GeoSource 2.0. This method is based on a Sun-Stok 4-Shell Sphere head model with a Tikhonov regularization of 1 x 10^{-2}.

4   Results

After overlaying evoked potentials of 4 types of stimuli (Fig. 1), one can see that over 700 ms in the case of D-type graphemes the first reaction to the stimulus was much weaker, but later after the diagnosis of pattern brain reacted strongly. In the case of B-type graphemes the stimuli was quickly recognised and did not raise the reaction outcome, as in other cases. The C-type graphemes waveform look quite similar to
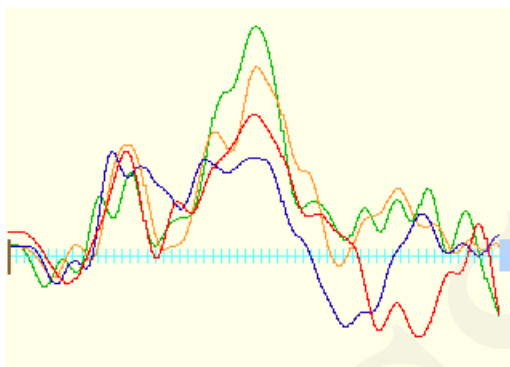
Fig. 1. Comparison of evoked potentials from the electrode 116 (O1 in 10 – 20 standard) in synesthete (orange colour: A-type grapheme, blue colour: B-type grapheme, red colour: C-type grapheme, green colour: D-type grapheme)

the original signal of B-type graphemes, although it can be seen that the reaction was slower. A-type graphemes signal is similar to the original signal of D-type graphemes, although the reaction was lower after recognition.

On the basis of the signal waveforms visualization was generated – showing the voltage distribution on the surface of the head. Fig. 2 presents TopoMap and Fig. 3 FlatMap generated by the NetStation and GeoSource software. They represent approximately brain response to the stimuli of 100 ms when looking at a) the chromatic names of days (A-type grapheme), b) the name corresponding to the specified colour (B-type grapheme), c) the names in different colours (C-type grapheme), d) the names of the colours assigned to other days of the week (D-type grapheme).

In Fig. 2a) and 2b) we can see the activity of the 19 Brodmann area, which is located in the area responsible for processing colours and shapes. In Fig. 2c) at the same time, the activity can be seen in the 21 Brodmann area, which is mostly responsible for the audio processing. In Fig. 2d) the reaction is much weaker.

5   Discussion

GeoSource helped identify the source of activity, and pointed to the fields that were activated in specific cases. On the basis of GeoSource it can be concluded that synesthete with grapheme-colour reacts differently to the names of days of the week. It depends on how these colours correspond to his personal vision of those days of the week. The 21 Brodmann area is often responsible for audio processing, so it would be assumed that the brain tries to cope with the unusual situation which days of the week have different colours than generally accepted by synesthete.
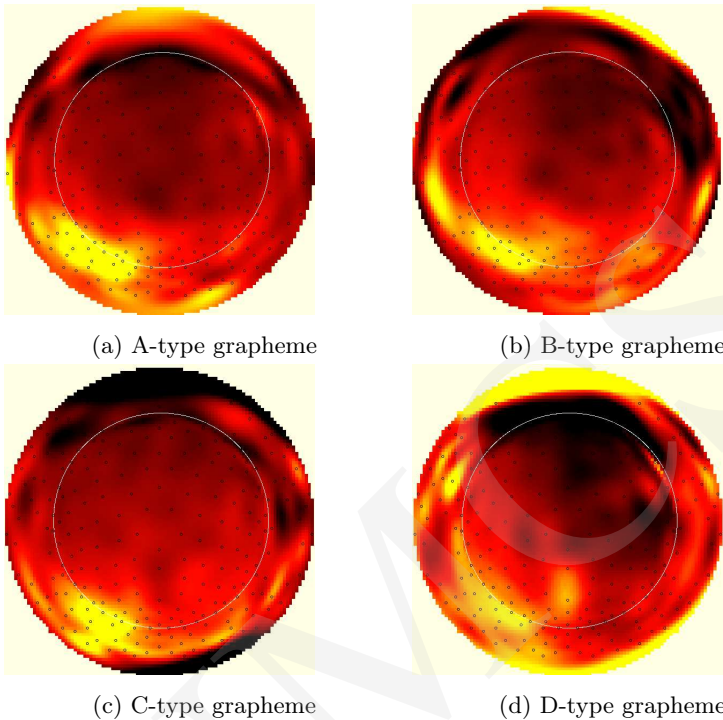
(a) A-type grapheme

(b) B-type grapheme

(c) C-type grapheme

(d) D-type grapheme

Fig. 2. TopoMap in 100 ms after different stimuli

(a) A-type grapheme

(b) B-type grapheme
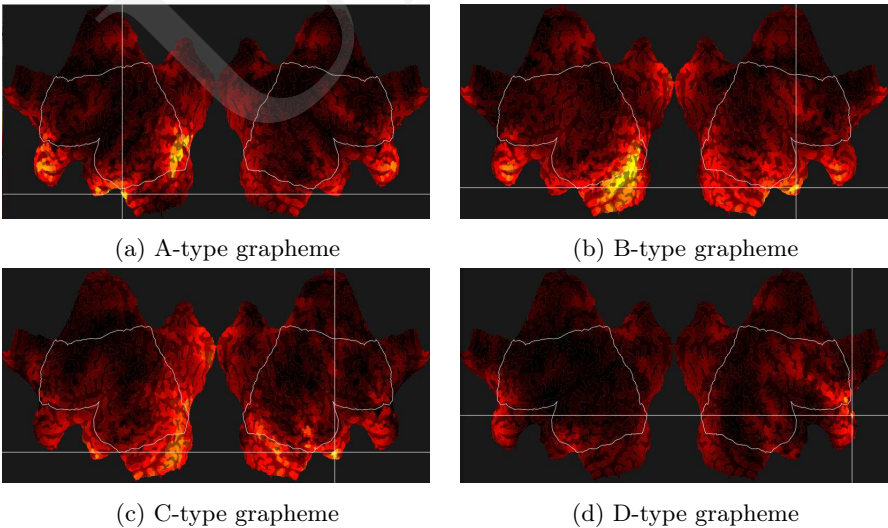
(c) C-type grapheme

(d) D-type grapheme

Fig. 3. Source activity on Flat Map for different stimuli in synesthete

6   Conclusions

Given that we have 256-channel electroencephalograph and geolocation station, the image of GeoSource can be considered to be relatively accurate. We can use it to identify the main sources of brain activity using EEG. S. reacts differently depending on how the colours correspond with his vision. In the case of a man without synesthesia, these reactions probably could not differ so dramatically. With the information on such schemes as opposed to psychological methods, we can clearly and reliably determine whether a person has the synesthetic ability. It should be considered to write a dedicated software, which on the basis of the above mentioned schemes could diagnose synesthesia.

Acknowledgement

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