EVENT-RELATED THETA OSCILLATIONS DURING SUSTAINED ATTENTION

ZEHRA ÜLGEN

Graduate School
Izmir University of Economics
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ABSTRACT

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Ülgen, Zehra

Master's Program in Experimental Psychology

Advisor: Prof. Dr. Canan Başar-Eroğlu

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Attention is a fundamental cognitive function we use frequently in our daily life. Sustained attention is the process of focusing attention on a certain stimulus for an extended period and can be measured with the sustained attention to response task (SART) paradigm which requires the response of frequent non-target one, withholding the response to the infrequent target one. The purpose of this thesis is to examine the differences in event-related theta oscillations and theta inter-trial coherence (ITC) values in terms of the electrode position and time, which has not been examined with the auditory SART paradigm before. To this end, EEG of 13 participants were recorded during a SART paradigm. Results replicated literature in terms of increased theta activity in the fronto-central region. The effect of time had not significant effect on the event-related theta oscillations (target and non-target stimuli) and theta ITC activity (target stimuli), which shows a stable level of selective attention did not alter much over the time. Even though, the theta ITC increased from the beginning to the middle of the experiment this increase is not significant; however, this activity decreased significantly from second block to end of the experiment for the non-target stimuli. The difference between the blocks can be due to the fact that the difference between the target and non-target stimulus becomes clear towards the end of the experiment, which may be related to memory processes. This thesis provided the first findings of changes related to time and brain region in event-related theta oscillations and theta ITC activity in the auditory SART paradigm.

Keywords: Sustained attention to response task (SART), electroencephalography, event realted theta oscillations, inter trial phase coherance in theta band (ITC), effect of time

ÖZET

SÜREKLİ DİKKAT SIRASINDA OLAY İLİŞKİLİ THETA SALINIMLARI

Ülgen, Zehra

Deneysel Psikoloji Yüksek Lisans Programı

Tez Danışmanı: Prof. Dr. Canan Başar-Eroğlu

Temmuz, 2022

Dikkat, günlük hayatımızda sıklıkla kullandığımız temel bilişsel bir fonksiyondur. Sürdürülen dikkat, uzun bir süre boyunca belirli bir uyarana dikkati odaklama sürecidir ve hedef olamayan sık olarak gelen uyarana yanıt vermeyi ve hedef olan seyrek olarak gelen uyarana ise yanıt vermemeyi gerektiren cevap görevinde sürekli dikkat (SART) paradigması ile ölçülebilir. Bu tezin amacı, olaya bağlı teta salınımları ve teta inter-trial koherans (ITC) değerlerindeki farklılıkları elektrot konumu ve daha önce işitsel SART paradigması ile incelenmemiş olan zaman etkisi açısından incelemektir. Sonuçlar, fronto-merkezi bölgede artan teta aktivitesi açısından literatürü tekrarladı. Zamanın etkisinin olay ilişkili teta salınımları (hedef ve hedef olmayan uyaranlarda) ve teta ITC aktivitesi (hedef uyaranlarda) üzerinde anlamlı bir etkisi bulunamamış, bu da kararlı bir seçici dikkat seviyesinin zamanla pek değişmediğini göstermiştir. Teta ITC hedef olmayan uyaranlar için, deneyin başından ortasına kadar artmış olsa da, bu artış anlamlı değildir; bununla birlikte, bu aktivite ikinci bloktan deneyin sonuna kadar anlamlı bir şekilde azalmıştır. Bloklar arasındaki fark, bellek süreçleriyle ilişkili olabilecek, hedef ve hedef olmayan uyaran arasındaki farkın deneyin sonuna doğru netleşmesinden kaynaklanabilir. Bu tez, işitsel SART paradigmasındaki olay ilişkili teta salınımlarının ve teta ITC aktivitesinin zamana ve beyin bölgesine bağlı değişiminin ilk bulgularını sağlamıştır.

Anahtar Kelimeler: Cevap görevinde sürekli dikkat (SART), elektroensefalografi, olay ilişkili teta salınımları, teta bandında inter-trial koherans, zaman etkisi

Dedicated to all beautiful people

who give meaning to my life while discovering life itself...

ACKNOWLEDGEMENTS

Every living mortal person meet many people while living the life bestowed on every living thing. Each of them has a unique touch in our lives and even though, it is not possible to fit all the beautiful people on these pages, I will start with one of the beautifiul person who has a heart of gold, Prof. Dr. Canan BAŞAR-EROĞLU. There are some people who teaches much more than what you can find in books. She became one of those people for me. She is a person from whom I have learned respect, kindness, and goodness in this life, honesty, perseverance, and determination from the way she does her job. All thanks to her who is like an angel and who touches the lives of all people!

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I would also like to express my gratitude to all readers who will read this thesis. I hope this thesis, which is a small part of my efforts to learn life itself, will contribute you in different ways.

PREFACE

I was a small child living in a village when I wanted to be a scientist. For as long as I can remember, the experiments I have done to understand life today have brought me to conduct research on a subject that I am curious about. Human brain… Hans Berger's sister, who lives miles away from Berger, felt something wrong with Berger, who had fallen off the horse and telegraphed. The thought that evokes telepathic communication in Berger's mind is like thoughts that make me curious about the human mind today. The human brain today is not yet fully understood.

I have had the opportunity to observe and be surprised by the effects of focussing and meditation on the human brain and its effects on the environment for years. The epidemic that ravaged the whole world presented me with a great opportunity at this point. Data collection could not be carried out due to the ban on entry to all official institutions and I had the chance to analyze the unpublished data that my supervisor Prof. Dr. Canan BAŞAR-EROĞLU and her team had gathered a long time ago in Germany. It was a great chance for me in this life, the sustained attention topic that I was really curious about was given to me by chance due to epidemic conditions.

Although I had the opportunity to learn new software in order to analyze the data in this whole epidemic process, after the epidemic ended I also had the chance to collect data on sustained attention which I was curious about. It is a beautiful thing that in a short human life span, people can research what they are really curious about and contribute to science even a little bit.

İZMİR

30/06/2022

Zehra ÜLGEN

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LIST OF ABBREVIATIONS

AD: Alzheimer’s Disease

AEPs: Auditory Evoked Potentials

CNV: Contingent Negative Variation

CPT: Continuous Performance Task

ECG: Electrocardiographic

EEG: Electroencephalogram

EPSP: Excitatory Postsynaptic Potential

fMRI: Functional Magnetic Resonance Imaging

GNG: Go/No-Go

Hz: Hertz

IPSP: Inhibitory Postsynaptic Potential

MCI: Mild Cognitive Impairment

MMN: Mismatch Negativity

MTL: Medial Temporal Lobe

OB-a: Active Oddball Task

OB-p: Passive Oddball Task

PET: Positron Emission Tomography

REM: Rapid Eye Movement

SART: Sustained Attention to Response Task

VEPs: Visual Evoked Potentials

CHAPTER 1: INTRODUCTION

Let's review the daily life of the average person. Wakes up in the morning with the sound of the alarm, washes her/his face, has breakfast if s/he has time. Then s/he leaves the house to go to work. S/he gets in her car and starts driving the same road as every morning. Her/his brain does not do something different than the thing s/he does every morning. If we had a high-tech device which shows the neurons in our brains while doing the same thing over and over again, probably we would see cheerily dancing neurons which are really happy to do the same thing every day. Because neurons know where a traffic light is, where to turn right or left, in short, they know the all possible stimuli they will probably encounter therefore they know the all possible reactions they should give to them. Unlike every morning, one day a cat jumps in front of the car and happy neurons suddenly stop dancing and try to figure out what's going on. In these situations, our happy neurons do something different from what they always do: Inhibition! The cat jumping in front of the car catches our hero's attention and our hero does something different from what s/he is used to doing all the time and puts on the brakes. These kinds of stories are actually what we experience in our lives most of the time. The human brain likes to act automatically so we often give same reactions to the stimuli we encounter. However, life sometimes presents us with situations where we must withhold our reactions like SART. Sustained attention to response task (SART) is a task that measures sustained attention, in which the participant continuously responds to frequent non-target stimuli over a period of time and tries to withhold the response to infrequent target stimuli. In this research, we tried to measure the activity of neurons in our brain while doing sustained attention to response task which is very similar to the flow of our daily life. EEG is a device that gives us a two-dimensional form of this three-dimensional neuronal activity in ours brains. So, what is the EEG? EEG is the abridgment of the Electroencephalogram. Electro means electrical activity, Encephalo means brain, Gram means picture. So, EEG means a picture of electrical activity in the brain.

1.1 EEG: Electro- Encephalo-Gram

1.2 What is the source of EEG?

In our brain, there are billions of neurons and they are communicating with each other via electrical signals. So, the basic source of EEG is this electrical activity between neurons. This electrical activity creates a current flow and EEG records this current flow between the electrical generator and the recording electrode called volume conduction (Olejniczak, 2006; Cohen, 2017). How this electrical activity occurs between a neuron and how EEG measures it? First, the structure of a neuron must be well understood to understand how EEG measures electrical activity in the brain.

1.2.1 Structure of a Neuron

There are different types of neurons in terms of structure. For example, there are three types of neuron structure which are unipolar, bipolar, and multipolar neuron. Most of the brain's neuron is the multipolar neuron (Figure 1). A neuron consists of four basic structures which are dendrites, cell body, axon and axon terminals (Carter, 2019). Dendrite takes information from presynaptic neurons and then information goes to the cell body. Information comes to the axon terminal via the axon. Finally, it is released to the synaptic cleft which is a gap between presynaptic and postsynaptic neurons for information transferring. This information transferring is called an action potential (Sanei and Chambers, 2013).

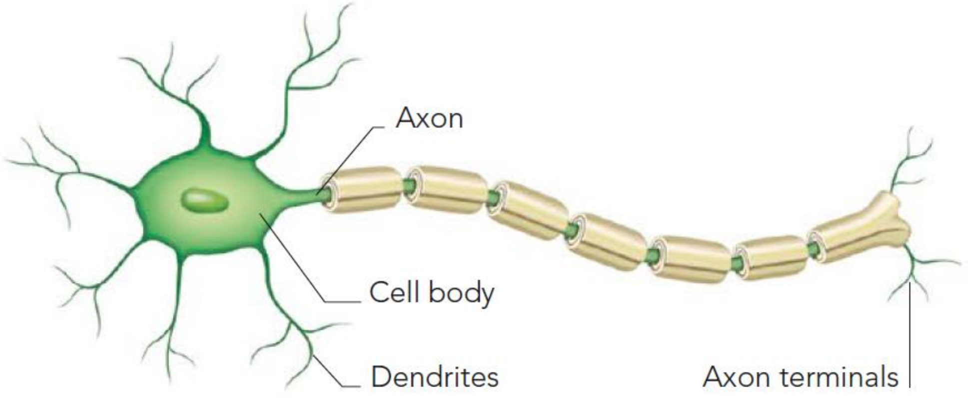


Figure 1. Representational multipolar neuron. (Source: Carter, 2019).

1.2.2 Action Potential

In normal circumstances, the inside of a neuron is negative (-70 mV) than extracellular which is called the resting state. There is more potassium (K) in the cell and more sodium (Na) outside of the cell. Nerves in the brain become stimulated by chemical activity at synapses. Action potential starts when stimulus strength goes above the threshold (Figure 2).

Then Na+ channels open and Na+ starts to the influx to intracellular which is called depolarization. After sodium gates close, K+ channels open and K+ starts to efflux to extracellular. So, the cell becomes repolarize then becomes hyperpolarize and potassium influx to intracellular and sodium efflux to the extracellular again. Finally, the cell reaches to resting potential again. In that process, the largest potential change occurs in the intracellular; however, the amplitude is so small at the extracellular. So, action potential activity is so small and takes only 1 ms which is a very weak signal for EEG. However postsynaptic potential changes take 10 ms so, postsynaptic potential changes are recorded by EEG (Kirschstein and Köhling, 2009; Sanei and Chambers, 2013).

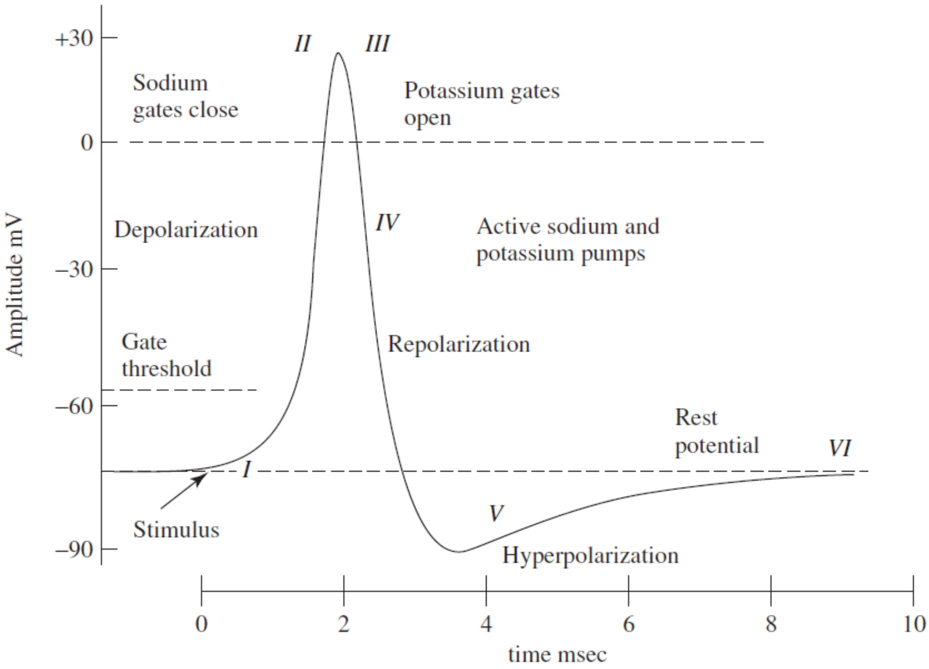


Figure 2. Changing the membrane potential (Source: Sanei, and Chambers, 2013).

1.2.3 Postsynaptic Potential

There are two possibilities after action potential changes reach the terminal button which is releasing glutamate or GABA from the presynaptic vesicles. Firstly, Ca2+ and Na+ channels open at the presynaptic neuron than glutamate is released to the synaptic cleft and binds to the specific receptors then Ca2+ and Na+ influx cause positive excitatory postsynaptic potential (EPSP). So postsynaptic membrane becomes depolarized (Figure 3a). However, if presynaptic neurons release y-aminobutyric acid (GABA), Cl- influx to the intracellular and K+ efflux to the extracellular. That makes intracellular more negative and hyperbolized (Figure 3b). This process is called inhibitory postsynaptic potential (IPSP) (Kirschstein and Köhling, 2009). So how EEG can measure this postsynaptic activity? The answer is the pyramidal neuron (Kirschstein and Köhling, 2009).

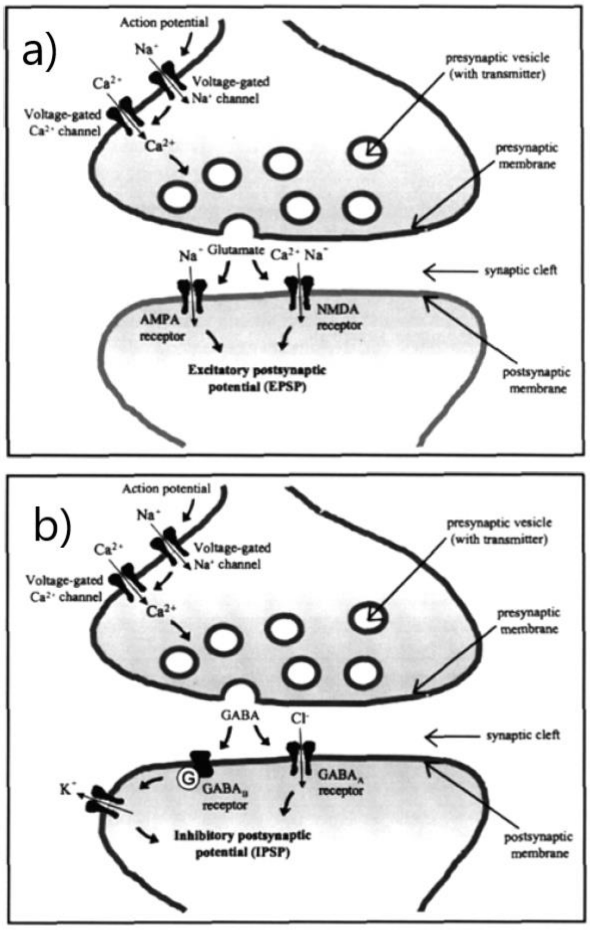


Figure 3. The prototypic excitatory (a) and inhibitory (b) synapse in the cortex (Source: Kirschstein, and Köhling, 2009).

1.2.4 Pyramidal neuron

Pyramidal neurons are very important for EEG. Because EEG measures the activity in those neurons. These neurons take place in grey matter. Their activity passes over many brain layers and reaches the EEG electrode. These layers are called pia matter, arachnoid matter, dura matter, skull, scalp respectively (Figure 4)(Drake, Vogl and Mitchell, 2019).

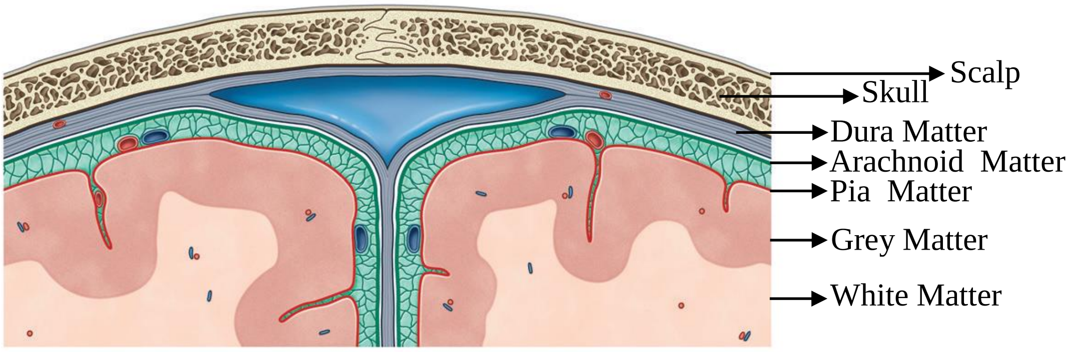


Figure 4. Arrangement of the meninges (Source: Drake, Vogl, and Mitchell, 2019).

Pyramidal neurons take place in grey matter and they take their name from their shape (Figure 5). They have a long apical dendrite that arises vertically against the cortical surface. They also have basal dendrites nearer to the cell and take place horizontally. They are very special neurons and they are excellent dipoles because of their unique anatomical structure. They are perpendicular to the cortical surface (Kirschstein and Köhling, 2009).

There are six layers in the grey matter and pyramidal cells can take activity from different layers (Figure 6). Both EPSP and IPSP from different layer reflect the recorded synaptic activity by EEG (Olejniczak, 2006). However, amplitude of recorded activity changes in terms of superficial or deep layer. Before examining the amplitude of a signal, first synaptic activation and dipole should be well understood.

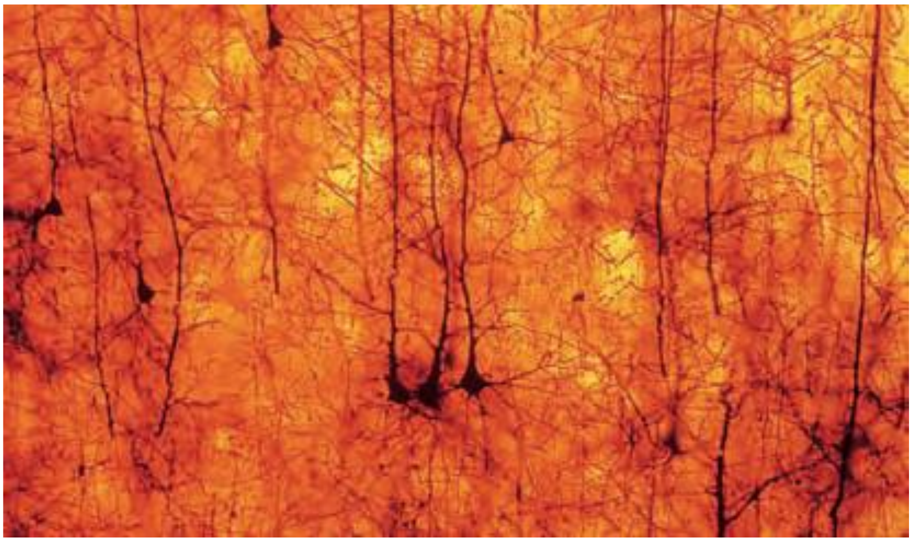


Figure 5. Human pyramidal cell spotted by Golgi technique (Source: Kolb, and Whishaw, 2012).

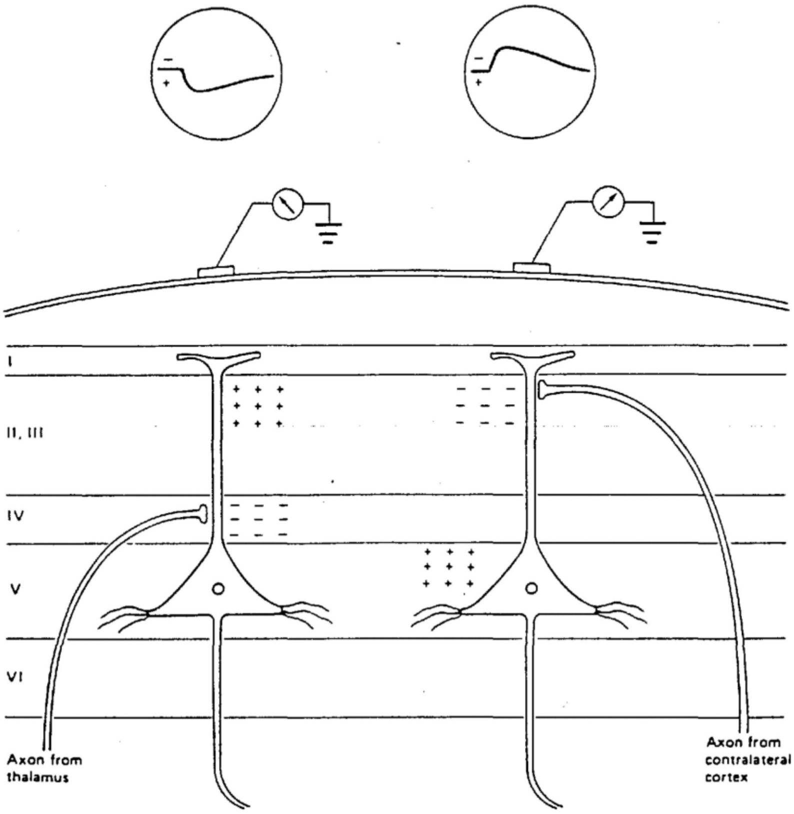


Figure 6. Site of dendritic postsynaptic potentials. (Source: Olejniczak, 2006).

1.2.5 Dipole

When presynaptic neuron releases excitatory neurotransmitter (Glutamate) from the terminal button, positive current flows to the dendrites of the postsynaptic neuron (Kolb and Whishaw, 2012; Bear, Connors and Paradiso, 2015). So inside of the postsynaptic cell becomes more positive and extracellular more negative (Figure 7). The outside of other parts of the neuron is still positive and this difference of electrical potentials create electrical dipoles between soma and apical dendrites (Kolb and Whishaw, 2012; Sanei and Chambers, 2013). The same procedure is also acceptable for inhibitory activation (GABA).

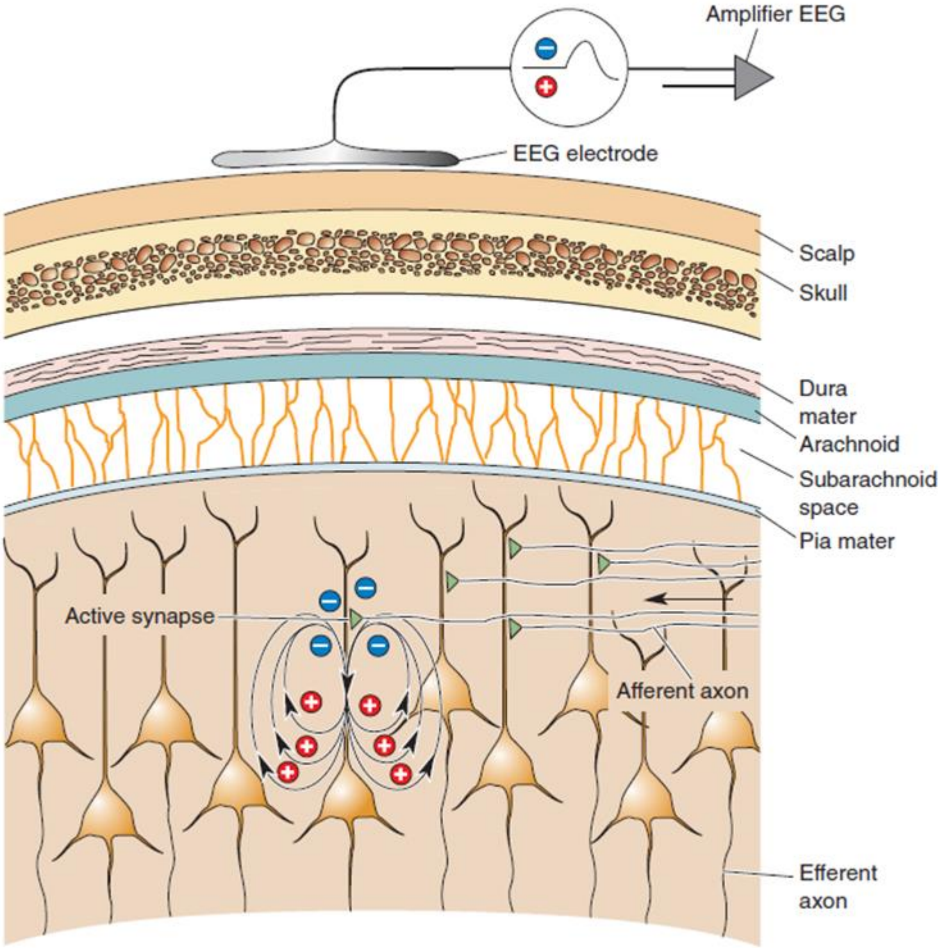


Figure 7. Generation of electrical and magnetic fields (Source: Bear, Connors, and Paradiso, 2015).

As it was mentioned earlier, neurotransmitters can stimulate the postsynaptic cells from different layers of grey matter. So, superficial or deep activity reflect the recorded synaptic activity differently. Superficial excitation makes the positive inside of the cell so, outside becomes more negative. The deep part of the extracellular neuron is still positive. So, the neuron becomes a dipole and from positive to negative current flows (Figure 8A). Then we see negative scalp activity at the EEG recording (Kirschstein and Köhling, 2009). If neurotransmitters come from the deep layer superficial part of the extracellular neuron becomes more positive. So, current flow from positive to negative and positive scalp activity is seen at EEG recording (Figure 8B). So, the procedure is also the same for deep (Figure 9A) and superficial inhibition (Figure 9B); but, opposite direction. This time deep input causes negative scalp activity, superficial input causes positive activity. The important thing is superficial inputs have more amplitude than deep inputs because of the distance to the scalp (Kirschstein and Köhling, 2009)

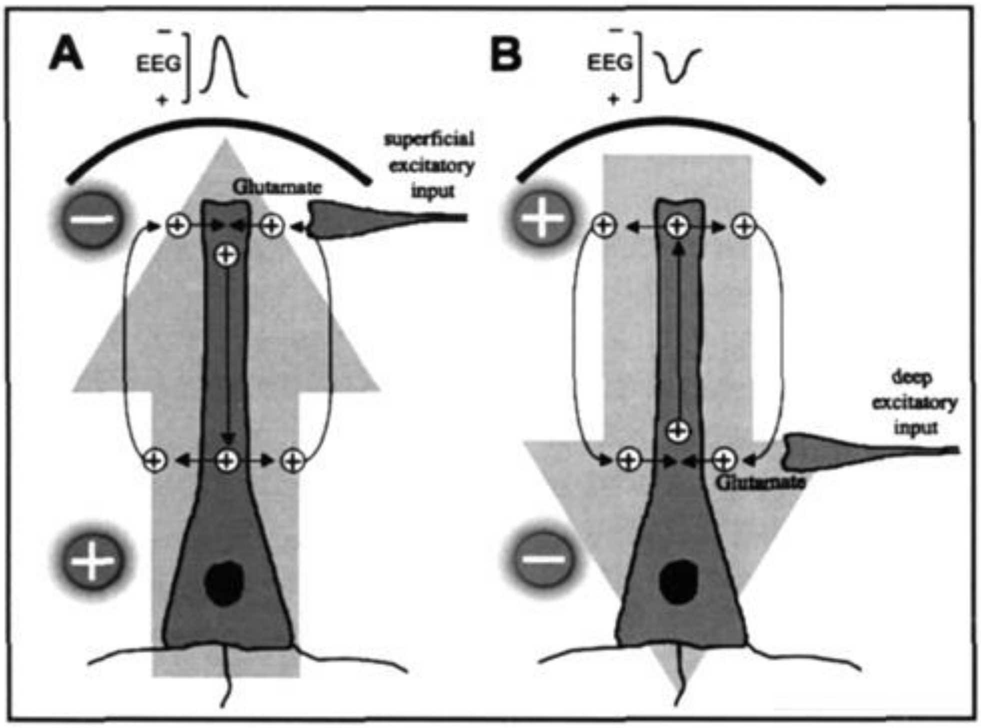


Figure 8. Superficial (A) and deep (B) excitatory input to the pyramidal neuron. (Source: Kirschstein, and Köhling, 2009).

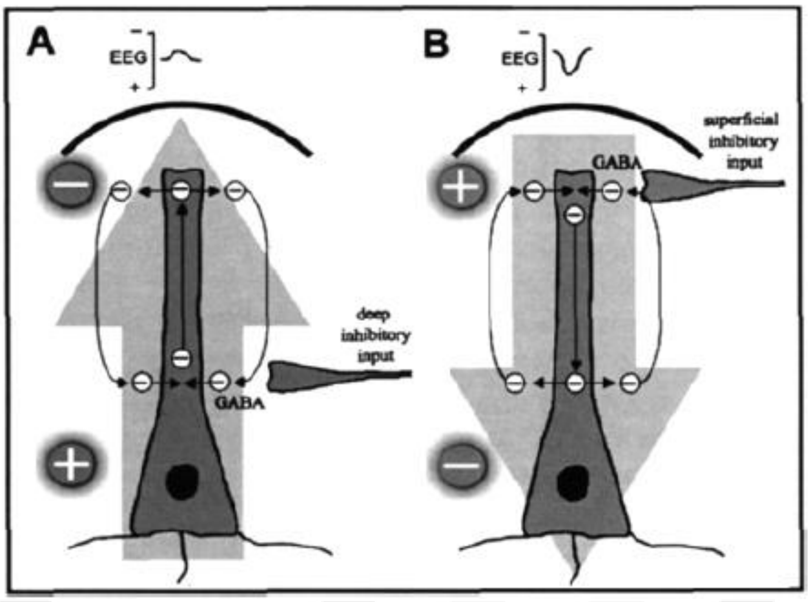


Figure 9. Deep (A) and superficial (B) inhibitory input to the pyramidal neuron. (Source: Kirschstein, and Köhling, 2009).

1.2.6 Electrical Signal

When neurons are firing, the different electrical potential consist and pyramidal neurons become a dipole (Sanei and Chambers, 2013). EEG measures this electrical signal. However, single neuron postsynaptic activity is very small to detect the activity at the EEG recording. Because of that reason if large number of postsynaptic potentials occur at the same time, EEG can detect that activity (Kirschstein and Köhling, 2009) So, there are two important things about electrical signals which are timing and orientation. When a group of cells is excited at the same time, synchronous activity is seen at the EEG recording (Bear, Connors and Paradiso, 2015) and summed EEG wave has a larger amplitude (Figure 10A). However, if pyramidal neurons take input at the different time their summed activity has a small amplitude (Figure 10B) (Olejniczak, 2006). The other important thing is the orientation of neurons. If neurons take place parallel to the scalp (Figure 11a) signal comes better. However, if they are in a opposite site to each other (Figure 11c) they neutralize each other (Ebersole and Pedley, 2003; Olejniczak, 2006; Cohen, 2014).

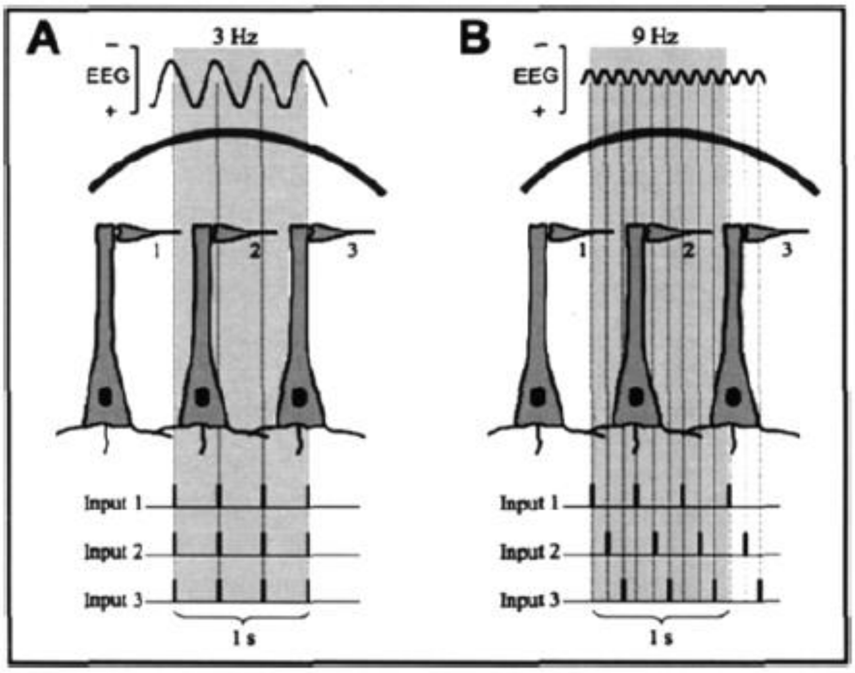


Figure 10. Synchronization (A) and desynchronization (B) of pyramidal neurons (Source: Kirschstein, and Köhling, 2009).

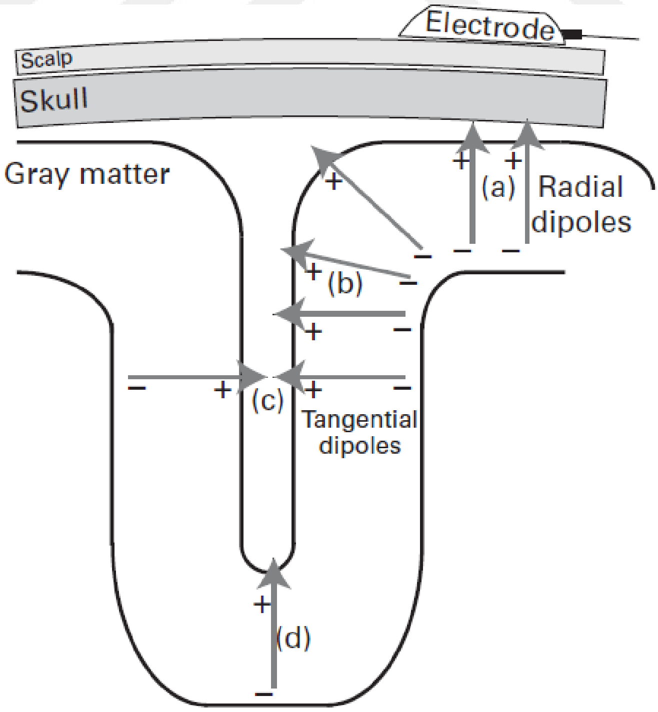


Figure 11. Representative cortical EEG sources. (Source: Cohen, 2014)

1.3 International 10-20 System

When measuring these menationed above electrical signals, the international 10/20 system is used (Klem et al., 1999) and 21 electrodes attached to the surface of the scalp. There is two reference point when electrodes are placed which are nasion (a tap of the nose) and inion (bony lump back of the head). The length between these two reference points is used when dividing this length into 10% and 20% intervals (Sanei and Chambers, 2013). Electrode names are called according to the region that they take place; odd numbers take place in the left hemisphere and even numbers are in the right hemisphere (Figure 12).

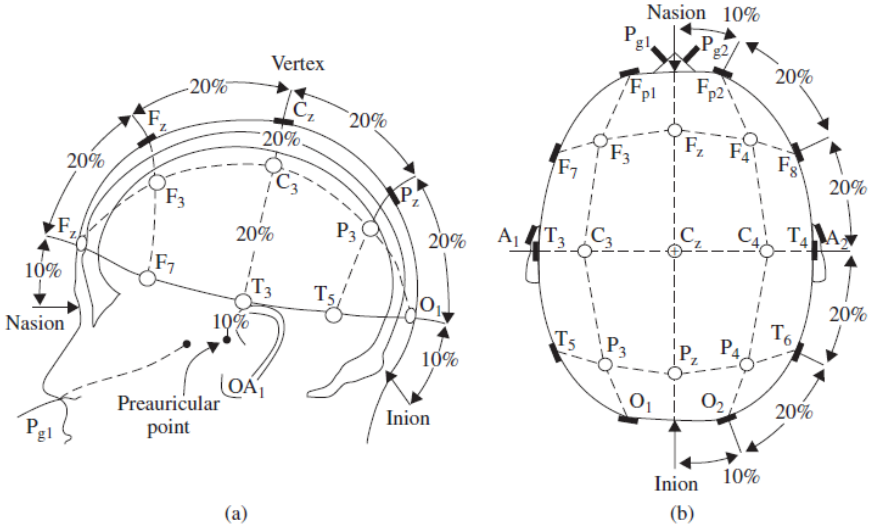


Figure 12. International 10/20 System. (Source: Sanei, and Chambers, 2013).

1.4 The History of EEG

We all know that Hans Berger is an important person for the discovery of EEG. Also, there are lots of important names who paves the way for EEG’s development. So how did we get to this level of knowledge about EEG? Today we know that there are pyramidal neurons in the cortex and EEG measures the electrical activity of these neurons. Understanding this process can be easy for us now, but if we were living in ancient times like the 1800s it would be difficult to understand this process. Thinking about measuring the electrical activity of neurons is an unimaginable thing at those times. So, the first thing we need to do is to understand the past well if we want to understand today better.

1.4.1 What is Electricity?

All history begins with electricity and continuous with measuring the electricity. So firstly, looking at the simple description of electricity can be good in terms of understanding the topic better. Today we know that electricity is everywhere from the sky to the human body. All matter in the world consists of atoms which are the smallest part of the material. Atoms are consisting of *the nucleus* that has protons (+) and neutrons (0); and *electrons* (-) that take place at the orbit of the atom. Electrons can move quickly from one atom to another in some material (Figure 13). So, these motions of electrons are called electricity (Gibilisco, and Monk, 2016). Today we know that this is the simple description of what is electricity; however, in ancient times, people did not know as much about atoms and electricity as we know today. So, they were trying to measure and understand electricity in the 18th century.

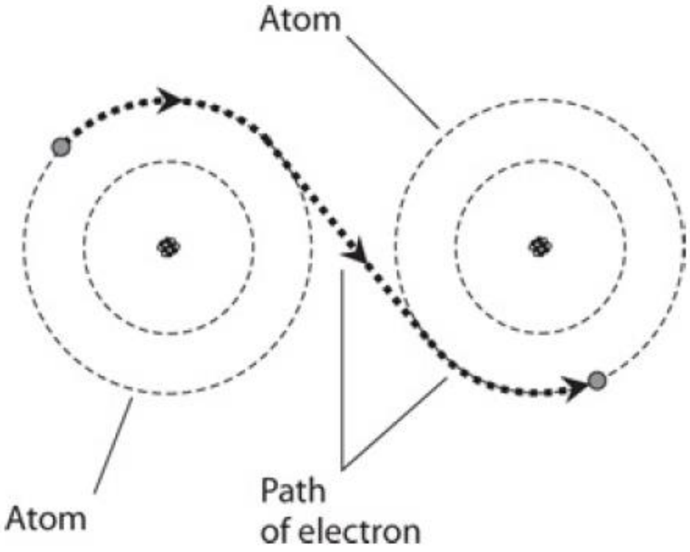


Figure 13. Electron passage from one atom to another. (Source: Gibilisco, and Monk 2016).

1.4.2 Early Electrometers

In the 18th century, physicists developed a tool to measure the electricity that was called a galvanometer. The first time it was invented by Lord Kelvin. Then d’Arsonval improved Kevin’s ideas and invented the d’Arsonval galvanometer in

1870 (Figure 14a). Then Gabriel Lippman (1845-1921) improved the capillary electrometer. It was used to first time record the ECG (electrocardiogram) in dog and man by Waller in 1880. John Burdon-Sanderson (1828-1905) used a capillary electrometer produced by Frederick J. M. (Figure 14b). He achieved to record potential from the heart of the frog. In 1901 Wilhelm Einthoven developed the first device that can record the potentials without distortion was called Einthoven String Galvanometer (Figure 14c). Then Einthoven earned a Nobel prize in 1924 with this galvanometer (Collura, 1993).

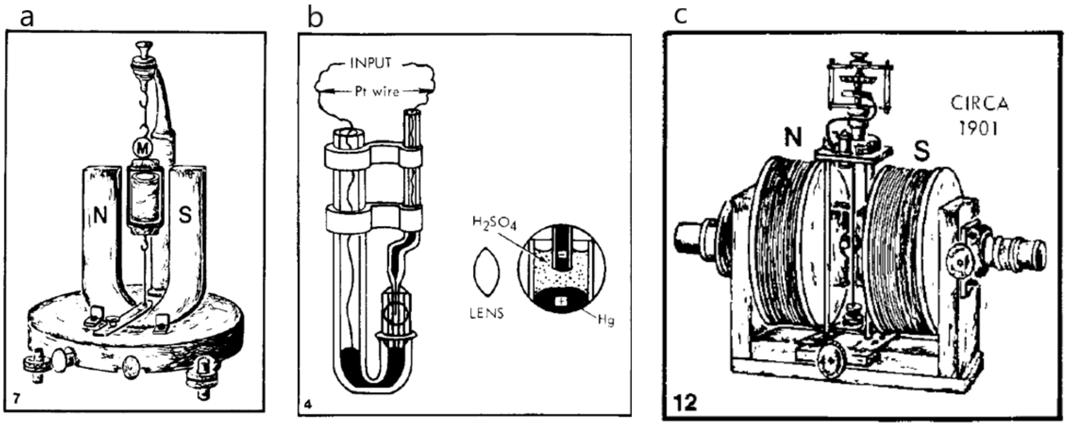


Figure 14. Representative early electrometers (Source: Collura, 1993).

1.4.3 Pre-EEG and Stimulation Studies

Today we know that the origin of EEG is based on experiments of physicists like Italians Luigi Galvani (1737-1798), Alessandro Volta (1755-1832), and Englishmen George Ohm (1787-1854), Michael Faraday (1791-1867). They are an important person in terms of today’s general understanding of electrical potential and current. Luigi Galvani is especially important with his studies on electrical activity on nerves in 1791 (Kolb and Whishaw, 2005). Galvani developed frog nerve-muscle preparation (Figure 15) and developed the concept of animal electricity (Collura, 1993; Kolb and Whishaw, 2005). Hermann Von Helmholtz also studies with frog and stimulated motor nerve of muscle. He measured the first-time rate of conduction (Kolb and Whishaw, 2012; Sanei and Chambers, 2013)

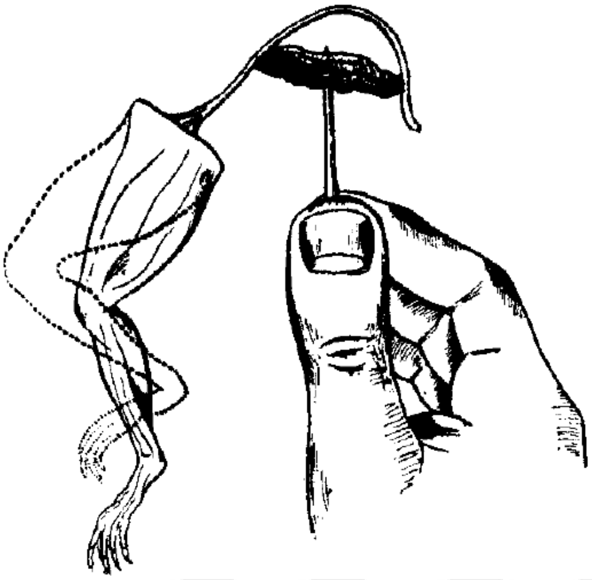


Figure 15. Stimulated frog-nerve (Source: Collura, 1993).

Gustave Theodor Fritsch and Eduard Hitzig were also studying with other animals like rabbits and dogs in the mid-nineteenth. They even worked with a human who has had head injuries. They observed specific motor responses in an anesthetized dog in 1870 (Collura, 1993). They also stimulated the neocortex of a person with a head to injure and they observed action on the arms and legs of subjects (Kolb and Whishaw, 2005) In the twentieth century, brain stimulation became very popular and Wilder Penfield (1891-1976), a neurosurgeon, gave electrical stimulation to patients' neocortex in 1950 to determine the function of the area.

1.4.4 EEG Recording Trials

Richard Caton was the first electroencephalographer who recorded the brain activity of rabbits and monkeys with mirror galvanometer (Figure 14a) and non-polarizable electrodes in 1875 (Brazier, 1984; Collura, 1993). He also discovered the event-related potential and named them as “negative variation” (Caton, 1875).

Adolph Beck is another person who also could record the activity of the brain in animals. In 1890, he gave light stimulation to the dog and observed the blocking of spontaneous activity (Collura, 1993). That was desynchronized EEG recording but he did not name it like that.

In 1912, Russian physiologist Vladimir Vladimirovich Pravdich-Neminsky (1879-1952) recorded oscillations on moving photographic paper (Figure 16) and he published results in 1913 (Collura, 1993). So, the picture of electroencephalogram and evoked potentials were seen the first time in the literature (Brazier, 1984). While he was recording these oscillations, he examined the brain of the dog and record brain activity with an Einthoven string galvanometer (Figure 14c) and found 12-14 cycles under normal circumstances (Collura, 1993; Sanei and Chambers, 2013). Another Russian physiologist Napolean Cybulski (1854-1919), Beck's mentor, gave electrical stimulation to the dogs and studied epileptic seizure in dogs (Collura, 1993; Sanei and Chambers, 2013).

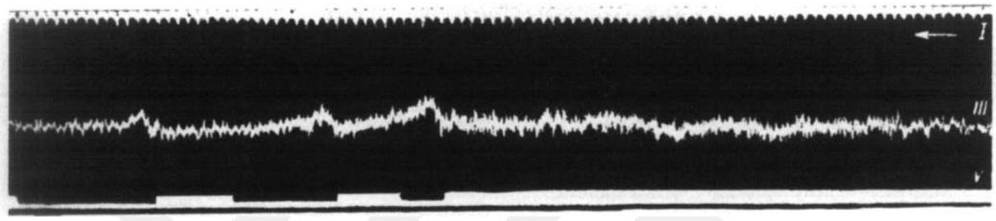


Figure 16. The first picture of evoked potential (Source: Brazier, 1984).

1.4.5 Fist Alpha and Beta Rhythm in Human

German psychiatrist Hans Berger (1873-1941) started to interest in EEG with an interesting event that happened to him. One day he fell off a horse and his sister who lived far from him felt that there is something wrong with Berger. Then she sent a telegram in a hurry to Berger. Berger thought that this was a telepathic communication and then he decided to start study psychiatry (Kaplan, 2011).

In 1902 he started to investigate the electrical activity of the dog brain with a capillary electrometer (Figure 14b) and he found spontaneous activity like Caton, Beck, and Neminsky (Collura, 1993). Then he used a string galvanometer in 1910 and a smaller Edelmann model respectively (Sanei and Chambers, 2013). First human EEG recorded with a small Edelmann galvanometer and nonpolarizable clay cylinder electrodes on July 6, 1924, during the neurosurgery done by Nikolai Guleke from a 17 years old boy (Collura, 1993; Sanei and Chambers, 2013; İnce, Adanır and Sevmez, 2020).

In 1926 he used the Siemens double-coil galvanometer and studied with nonpolarizable electrodes that bypassing to the skin. He took 73 recordings from his son Klaus and after five years of studying, he published the first human EEG recording results at *Über das Elektrenkephalogramm des Menschen* in 1929 (Collura, 1993). In that report, he described 10-Hz alpha waves and beta waves (Berger H., 1929). He also showed that the alpha-blocking with light stimulation from different ages and genders (Figure 17) (Collura, 1993; İnce, Adanır and Sevmez, 2020).

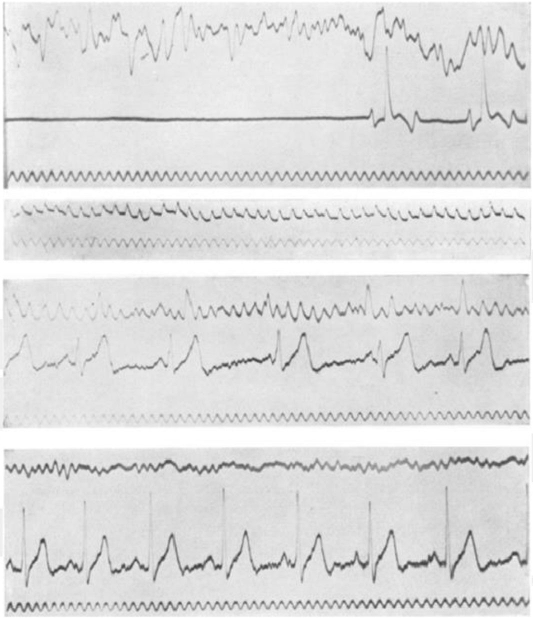


Figure 17. EEG recording from different ages and genders. (Source: Berger, 1929).

In 1930, Berger started to record brain activity with sleep and the first time he showed the sleep spindles (Kaplan, 2011; Sanei and Chambers, 2013; İnce, Adanır and Sevmez, 2020). He also studied the effect of hypoxia, localized brain disorder, (Haas, 2003; Sanei and Chambers, 2013) and electrical wave difference around the brain tumor (Kaplan, 2011; İnce, Adanır and Sevmez, 2020). In 1931, he started to use an amplifier/oscillograph from Siemens and the first time he showed the different recordings from different subjects and sessions (Figure 18). He started to use silver needles in 1932 then he used two silver scalp electrodes and reported it in 1938 (Collura, 1993).

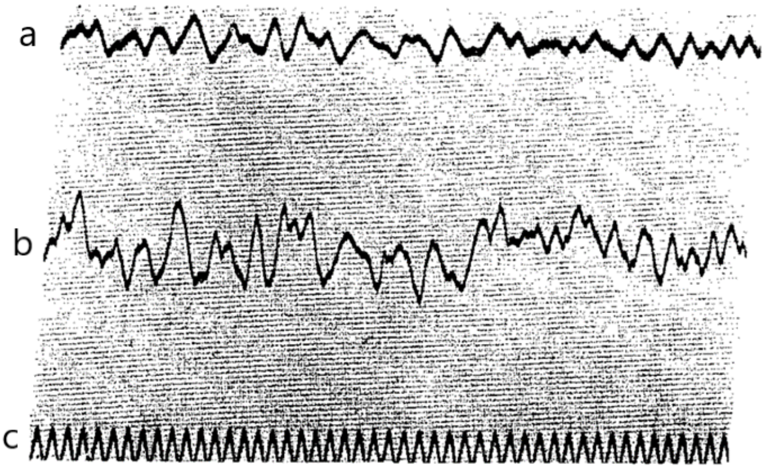


Figure 18. EEG recording made by Berger in 1932. (a) EEG recorded from Edelmann string galvanometer, (b) Siemens double-coil oscillograph, (c) 10 Hz reference (Source: Collura, 1993).

1.5 EEG Recording and Measurement

Recording the electrical activity of the brain took a long time. The story began with electricity and today we can measure electrical activity in the brain thanks to cumulative information throughout history. Although we are measuring the electrical activity of the brain, we cannot say what a person is thinking. However today we can understand whether a person is awake or asleep thanks to the EEG. Also, EEG is important in terms of diagnosing some diseases like Alzheimer’s disease (AD) or Mild Cognitive Impairment (MCI) (Yener, Güntekin and Başar, 2008; Yener et al., 2012; Yener et al., 2013).

EEG has a wide range of uses from sleep recording to diagnosis of diseases. So, there are different techniques for EEG while measuring and recording electrical activity in the neurons. These techniques are single-cell recording, electroencephalographic recording, and event-related potential recording.

The single-cell recording is very hard in the human or animal brain because neurons are tiny. But zoologist J. Z. Young realized that the North Atlantic squid has a very big axon (Figure 19A) so he decided that single-cell electrical recording can be observed at the squid. Then Alan Hodgkin and Andrew Huxley made an experiment with North Atlantic squid. The first time they measured the electrical activity in the neuron by implanting microelectrodes (Figure 19C). Then they recorded the electrical activity with an oscilloscope (Figure 19B) which can record any small electrical signals at the nerve (Kolb and Whishaw, 2005). This single-cell recording is measuring the action potential (Buzsáki, Anastassiou and Koch, 2012). Single-cell recording is easier in animals than humans. However, researchers also recording a single cell from the human brain while in surgery. Itzhak Fried and his colleagues found specific neurons for the image of a specific person in the MTL (Medial Temporal Lobe) (Gazzaniga, Ivry and Mangun, 2013). For example, a single neuron in the left posterior hippocampus became active during the surgery when the patient sees the picture of Jennifer Aniston, but that neuron did not become active when the patient see other celebrities (Quiroga et al., 2005).

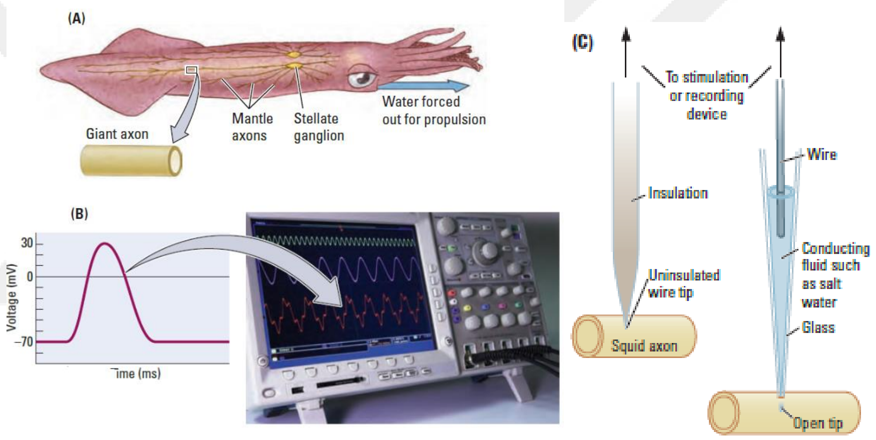


Figure 19. (A) North Atlantic squid (B) Example of a digital oscilloscope (C) Wire (left) and glass (right) microelectrode (Source: Kolb, and Whishaw, 2012).

EEG cannot detect the single neuronal activity, but it can measure electrical potential when single neurons become active together. This technique is called EEG recording and it has been used for years. As mentioned in the “History of EEG”, the first time Hans Berger recorded the electrical activity of the brain. Today measuring the electrical activity of the brain took a popular name which is *measuring brain waves*. These waves were recorded with a polygraph (Figure 21A) in the past. Then computers became popular and digitalized EEG recording entered our life (Kolb and Whishaw, 2012; Sanei and Chambers, 2013). Today EEG is recording the summed graded potentials from neurons at the cortex. Electrical potentials at the cortex can be measured because the tissue of the brain, skull, and scalp conduct the electrical activity. So, each electrode is placed on the scalp about the international 10/20 system, and one reference electrode is placed on the mastoid bone. Voltage in each electrode is compared with the reference electrode and recorded. This recording is called an electroencephalogram (Gazzaniga, Ivry and Mangun, 2013). We can understand the behavioral state of a person by looking at the EEG pattern. For example, when a person feels excited, low amplitude and fast frequency are seen (Figure 20A). If a person closed eyes or feel relaxed high amplitude and low frequency are seen (Figure 20B). So, EEG is a useful tool to understand the behavioral states or sleep stages. Also, it is important for research and diagnoses of abnormalities in the brain (Kolb and Whishaw, 2012).

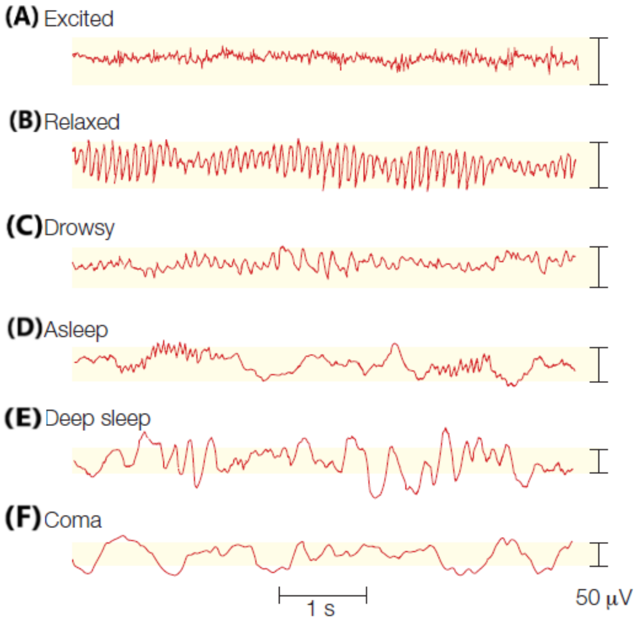


Figure 20. EEG Recording, time on the x-axis voltage on the y-axis. (Source: Gazzaniga, and Mangun, 2013).

EEG recording gives little information about the cognitive process. It generally reflects the global activity of the brain. But, ERP (Event-Related Potentials) is an important technique that shows the major changes in the EEG pattern that occurs at the stimulus. If we want to see how the brain gives a response to the task, we should look at the ERP. However, detecting the evoked response to the sensory stimuli from a single trial is not easy because of the background oscillations of EEG. So, all trials are averaged, and the background EEG is removed to detect the ERP (Kolb and Whishaw, 2012; Gazzaniga, Ivry and Mangun, 2013). For example, the participant hears tone 100 times during the experiment. Detecting the ERP is hard by just looking at the first trial (Figure 21B). But, after averaged the 100 trials, ERP can be detected easily (Figure 21C). As can be seen in the figure there are there different ERPs which are P1, N1, and P2. The features of each ERPs will be discussed in the next title.

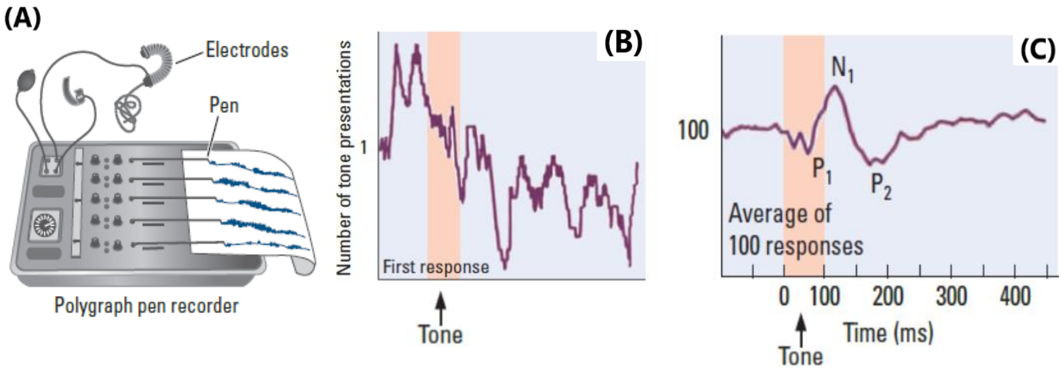


Figure 21. (A) Example of a polygraph pen recorder (B) Unclear positivity and negativity with first stimulus, (C) Average of 100 trials. (Source: Kolb, and Whishaw, 2012).

1.6 What is the Evernt Related Potentials (ERPs)?

Event-related potentials (ERP) will be discussed in detail in this part. However, before starting to understand the logic of the ERP we should know some terms about ERP. EEG is the recorded electrical activity of the brain from the scalp. These electrical activities express the cortical electrical activity. There are two important terms for an electrical activity which are signal intensity and signal frequency. The signal intensity of EEG is quite small, and it is measured in microvolts (μV). Signal frequency is the number of the oscillation at the 1 second (Sanei and Chambers, 2013; Luck, 2014). Theta, Delta, Alpha, Beta, and Gamma are the type of frequencies and they will be discussed in detail in the next title.

ERP, event-related potential. Our brain gives responses to the external stimulus and these responses reflect the paper as we can read. After a specific event, some potentials are seen which are ERPs. However, as discussed earlier detecting the ERP from the EEG recording is not easy. Because background EEG signal has higher signal intensity than ERP (Figure 22). ERPs are smaller than EEG background activity and they are at the 1-30 μV range (Sanei and Chambers, 2013). As it can be seen in figure 22, ERP has 2 μV amplitude, however, EEG recording has 20 μV amplitude. So, the tens or hundreds of trials are averaged, and background EEG is removed to see the event-related potentials (Gazzaniga, Ivry and Mangun, 2013).

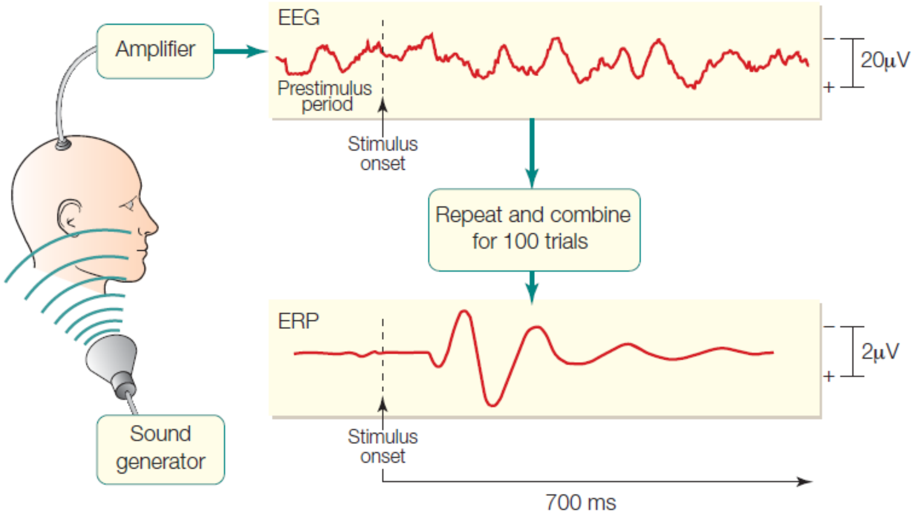


Figure 22. The scale difference between EEG and ERP waveforms. (Source: Gazzaniga, Ivry, and Mangun, 2013).

1.6.1 The History of ERPs

ERP derived from the EEG; so, the history of ERP is similar to the history of EEG. Richard Caton was the first person who reported the electrical activity in the brain. He studied with animals and showed his finding at the 43rd meeting of the British Medical Association in August 1875. He reported these finding because he had no camera to that findings (Caton, 1875; Brazier, 1984). In 1887 he made experiments with animals and although he could not find a response to the odors or sounds, he could find the response to the light. Adolf Beck and Napoleon Cybulski have not become aware of the experiments of Caton. They also found the evoked potential to the light on the occipital cortex (Brazier, 1984). No scholar published the photograph of the evoked potential until 1914. First-time Russian physiologist Vladimir Vladimirovich Pravdich-Neminsky demonstrated the photograph of ERP at the brain of a dog in 1913 (Figure 16) (Brazier, 1984)

The first human evoked potential recording was recorded by Pauline and Hallowell Davis in 1939 (Brazier, 1984; Luck, 2014). They were studying the electrical activity of the brain on a sleeping person. They were stimulating the sleeping subject and observing the K-complex. They were first time recoded the evoked potential on the waking brain (Figure 23) (Davis, 1939).

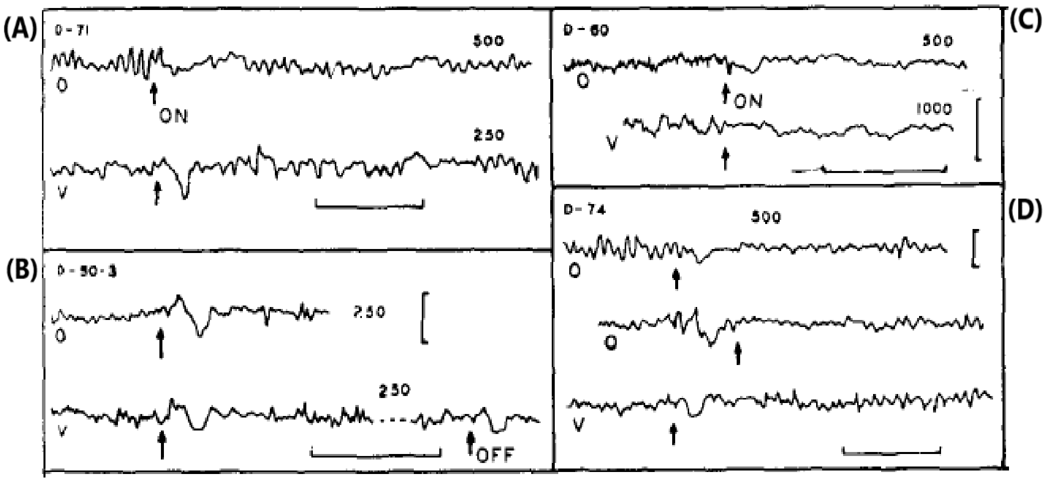


Figure 23. The first picture of evoked potential in man. (Source: Davis, 1939).

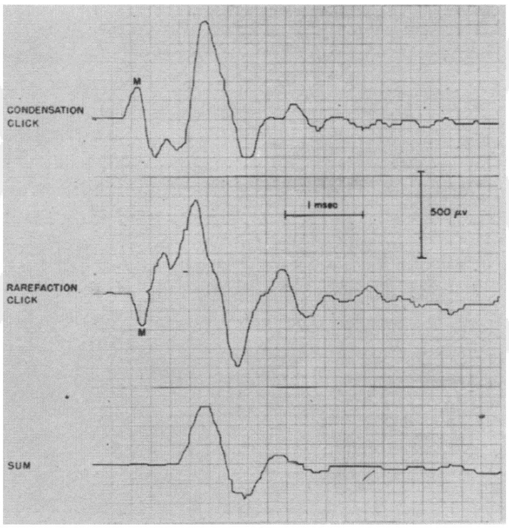


Figure 24. Electrical responses in the cochlea of an anesthetized cat (Source: Clark et al., 1961).

In 1958 Clark and his colleagues designed the electronic instrument in the Research Laboratory of Electronics at the Massachusetts Institute of Technology. They worked with the anesthetized cat and gave the acoustic stimuli at 1/ sec (Figure 24). First line demonstrates average of 64 trials. Second line shows the average of rarefaction click. Then they published results of average response computer (ARP) in 1961(Clark et al., 1961).

The first cognitive ERP was published by Grey Walter and his colleagues in 1964. They called it contingent negative variation (CNV) (Luck, 2014). The other discovery was the P3 that was found by Sutton et al. (1965). In their experiment participants could not predict which stimulus will come auditory or visual. They found the positivity occurred at 300 ms after participants took the stimulus. They called it P300 (Sutton et al., 1965a).

After Sutton and colleagues published this paper, lots of researchers focused on ERP and developed new methods for 15 years. Although ERP experiments had disrepute among the cognitive psychologist and neuroscientists in the late 1970 and early 1980, ERP experiments again became more popular in the mid-1980s. Then positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) were developed. These advancements caused to think of ERP experiment might die. However, the situation was the opposite, most of the researchers understood that ERP studies have high temporal resolution while investigating the cognitive processes (Luck, 2014). So today ERP experiments are still important, and it is developing rather than fade away. Today ERP is very popular because it has three important advantages: 1) time resolution of EEG is very high. So, information processing in the brain can be analyzed quickly (Sanei and Chambers, 2013). 2) ERP is a very sensitive method to specify the cognitive dysfunctions (Gaetz and Bernstein, 2001; Olichney et al., 2011) 3) ERP has a high rate of test-retest reliability (Cassidy, Robertson and O’Connell, 2012)

The development of ERP is an accumulated process. Today ERP is very important for the investigation of cognitive processes and diagnosis of some of the diseases. We can measure the electrical response of sensory, affective, or cognitive events on the cortex with EEG, also understand the effects thanks to the ERP (Sanei and Chambers, 2013). Firstly, to understand the ERP better we should look at the dimensions of ERP. ERP waveform has three dimensions: amplitude, latency, and scalp distribution. Amplitude is the sign of neural activity. It is called positive or negative according to the polarity. Latency is the time of the peak of the amplitude occurs. Scalp distribution is the where is from signals are coming on the scalp (Gazzaniga, Ivry and Mangun, 2013; Sanei and Chambers, 2013). For example, N100 ERP component is seen after the auditory stimulus is presented and has a negative peak around the100 ms at the fronto-central scalp location (Näätänen and Picton, 1987).

1.6.2 The Components of ERP: P100 / N100

The earliest amplitude and latency of components that are seen at first 100ms after a stimulus come are related to the sensory process. The waves after the stimulus presentation that occur at 100ms like P100 and N100 are related to the selective attention (Gazzaniga, Ivry and Mangun, 2013) and they are labelled exogeneous (Sanei and Chambers, 2013). However, the positivity is seen at later time like P300 ms is about the strategies, and expectancies; and are labelled endogenous components (Sanei and Chambers, 2013). Early components of ERPs that occur before the N100 and P100 are very important for clinicians. For example, tumors damaging the auditory processing areas can be diagnosed with auditory evoked potential (AEPs). After the sound come, series of AEP waves that occur at the first 20 to 30 ms shows the neuronal firing in the brainstem, midbrain, thalamus, and cortex respectively (Figure 25). So, these waves can be used for diagnosis (Gazzaniga, Ivry and Mangun, 2013).

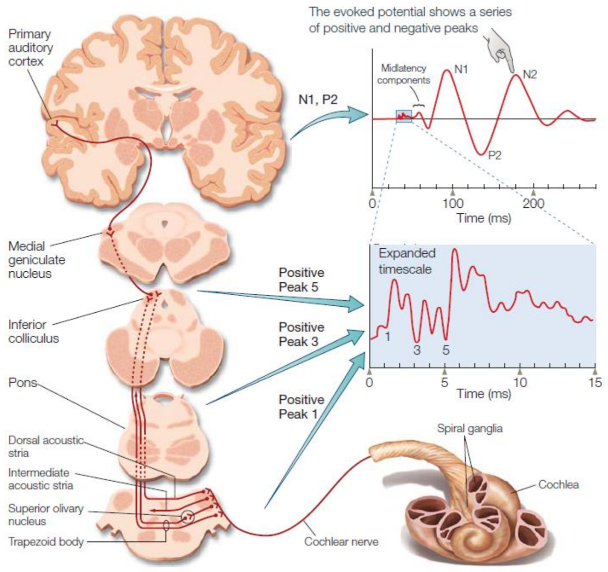


Figure 25. Auditory Evoked Potential (AEP) recording. (Source: Gazzaniga, Ivry, and Mangun, 2013).

The early component of ERP P100 is seen onset at the 60-90 ms after stimulus is presented and peak at the 100-130 ms and largest at the lateral occipital electrode sites. (Luck, 2014). P1 is about the selective attention (Gazzaniga, Ivry and Mangun, 2013; Luck, 2014) and it can be seen as Visual Evoked Potentials (VEPs) after a visual stimulus. Visual Evoked Potentials (VEPs) are important for the diagnosis of psychiatric diseases like dementia or AD (Visser et al., 1976; Cosi et al., 1982) or schizophrenia (Başar-Eroğlu et al., 2018). For example, abnormal VEPs are seen in the (Figure 26b) and there is an increase in the latency of the P100 compared to the normal VEPs (Figure 26a) (Sanei and Chambers, 2013).

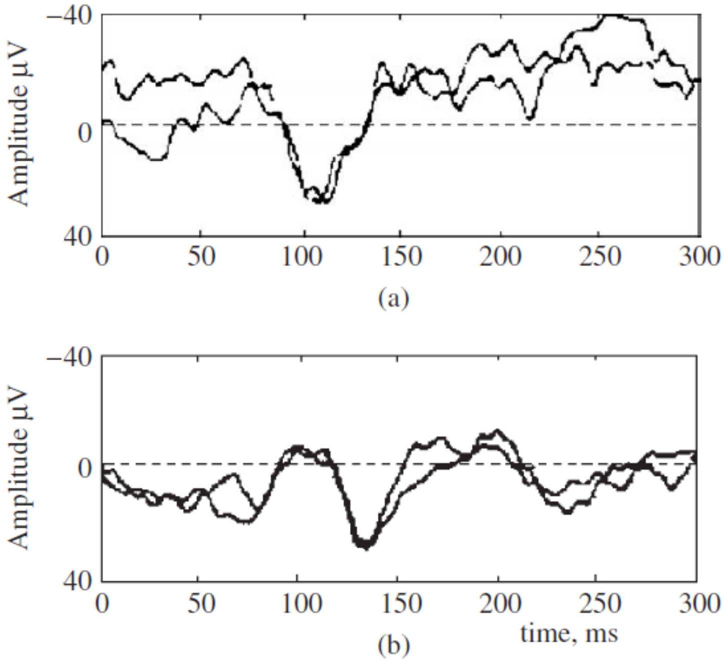


Figure 26. Example of a normal (a) and abnormal (b) P100 component. (Source: Sanei and Chambers, 2013).

N1 wave comes after P1 and is seen at the approximately 100 ms after a stimulus presentation. N1 also has subcomponents and earliest peaks take place at the 100-150 ms at the anterior part after the stimulus presentation. Posterior N1 components peak at the 150-200 ms after stimulus presentation (Luck, 2014). Primary sensory cortex produces the necessary response which is N100 ERP component. For example, participant takes an auditory stimuli and external sound goes to the auditory pathway then arrive to the primary auditory cortex. This process reflects as negative peak at the nearly 100 ms after presentation of auditory stimulus (Martin, Tremblay and Korczak, 2008). Classical visual discrimination task is a good way to see selective attention at N1 wave (Vogel and Luck, 2000).

1.6.3 The Components of ERP: P200 / N200

P200 comes after the N100 and seen at the anterior and the central scalp sites (Luck, 2014). This ERP component is seen in a classical oddball paradigm task. If the stimuli involve target features there is larger positive peak at the approximately 200 ms (Figure 27). If there is less target stimulus rate on the experiment, this peak increases more (Luck and Hillyard, 1994).

N200 is also known as the mismatch negativity and it is also seen at the deviant stimuli (Gazzaniga, Ivry and Mangun, 2013; Luck, 2014). Lots of researchers thinks that determinants of N2 are attention or novelty or mismatch, but some of the researchers also focuses on the effect of ‘cognitive control’ on the N200 (Fallgatter and Strik, 1999; Folstein and van Petten, 2008).

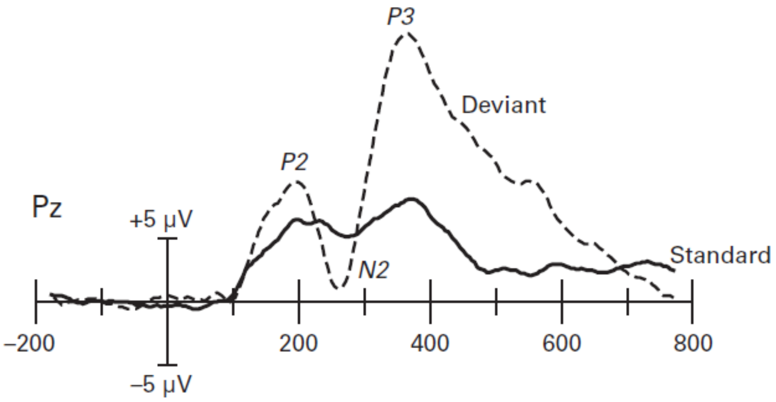


Figure 27. P200 ERP component in the oddball paradigm. P2 has a higher amplitude at the deviant stimuli (dashed line) than standard stimuli (solid line). (Source: Luck, 2014).

1.6.4 The Components of ERP: P300 / N400

P300 is a positive wave that peak at the approximately 300 ms after the presentation of novel stimuli or infrequent stimuli (Gazzaniga, Ivry and Mangun, 2013; Sanei and Chambers, 2013). P300 amplitude increases from frontal to the parietal electrodes (Polich and Kok, 1995; Comerchero and Polich, 1999). In early years, researchers explained the P300 as a mechanism of attention allocation and immediate memory (Sutton et al., 1965). Today one of the most known method for P300 is the oddball paradigm which is a task has frequent and infrequent stimuli presented. If the task of the participant is detecting target stimuli P300 is seen (Spencer and Polich, 1999; Başar-Eroğlu et al., 2001). The higher amplitude of P300 is seen after the presentation of infrequent stimuli. The rate of the infrequent and frequent stimuli is also important for the intensity of P300 (Dippel et al., 2017). If there is low probability of occurrence of target stimuli (uncertain) in the experiment participant must pay more attention to realize the target stimuli (Figure 28). So P300 has more intensity at the uncertain condition than certain condition which has high probability of occurrence of target stimuli (Sutton et al., 1965b; Polich and Kok, 1995; Spencer and Polich, 1999). Furthermore, if there are less probability of occurrence of target stimulus latency also increases because of the difficulty of detection (Picton et al., 1984). P300 has also two components which are P3a and P3b. P3a is found maximal at frontal and P3b maximal at parietal (Squires, Squires and Hillyard, 1975; Sanei and Chambers, 2013). Both are seen after the presentation of unpredictable, infrequent or novel stimuli, but P3b is task related (Luck, 2014)

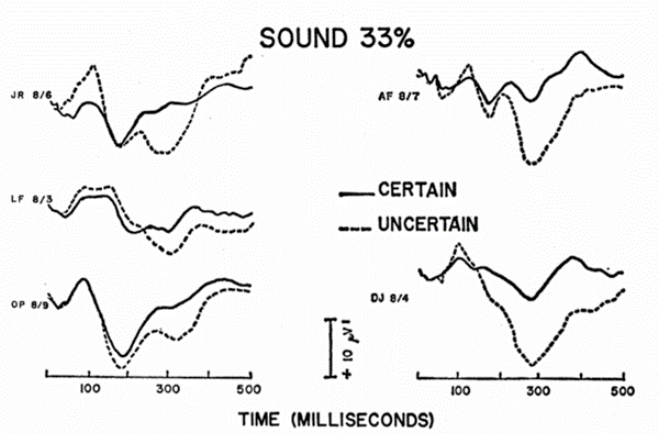


Figure 28. Average waveforms for certain and uncertain conditions. (Source: Sutton et al., 1965)

N400 was first time reported in 1980 and it was introduced as a language related wave (Luck, 2014). N400 is observed when a participant hears or reads something unexpected (Gazzaniga, Ivry and Mangun, 2013). For example, when participant hears or reads a sentence “the pizza was too hot to sing” the negativity is seen at the 400 ms because of the semantically unexpected word “sing”. This unexpected word is incongruent word and reveals N400 (Kutas and Hillyard, 1980; Kutas and Federmeier, 2011). This N400 ERP component is generally largest at the central and parietal side of the brain. Also, it has a bigger intensity at the right hemisphere than left hemisphere (Luck, 2014).

1.7 What is Event Related Oscillations (EROs)?

There are lots of neurons in our brain and firing all time. We learned that EEG recording is an image that comes from the group of neurons being active together. If this activation occurs after the specific event, we called it event related potential

(ERP). If we analyze the ERP, the rhythm of neurons (delta, theta and alpha) that are active together in a harmony can be seen (Figure 29). Figure shows the target (frequent (2000 Hz) and non-target (rare - 1950 Hz) in auditory oddball paradigm and its frequency components with wavelet analysis which are delta, theta and alpha. The task of participant is counting silently the target stimuli So, ERP reflects different functional sub processes and is seen the results of the classic auditory oddball paradigm. Participants has significantly more P300 amplitude at the targets than non-target and P300 is the maximal at the parietal lobe (Kolev et al., 1997)

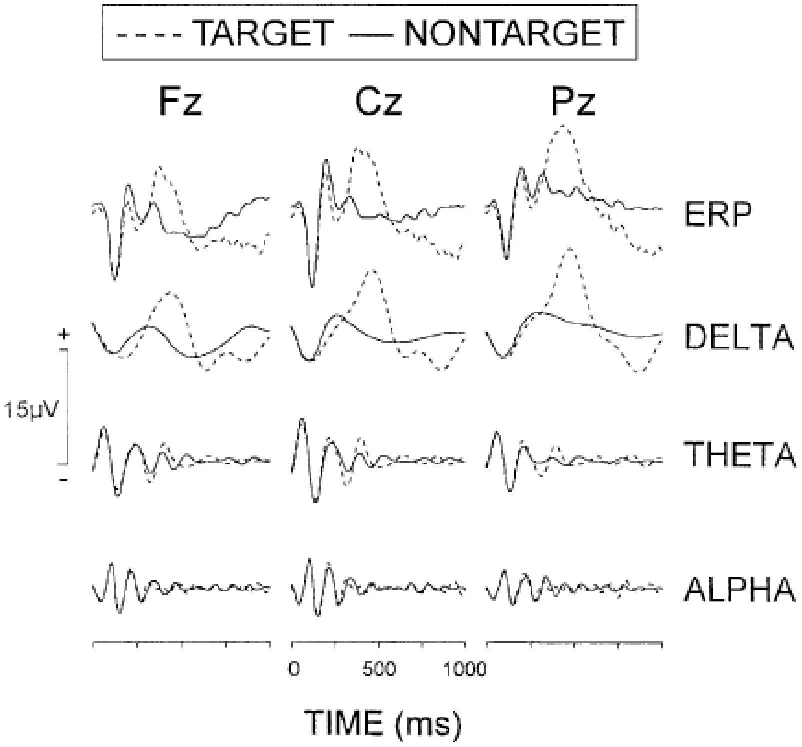


Figure 29. Grand average of ERP and its frequency compoents (Source: Kolev et al., 1997).

The rhythms are defined by looking the frequency of oscillations in a second. For example, if there are 10 oscillations per second it is called alpha (Gazzaniga, Ivry and Mangun, 2013). There are five basic rhythms that are seen naturally in the brain which are delta (δ), theta (θ), alpha(α), beta(β), and gamma(γ) (Başar et al., 2001; Sanei and Chambers, 2013). All these rhythms can also be seen together by applying time-frequency analysis (Figure 30). Figure shows that stimulus comes at the zero point. Activity of the frequency at various times is symbolized with the color. Blue is lowest activity; red is the highest. For example, alpha activity (8-13) is strong before the presentation of stimulus. There are different frequency regions and amplitude of the wave changes in that regions during -processing (Başar, 2006; Başar et al., 2007)

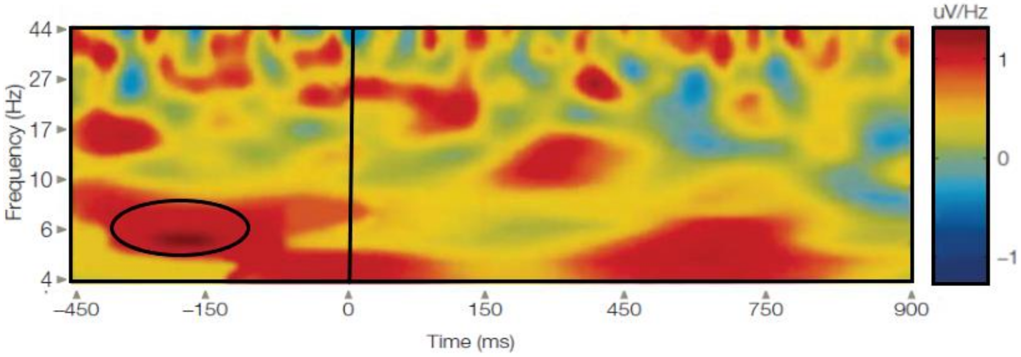


Figure 30. Plot of time-frequency analysis. (Source: Gazzaniga, Ivry, and Mangun, 2013).

Understanding the brain has been a curiosity for many researchers for years. EEG is a good way to understand the language of a brain. These oscillations (delta, theta, alpha, beta, and gamma) are like the phonemes of the language. If these oscillations are superimposed, they are like a word in a language. If these superimposed oscillations are seen at the different pathways, they are like syntax of the language in the brain. Finally, the super-synergy in the whole brain is like the sentences of language in the brain (Başar, 2006). So, analyzing the oscillations in the brain is a good way to understand the brain better. For example, the brain oscillations can be used to understand the memory process in the brain (Başar, 2006). They made the grandmother experiment and look the relationship between the attention, perception, learning and remembering. They found that the known (like picture of the grandmother) and unknown faces are differentiated by multiple brain oscillations. But before starting these interesting experiments, there are some terms important to understand the topic better. Oscillations has some parameters like amplitude (enhancement on the activity), latency (delay of the activation), desynchronization or blocking, prolongation (how long was the activation), and coherence (the harmony between different oscillation) (Başar, 2006). All these parameters are important to understand the experiments about EROs. Before start to examine each brain oscillation, first look at the history of the EROs.

1.7.1 The Discovery of the Event Related Oscillations (EROs)?

As we know, Hans Berger is the first researcher who recorded EEG from a man. He connected the electrodes to the head of a participant who in the horizontal position and recorded the continuous and regular potentials with the sensitive string galvanometer (Berger, 1929). He noticed the two types of waves are larger waves and smaller waves in the recording. Then he described the larger waves as “apha-waves” and the smaller waves as a “beta-waves” (Berger, 1930) Berger also was curious about the where does EEG come from. He made some mental effort and focused attention experiment with his son Klaus. He found smaller and shorter waves during the focused attention which is now called alpha blocking. Berger concluded that alpha waves are related to the relaxedness and wakefulness and beta waves are related to the attentive state (Berger, 1929).

In 1932, Dietsch applied the Fourier analysis to the EEG and reported the EEG frequency components in the range between 10 Hz to 50 Hz (Dietsch, 1932). Even the higher frequencies like up to 1000 Hz were described by Rohracher in 1935 and all these developments were reviewed (Herrmann et al., 2016). In 1934 Adrian and Matthews discovered the induced frequencies by flicker up to 25 Hz and recorded the first steady-state visual evoked potentials for the first time (Adrian and Matthews, 1934). The slow waves (theta and delta) were introduced as all frequencies below the alpha rhythm (Sanei and Chambers, 2013) and “delta waves” were described as abnormal waves in the cerebral tumor location (Walter, 1936). In 1938, Jasper and Andrews showed that “beta rhythm” mostly found in the sensory-motor brain areas (Jasper and Andrews, 1938) and also they used the “gamma rhythm” refer to above 30 Hz wave for the first time (Jasper and Andrews, 1938; Sanei and Chambers, 2013). Also, Adrian described the gama oscillation to response to the stimulation in the hedgehog (Adrian, 1942). Over years attention to the brain oscillations is fluctuated (Karakaş and Barry, 2017). Even though in 1970’s there was less interest to the brain oscillations, some important experiments are made like 40 Hz response in the cat (Başar, 1972) and human brain (Başar, Gönder and Ungan, 1976) The interest to the brain oscillation become popular again in the late 1980s and gama oscillations were studied at the cellular level (Eckhorn et al., 1988). In 1990s the concept of “diffused and distributed alpha system” was popular and this concept also became popular in other frequencies like delta, theta, and gama (Başar et al., 2001; Herrmann et al., 2016)

Today the accepted frequency range and major component of oscillations were defined as like: delta (0.5-3.5 Hz), theta (4.0-7.5 Hz), alpha (8.0-13.5 Hz), beta (14.0-29.0 Hz) and gama (30.0-70.0 Hz) (Karakaş, 2020).

There are three important information for the oscillations which are frequency, power, and phase (Cohen, 2014). Frequency is the number of cycles in a second and described with hertz (Hz). For example, theta wave is 4 Hz which means there are 4 cycle per second. Power is the energy in the frequency, and also squared amplitude of oscillation. Phase is measured in radian or degrees and position throughout the sine wave (Figure 31).

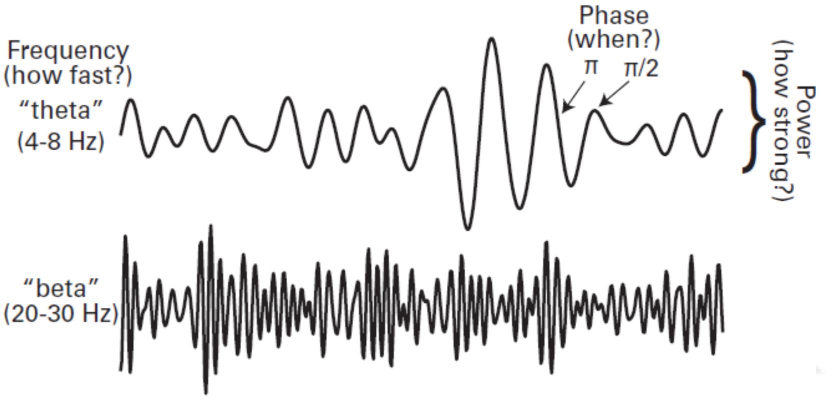


Figure 31. Oscillations, frequency, power and phase (Source: Cohen, 2014)

1.7.2 Delta Wave

Delta waves take places in the range between 0.5-3.5 Hz and it is generally seen in the deep sleep but sometimes seen in waking stage (Sanei and Chambers, 2013). Sleeping cat and human brain showed the phase-locked delta responses (Başar, 1980). The most known event related delta activity is the identifying a target or go-stimulus from the non-target or no-go (Herrmann et al., 2016). Oddball paradigm is the best way to see this delta activity (Atli et al., 2019; Başar-Eroğlu et al., 1992; Karakaş, Erzengin and Başar, 2000). Delta response has more amplitude during the oddball paradigm especially in the target stimulus (Figure 32), so it can be concluded that delta wave is seen during the signal detection and decision making processes (Başar-Eroğlu et al., 1992; Başar et al., 1999; Başar et al., 2001). The role of delta at the signal detection and decision making (Başar-Eroğlu et al., 1992; Karakaş, 2020) process is also showed at the hearing threshold experiments (Başar, 1999). P300 is seen at the target stimulus that requires to attention and it mainly composed of delta and theta oscillations (Başar-Eroğlu et al., 1992; Karakaş, 2020). Attention is seen especially in the P300 (P3b) latency with more amplitude and extended duration which is the superimposed theta response on the delta response (Karakaş, Erzengin and Başar, 2000; Polich and Criado, 2006; Karakaş, 2020). In the figure 32 the target stimulus is auditory, so the largest activity is seen especially in the central and frontal areas. However, if the target stimulus is visual, largest activity is observed in the parietal areas (Schürmann et al., 1995; Başar, 1998; Başar, 1999; Başar et al., 2001).

1.7.2 Theta Wave

Theta activity first time recorded from the hippocampus of the rabbits (Jung and Kornmüller, 1938). It had large amplitude and sinusoidal rhythm. The interest to the theta rhytym increased and it also found in the other animals like cats and rats (Grastyán et al., 1959; Vanderwolf, 1969; Başar-Eroğlu, Başar and Schmielau, 1991). Theta waves are taking place in the range between 4-7.5 Hz. It is seen when passing from consciousness to drowsiness (Sanei and Chambers, 2013) and during the rapid eye movement (REM) sleep (Vanderwolf, 1969; Winson, 1974). One possible explanation for theta activity during the REM sleep is the relationship between memory and theta oscillation (Colgin, 2013). Theta oscillation is very important for memory (Klimesch, 1999) and it was found that cortical theta oscillations related to the hippocampus which is an important region for memory processes (Başar-Eroğlu, Başar and Schmielau, 1991; Mitchell et al., 2008; Herweg, Solomon and Kahana, 2020). It is also generally associated with the reaching to the unconscious material, creative thinking, and deep meditation (Lagopoulos et al., 2009; Sanei and Chambers, 2013; Cavanagh and Frank, 2014; Katahira et al., 2018). Theta wave is important in the childhood and infancy. If the theta is seen in the adulthood, that can be because of the various pathological problems (Sanei and Chambers, 2013).

Event related theta oscillation are associated with the cognitive processes and cortico-hippocampal interaction (Miller, 1991; Klimesch, Schimke and Schwaiger, 1994; Başar, 1998) and it was studied on both human and animal brain (Başar-Eroğlu and Demiralp, 2001). Event related theta oscillations generally underlie in the N200 and P300 components (Karakaş, Erzengin and Başar, 2000) and oddball paradigm or omitted stimulus paradigm is a good way to see the event related theta activity (Figure

32). These paradigms can be applied both version which are visual and auditory paradigms (Demiralp and Başar, 1992).

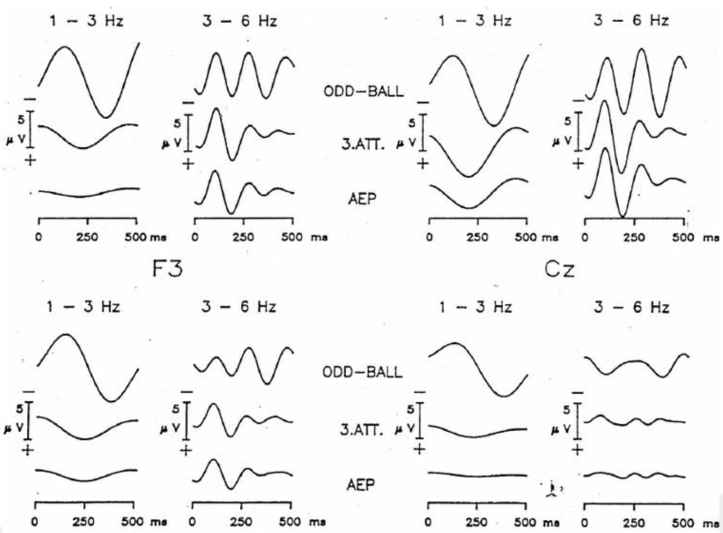


Figure 32. The task of Oddball, Omitted Stimulus Paradigm and, auditory evoked potentials (AEP) in the delta and theta frequency band. (Source: Başar-Eroğlu et al., 1992).

There are two different time windows for theta oscillations which are early time window (0-250 ms) and late time window (250-500 ms) (Başar and Stampfer, 1985; Stampfer and Başar, 1985). Theta oscillations are prolonged at the second time window which is 300 ms after the presentation of stimulus can be interpreted as selective attention (Başar-Eroğlu et al., 1992). So, theta response is closely related with the forms of attentional processes (Karakaş, Erzengin and Başar, 2000). Any experiment requires attention can be used to see the theta activity. For example, paying attention to the picture of our grandmother increases theta oscillation at the frontal region regarding unknown face (Başar et al., 2007). Also, the bimodal sensory stimulations reveal theta response in the frontal region; so, theta in the frontal region is important for the complex events (Başar, 1999).

1.7.3 Alpha Wave

Alpha waves (8-13.5 Hz) are generally seen in the posterior part of the brain and normally has an amplitude less than 50 µV (Sanei and Chambers, 2013). Alpha wave is usually known with the ‘spontaneous alpha rhythm’ concept (Başar et al., 2001) which is occurred in the relaxed mood without attention or concentration (Sanei and Chambers, 2013). It becomes maximum when eyes closed and become blocked when eyes open. The other form of alpha is the ‘work alpha’ or ‘functional alpha’ is seen during the sensory stimulation (Schürmann and Başar, 2001), cognitive and motor process (Başar et al., 1997; Başar, 1998; Başar, 1999; Başar et al., 2001) and also during the memory processes (Başar, 1998). Experiments with animals shows that alpha is seen in the hippocampus and reticular formation during the auditory and visual stimulation without filtering. Also, human alpha responses are similar with the animal experiment (Schürmann, Başar- Eroğlu and Başar, 1997; Başar, 1998; Başar, 1999). Oddball paradigm is also a good way to see event related alpha activity (Kolev et al., 1997) at the P300 during the cognitive event that requires detecting the target stimuli (Figure 29). Also, prolonged event related alpha activity is seen nearly at the 400 ms (Başar, 1998; Başar, 1999). Alpha oscillation has a converse relationship with the cognitive performance so, irrelevant cortical areas are inhibited during the cognitive process (Jensen and Mazaheri, 2010). The event related alpha activity can be also seen in the memory related experiments 1 s before the expected stimulus (Klimesch, Schimke and Schwaiger, 1994; Başar et al., 1997; Başar et al., 1997; Klimesch, 1997) and attentional processes (Başar-Eroğlu et al., 2016; Hanslmayr et al., 2011). Memory performance can be also shown with phase-locking between the theta and alpha oscillations at the P100-N100 (Klimesch et al., 2004; Klimesch, Schack and Sauseng, 2005). So, it can be concluded that theta oscillations are related to the working memory and alpha oscillations are related to the semantic memory (Karakaş, 2020).

1.7.4 Beta Wave

Beta wave (14-29 Hz) is normally under 30 µV (Figure 31) known as waking rhythm which is related to the active thinking and attention. It is seen in the adult brain while solving a concreate problem and generally in the frontal and central regions (Sanei and Chambers, 2013). Beta wave is also seen when participant performing a motor task (Neuper and Pfurtscheller, 2001) and cognitive task required sensory motor interaction (Kilavik et al., 2013).

1.7.5 Gama Wave

Gama wave (30-70 Hz) has low amplitude and it is seen rarely (Sanei and Chambers, 2013). It has a significant role in the neurophysiological mechanism of cerebral cortex (Başar-Eroğlu et al., 1996a). Low-frequency gama oscillations are usually associated with the functional inhibition; but faster gama oscillations are associated with the cortical activation (Merker, 2013). Gama oscillation has an important role in active sensory processing (Tiesinga and Sejnowski, 2009; Wang, 2010) and conscious perception (Singer, 2001). Oddball or omitted stimulus paradigm is also good way to see event related gama activity. For example, P300-40 Hz component is seen in the cat hippocampus, and reticular formation in the omitted auditory target stimulus and superimposed with the 4 Hz (Başar-Eroğlu and Başar, 1991). Also, the other paradigms showed that early (evoked) gamma oscillations at the first 100 ms is about the sensory stimulation (Karakaş and Başar, 1998), late (induced) gamma response is about the higher cognitive processing (Karakaş et al., 2001). Gamma oscillation can be spontaneous, evoked or induced (Başar-Eroğlu et al., 1996). Spontaneous oscillations are known as background activity and do not have relation with the stimulus. Evoked oscillations are seen after the presentation of the stimulus and they are phase lock to the stimulus. Induced oscillations are also seen after the stimulus but, they are not phase lock (Başar et al., 1999) (Figure 33). Multistable perception is the reversibility of the ambiguous figure has an important role on the frontal gamma oscillation. Frontal gamma activity increases nearly %50 during the perceptual switching (Başar-Eroğlu et al., 1996b). Gamma oscillation has also close relationship with the attention (Fries et al., 2001; Herrmann and Knight, 2001; Womelsdorf and Fries, 2006) and memory (Herrmann, Munk and Engel, 2004). Attention related gamma oscillation is especially seen in the central and frontal areas (Tiitinen et al., 1993).

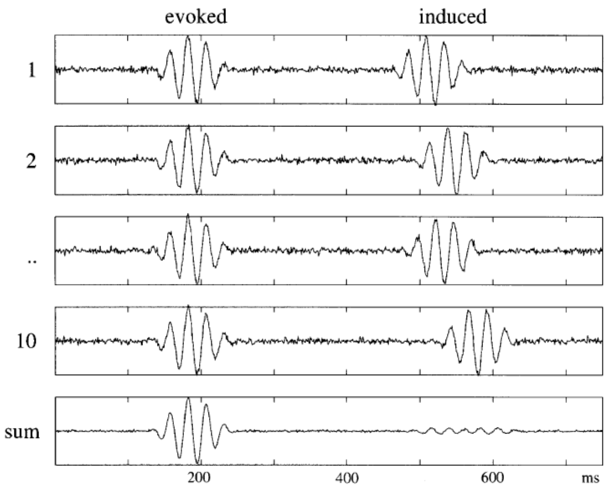


Figure 33. Evoked and induced gamma responses (Source: Herrmann, and Knight, 2001)

1.8 Looking Human Brain from Different Windows

In this chapter so far, we have learned about spontaneous brain activity, event-related potentials and event-related oscillations. Event-related activity characterized as responses to the sensory and cognitive events (Başar et al., 2001) and these brain activities can be represented in three different ways in time domain, frequency domain or time-frequency domain. Figure 34 shows these different types of representing methos via spontaneous activity which was explanined detailly and reviewed studies have implemented time-frequency analysis to mismatch negativity (MMN) paradigm (Herrmann et al., 2013). Figure 34a shows the changes of amplitude in time domain however frequency information cannot be easily grapped from this representation. If we want to see the information about frequency the representation like in figure 34b would be better. But this information about time cannot be seen. So, time-frequency contains knowledge from both time and frequency and also give information about the amplitude of brain oscillation with colors.

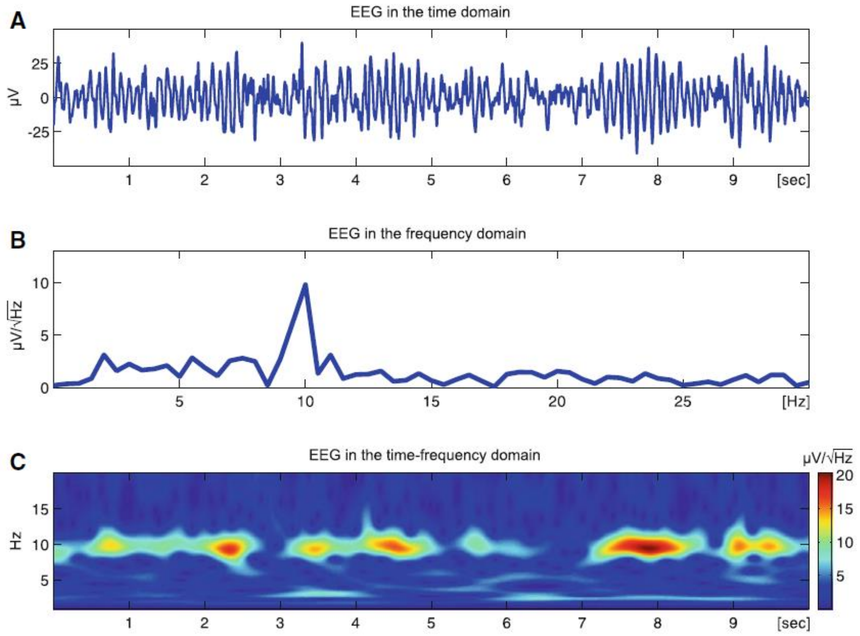


Figure 34. EEG data in time domain (a), frequency domain (b), and time-frequency domain (c). (Source: Herrmann et al., 2014)

1.9 What is Inter-Trial-Coherence (ITC)?

Inter-Trial Phase-Locking (ITPC or Inter-Trial-Coherence/Phase-Locking Factor) is a method shows synchronized EEG data trials at the same time and most of the time showed in time-frequency domain (Tallon-Baudry et al., 1996). Phase locked or time locked response can be easily identified in ITC. High or low inter trial coherence gives information about compatibility of response. An ITC number near to 0 shows that phase positions differ significantly among epochs, whereas an ITC value of 1 shows their perfect synchronization and all epochs have the same phase position. ‘Inter-trial coherence’ states to event-related phase coherence (ITPC) between recorded EEG activity and an event-phase indicator function (Figure 35). Inter-trial Coherence (ITC) is an important method and used while investigating the event-related modulations in adolescence (Mathes et. al., 2016) and also while diagnosing psychiatric diseases like Alzheimer’s disease (Babiloni et al., 2006; Rossini et al., 2006; Başar et al., 2010; Güntekin et al., 2008; Yener et al., 2007), schizophrenia (Başar-Eroğlu et al., 2008; Başar-Eroğlu et al., 2009; Başar and Güntekin, 2013; Güntekin et al., 2013), bipolar (Özerdem et al., 2008; Özerdem et al., 2011), and attention deficit hyperactivity disorder (ADHD) (Groom et al., 2010).

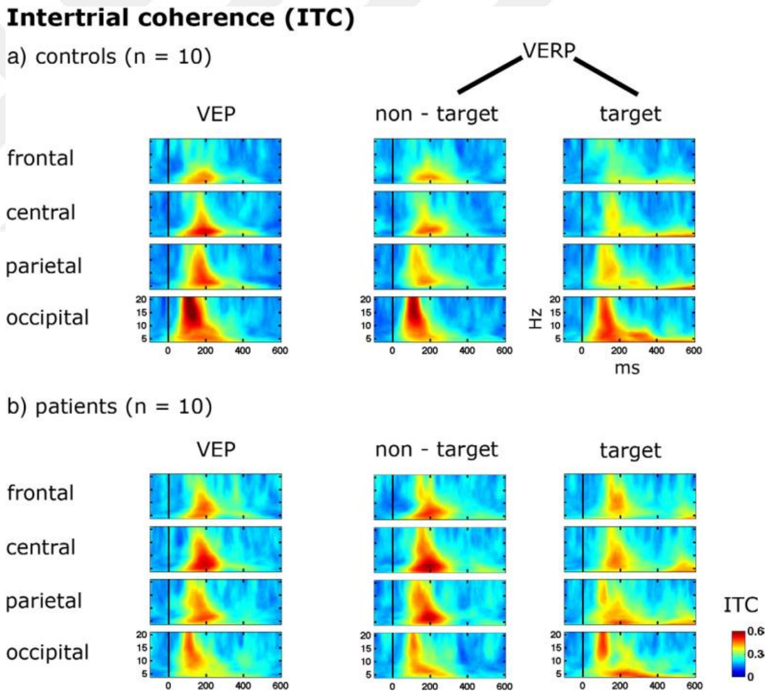


Figure 35. Demonstration of the ITC in schizophrenia and healthy participants. (Source: Başar-Eroğlu et al., 2008).

1.10 What is Sustained Attention?

Attention has a crucial meaning in our daily life. It is required from basic task like cutting a vegetable to complicated task like surgery which requires long term attention. For example, driving the long distance also requires long term attention and if there is decline in the attention the driver can be injured or even died (Barkley and Cox, 2007). Sustained attention is also very important for the modern day's jobs like from education (Ko et al., 2017) to long-distance driving, airport baggage inspection, military surveillance, and air traffic control (Hancock and Szalma, 2008). Attention deficit can cause the decrement in the system productivity or workplace injures (Barger et al., 2006). So, understanding the sustained attention is very important which is very crucial in lots of the part of life and EEG is a useful method to detect declined attention to prevent human errors.

There are two types of attention are passive and active attention (Karakaş, 2020). Passive attention is defined as preattentional and triggered by passive oddball task (OB-p). It reflects as mismatch negativity event related potential (Näätänen et al., 2007). Active attention is defined as selective, focused, or sustained attention and triggered with active oddball task (OB-a). It is identified with P300 component P3a which is about novelty (Sokolov, 1990; Polich, 2007). Selective attention is selecting the target stimulus from the other stimuli. Focused attention is turning the attention to the selected stimulus. Sustained attention is focusing attention to the selected stimulus over a long time (Driver, 2001; Oken, Salinsky and Elsas, 2006). It is a kind of ability of a person to continue the conscious processing of recuring stimuli which is not arousing otherwise cause to habituation and distraction to other stimuli (Robertson et al., 1997). Sustained attention is characterized with the keeping carefully watch for possible difficulties or danger which is called vigilance. If state of vigilance decreases over the time is called vigilance decrement (Sarter, Givens and Bruno, 2001). Vigilance decrement is important for psychological experiments and for the realistic life like air traffic control or radar operations (Colquhoun, 1967; Pigeau et al., 1995).

Sustained attention was measured with long and repetitive tasks like Continuous Performance Task (CPT) (Rosvold et al., 1956). CPT requires focused attention to concentrate on a single simple task (e.g. pressing the button for the rare target stimuli) for a long time. There is also another task to measure the sustained attention which is simpler and shorter version of the CPT is called as Sustained Attention to Response Task (SART). This task requires giving response to the frequent stimuli but withhold the response to the rare target stimuli. It was argued that CPT requires automatic responses, but SART requires controlled responses (Robertson et al., 1997) which is more sensitive to the even small lack of attentions that can be increases the probability of making error (Cheyne, Carriere and Smilek, 2006).

SART is a very known task to measure sustained attention and there are lots of research about SART in literature. Even though there are lots of experiments to measure the psychological and cognitive processes with SART (Smit, Eling and Coenen, 2004; Zordan, Sarlo and Stablum, 2008; Mückschel, Dippel and Beste, 2017; Rostami et al., 2021), it is mostly used in clinical population who experience difficulties in sustained attention like attention-deficit/hyperactivity disorder (Greene et al., 2009), ALS (McMackin et al., 2021), traumatic brain injury (Robertson et al., 1997), schizophrenia (Başar- Eroğlu et al., 2008, Başar- Eroğlu et al., 2009). However, researchers mostly use visual SART task and there is not enough focus to the auditory SART. Most of the experiment showed that there is a difference between visual and auditory vigilance (Szalma et al., 2004; Seli et al., 2012); and participants gave slower response and less errors to auditory SART than visual (Seli et al., 2012).

1.10.1 Sustained Attention and ERP Studies

Sustained attention is crucial for our life and the most common methods used while measuring sustained attention are visual or auditory CPT and SART which are kind of Go/No-Go (GNG) Test. The most important feature of GNG Test is the random stimulus presentation generates the ERP components (Falkenstein et al., 1995; Falkenstein, Hoormann and Hohnsbein, 1999; Falkenstein, Hoormann and Hohnsbein, 2002). Falkenstein and colleagues in 2002 works with the visual and auditory GNG test and looks to features of the N2 and P3. They found that N2 had more amplitude in the No-Go response than Go response and No-Go N2 was larger in visual task than auditory task. However, modality of the presentation of the No-Go stimuli was not affect the P3. Another experiment was made with visual GNG test, and they found that N2 and P3 was maximal for the No-Go stimuli at the FZ/FCZ electrode (Roche et al., 2005).

Similar results also found in the visual version of CPT. It was found that P300 at No-Go response had more amplitude at the fronto-central electrodes but not in the go response which was interpreted as No-Go anteriorization and it is an electrophysiological presentation for the cognitive control response (Fallgatter and Strik, 1999). These are the experiments that examines the N2 and P3 with GNG and CPT.

There is also another study made by Zordan and colleagues which examines the ERP components with visual SART. Results are consistent with the literature. They find that No-Go N2 has more amplitude than Go response and maximal at the central electrode. Amplitude of the P3 is larger for the No-Go responses than Go responses and maximal at the FCZ electrode. But P3 activity at the Go response is maximal at the POZ electrode (Zordan, Sarlo and Stablum, 2008). Another visual SART experiment also finds same results about N2 and P3. But also, the P1 and N1 was also examined, and it concluded that P1 has significantly more amplitude at the No-Go response than Go responses. In contrast, N1 Go response is more than the No-Go response (Mückschel, Dippel and Beste, 2017). It was showed that amplitude difference between type of stimuli depends on the probability of occurrence of the No-Go and Go stimulus (Dippel et al., 2017).

ERP component in sustained attention is also examined with different kinds of test in terms of the amplitude difference between at the early and late time window. It was found that P300 activity at the parietal location decreased over the experiment in the n-back task (Hopstaken et al., 2015), Simon task (Möckel, Beste and Wascher, 2015), and vigilance task (Haubert et al., 2018). N2 ERP component also decreases with increasing time on the task in Flanker paradigm (Faber, Maurits and Lorist, 2012), and simon task (Möckel, Beste and Wascher, 2015).

So, as it can be seen from the literature review the task GNG, CPT, and SART are consistence each other in terms of ERP components. However, no experiment has examined the ERP components with auditory SART. Furthermore, SART requires long term attention and there are no experiments with SART shows the difference between early and late time windows. Keeping attention vigilant for an auditory stimulus for a long time is important for most of the real life. So, ERP components are very useful to understand the cognitive processes better in a long time.

1.10.2 Sustained Attention and Theta Oscillations

The relationship between theta oscillation and attention was first discovered in 1960 (Adey, Dunlop and Hendrix, 1960). Today researchers show that theta oscillation is seen during the focused attention. For example, experiments with omitted stimulus paradigm at the human and cat shows that omitted stimulus produces event related theta oscillation (Demiralp and Başar, 1992; Demiralp et al., 1994). Also, it was showed that while preattentional change detection has short duration theta response, selective attention has high amplitude theta response with long duration (Karakaş, Erzengin and Başar, 2000). Sustained attention was also studied with the GNG and CPT which are requires response inhibition. Results showed that mid-frontal theta activity increases during the response inhibition (Kirmizi-Alsan et al., 2006; Barry, 2009; Yamanaka and Yamamoto, 2010). Furthermore, the relation between N2, P3 and theta was showed (Harper, Malone and Bernat, 2014).

1.10.3 Sustained Attention and ITC Studies

Inter-Trial-Coherence (ITC) is a fruitful method to see phase locked response while measuring the attention. Although there are many studies working on attention and ITC in gamma band, there are not enough studies on theta ITC and attention. Study which applied passive listening, simple reaction task, and choice-reaction task insvestigated the difference between early and late gamma and found that early gamma is about the focused attention and late gamma changes depend on the motor responses (Yordanova, Kolev, and Demiralp, 1997). Another study works with auditory oddball task found phase locked gamma response both for target and non-target stimuli (Gurtubay et al., 2001) and late activity peak at around 360 ms on only target stimuli.

Gamma band is quite popular while studying the attention with ITC. However, there are also some studies investigates the relationship between attention and theta with ITC. One of the study works with auditory and visual oddball paradigm. They measured attention on auditory, visual and simultaneous audiovisual stimuli and they found most significant theta ITC activity is seen in fronto-central area at audiovisual stimuli (Keller et al.,2017). An additional of the experiement which used also auditory oddball paradigm found that infrequent tones increase theta ITC around the 250 ms compared to standart tones (Ko et al., 2012).

1.11 The Present Study

Many studies used SART to measure overall vigilance and vigilance decrease behaviorally. (Brache et al., 2010; Carrier et. al., 2010; McAvinue et al., 2012; Roebuck et al., 2015). The majority of these studies are centered on the visual paradigm, and there aren't enough behavioral data on auditory SART (Roebuck et al., 2015). Furthermore, there haven't been enough research into the electrophysiological correlates of overall vigilance and vigilance decrease. If a research is going to be done about the measurement of cognitive processes, electrophysiological measurement is quite importartant. Measuring the oscillatory activities while investigating the cognitive processes is also the most important part and lots of studies was conducted and summarized to understand the critical role of EEG in cognitive processes (Başar-Eroğlu, 2021). Theta oscillation was chosen because it is related with cognitive functions (Başar, 1998; Erdoğdu et al., 2019; Mathes et al., 2014; Mathes et al., 2016; Rürup et al., 2020; Schmiedt et al., 2005), focused attention and signal detection (Schürmann et al., 2012) and it was studied on both human and animal brain (Başar-Eroğlu and Demiralp, 2001). Previous research has shown that theta activity rises in the mid-frontal area during the GNG and CPT tasks (Kirmizi-Alsan et al., 2006; Barry, 2009; Yamanaka and Yamamoto, 2010). Furthermore, a study compared the normal and schizophrenia participants with auditory Continues Performance Task (CPT) and found decreased theta amplitude with time in both groups (Başar-Eroğlu et al., 2009).

To the best of our knowledge, no research has been studied the influence of time on overall vigilance and vigilance decrease during auditory SART. So, additional insights are required, particularly for event-related theta oscillations. This study aims to enhance new information to the literature in parallel with the existing auditory findings and the findings of previous studies with similar modalities.

Present study combined the data set from Germany and Turkey to investigate the event related theta oscillation during the auditory sustained attention to response task (SART). The literature demonstrates the behavioral effects of time on the visual SART paradigm. However, no investigation has shown behavioral evidence regarding the influence of time on the auditory SART task. As a result, for the first time, this study will investigate the behavioral influence of time on auditory sustained attention.

Another unique aspect of the study is the use of EEG to investigate the influence of time on the auditory SART task. Other research looks at the ERP(s) on visual SART and theta oscillations with GNG and CPT tasks. This study, however, will be the first to look at the influence of time on event-related theta oscillations based on the new analytical methods event related theta response and inter-trial coherence (ITC) during auditory SART.

CHAPTER 2: METHODS

2.1. Participants

A total of 20 healthy participants participated the experiment in Bremen, Germany (9 participants), and Izmir, Turkey (11 participants). Prof. Dr. Canan BAŞAR EROĞLU (my supervisor) and her colleagues (Christina Schmiedt-Fehr, Birgit Mathes, Jörg Zimmermann, and Andreas Brand) collected the data from the German participants and never published in previous studies. Data of Turkish participants were collected in EEG Laboratory in Izmir University of Economics, Izmir, Turkey by the author of this thesis. Eight of the healthy (7F /1M) subjects (M_{age}=32 ± 4) from German data and five of the healthy (3 F/ 2M) subjects (M_{age}=26 ± 4) from the Turkish data were used for EEG data analysis because of the artifacts and technical problems. In total 13 participants whose data without artifact was used in this thesis. All participants were right-handed in German data and only one participant was left-handed in Turkish data. All participants in both countries had normal or corrected-to-normal vision and data did not include participants who had history of substance abuse in the past 6 months, known history of learning difficulties, head trauma with loss of consciousness, and disease of the central nervous system.

2.2 Apparatus and Material

2.2.1 Equipments of EEG

For this experiment, Ten-20, Abralyt 2000, Nuprep, and alcohol was used while putting the cap on the participant's head. As devices Brainvision Professional Brainamp Amplifier, Brainvision Professional USB 2 Adapter, Brainvision Professional Powerpack, Brain Products Electrode Input Box 64 Channel, 64 Channel EEGcap Electrode Cap, a Custom-built button press device, Custom Built Port Integrator, HP S2031a Monitor 20", PreSonus Eris E3.5 Speakers, Restmoment RX D48 Microphone, HD Pro Webcam C920 was used. Before starting the experiment four computers are opened and participant gives reactions with button press and can easily communicate with experimenter with microphone during the experiment (Figure 36). Also, participant is observed by camera during the experiment.

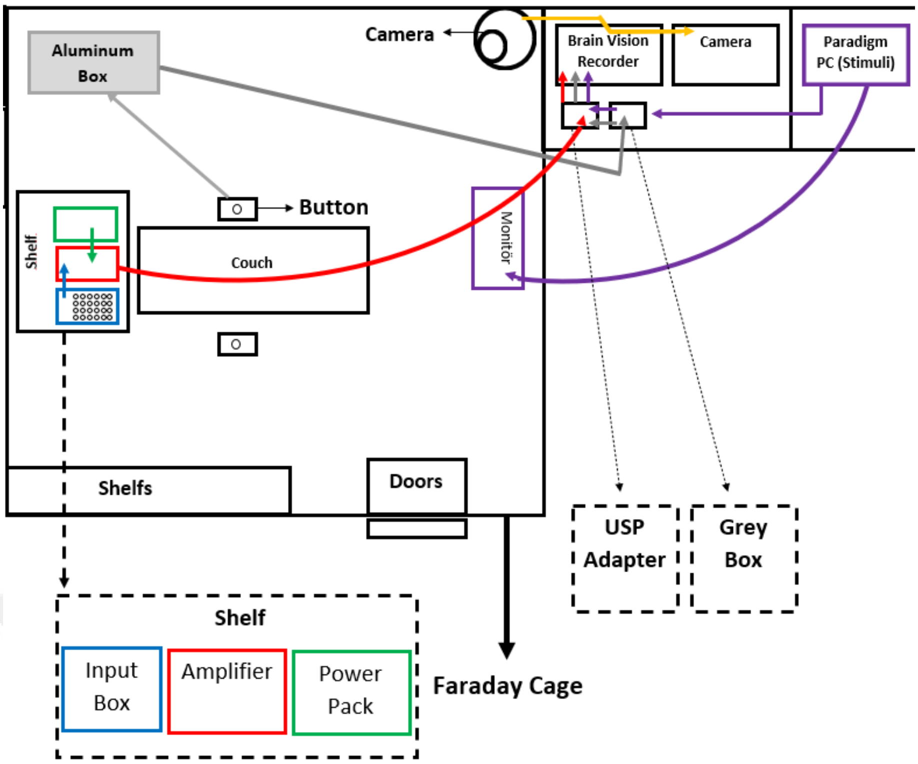


Figure 36. EEG Laboratory Plan

2.2.2 Stimuli

In this experiment auditory version of the SART was used and sinusoidal tone stimuli were presented with pseudo-randomized sequence and had an intensity of 80 dB SPL with different type of frequency (1400, 1420, 1440, 1460, 1480 Hz) which had long (300 ms) or short (100 ms) durations. Duration determined the target stimuli in this experiment. Each tone frequency was presented with equal probability, but probability of occurrence was 0.14 for longer durations (target stimuli), 0.86 for shorter durations (non-target stimuli). In total there were 105 target trials out of 765 test trial and interstimulus-interval was 1000 ms.

2.2.3 Stimulus Presentation

Stimuli were created and presented via custom scripts written in MATLAB 2021b using Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007). Auditory stimuli were given via PreSonus Eris E3.5 Speakers. In the experiment in Turkey, HP S2031a Monitor 20" was used for fixation cross (eye open trial) and feedback presentation (practice trial).

2.3 Experimental Task

The most common task to measure sustained attention is Continuous Performance Task (CPT) and Sustained Attention to Response Task (SART). They are similar task; CPT is a very long, old, and repetitive task that requires pressing button on the target (infrequent stimuli) and not pressing button on the non-target (frequent stimuli). Robertson and his colleagues (1997) realized that CPT requires the automatic process, so they modified the task and made SART. Fist type of SART was a visual version and it took 4.3 minutes. In that version participants were giving response to all numbers (1,2,4,5,6,7,8,9) and withholding the response at the “3” number by ignoring the font difference. Then longer version of the SART and auditory version started to be used.

Both experiments in Turkey and Germany used the auditory version of Sustain Attention to Response Task (SART). In these experiments, a total of 765 sinusoidal tone (300 ms or 100 ms of duration, 10 ms of rise and fall) were presented (PreSonus Eris E3.5 Speakers-Turkey) at the intensity of 80 dB SPL and in standard interstimulus-interval 1000 ms. 660 tones (probability 0.86) and 105 tones (probability 0.14) were presented with their different type of frequency set (1400, 1420, 1440, 1460, 1480 Hz with equal probability) (Figure 37). The long duration tones were assigned as target stimuli and were randomly interspersed with the short duration non-target tones. Task required to pressing button whenever a non-target (shorter durations - 100 ms) was perceived and withholding the motor response to a target stimulus (longer durations - 300 ms) by ignoring the changes in tone pitches.

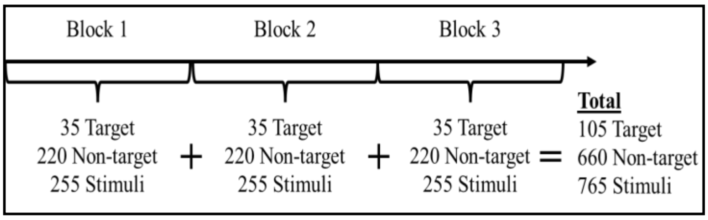


Figure 37. Schematic illustration of blocks and stimuli on the task.

2.4 Procedure

Participants were invited to the EEG Laboratory at Izmir University of Economics for EEG recordings in Turkey. Firstly, an informed consent form was given to all participants to make sure that their participation is voluntary and that they understand that they can stop experiment whenever they want. Later demographic information form was given to collect information about their sex, age, handedness, education level. Furthermore, they were asked about amount of sleep, when they have woken up, coffee, alcohol, and cigarette consumption and their frequencies, and their state of hunger. Also, information about physical health was asked like vision problem, usage of drug and previous diagnoses including, psychiatric, and chronic conditions, any medication use, or previous head traumas.

After they filled the informed consent and demographic form, participants were informed about the EEG and its equipment (64 Channel EEG cap, Electrode Cap, Ten-20, Abralyt 2000, Nuprep). Firstly, head size of each participant was measured. Then according to International 10-20 System, the participant's head was marked, and suitable EEG cap was worn on the participant's head by checking marked reference points. After each electrode place was cleaned with alcohol, the electrodes were fixed to reference points (earlobes), over the eye (vertical electrode to detect eye blink), near the eye (horizontal electrode to detect the horizontal movement of eye), and to a point on participant’s back (ground electrode) by applying TEN-20. Next, each electrode position (Fz, Cz, Pz, and Oz) was cleaned with alcohol and Nuprep then Abralyt 2000 was squeezed with syringe to increase the conductivity.

The participant, whose electrode placement process is completed, was taken to the Faraday cage, which is a dimly lit, soundproof, and electromagnetically shielded room and they sat 130 cm away from a computer monitor. Each electrode cable was plugged into Brain Products Electrode Input Box 64 Channel and electrode impedance were checked below 10 kΩ for all electrodes.

Before the recording experimental session, participant was informed that the data will be recorded for 1 minute with eyes open and closed for the baseline measurement, then the task was explained for practice trials of 20 tones (5 targets) was presented by giving feedback from the screen to each subject to ensure a good level of performance. Then experiment start, and participants were briefed about SART. Next, experimenter instructed them to listen the auditory stimulus and press button for each sound with short duration and not press to the button whenever they realize sounds with long duration. Participants were also informed about time of experiment (15 minutes) and artifacts which causes disruption on EEG data and asked to fixate their eyes on fixation points to prevent head movements and eye blinks as much as they can. After verbal instructions, participants are left alone in the faraday cage and instructions were presented on the computer monitor were nearly identical to the verbal ones.

The task of the participant was following the presented tone series at a time over loudspeakers and withholding the motor response to a target stimulus (longer durations - 300 ms) by ignoring the changes in tone pitches. Participant only respond the non-target stimuli (shorter durations - 100 ms) by button-press using their index finger, whenever a non-target was perceived. Accuracy (Correct Hit) and response time (RT) to non-target stimuli were recoded within 200-930 ms. Responses (Commission Error), and non-responses (Correct Rejection) to the target stimuli and failures to respond to non-target stimuli (Omission Error) were also recorded (Figure 38). Nearly same procedure was also conducted for German participant in the 1980 in Germany. Participants were invited to the EEG Laboratory at University of Bremen. All participants were given informed consent. Subjects were instructed to listen a tone series presented one at a time from loudspeakers and respond as quickly as possible by a right-hand button-press using their index finger, whenever a target was realized.

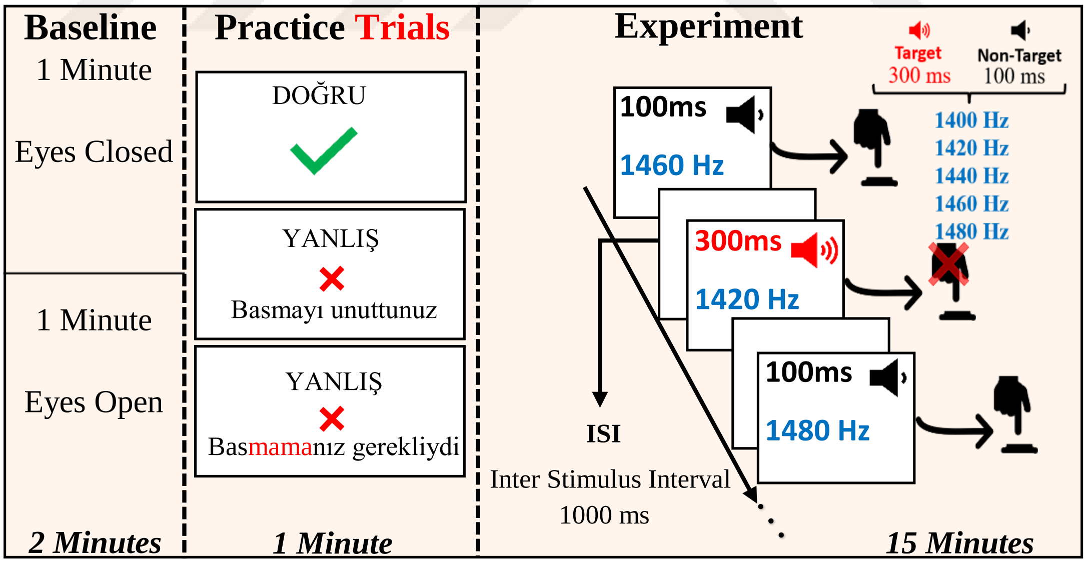


Figure 38. Presentation of the procedure of the experiment with baseline measurement, practice trials and experimental trials

2.5 Electrophysiological Recordings

Dimly lit, soundproof, and electromagnetically shielded room was used while recording the electroencephalogram (EEG) activity which was recorded from Ag-

AgCl electrodes at the Fz, Cz, Pz, Oz locations with linked earlobes as references. Electrode impedance were below 10 kΩ for all electrodes. EEG was recorded by Brain Vision Recorder at 500 Hz then 50 Hz notch filter (36 dB/octave) were applied.

2.6 Segmentation and Artifact Rejection

The raw EEG data was analyzed with Brainvision Analyzer Professional USB Adapter and firstly 50 Hz notch filter (36 dB/octave) was used, and 0.5-48 Hz band limits were applied. Then data was segmented into 3 blocks (each block has 35 target and 220 non-target trials) using 1150 ms epochs (250 ms pre-stimulus/900 ms post-stimulus) to include trials with motor response only within the 200-900 ms window. Non-target epochs were a time window which had an only one button press representing perceived non-target stimulus and target epochs were a time window which had no button press representing perceived target stimulus.

2.6.1 Artifact Rejection

The reaction time within 200-900 ms were accepted for non-target epochs but excluded for target epochs. Button press at pre-stimulus were excluded from both target and non-target epochs for all blocks. Also, epochs with eye movement, muscle activity, and sweating artifactsand changes in conductance were manually excluded from the data analysis. Finally, all artifact free epochs are segmented again 1 s epochs (250 ms pre-stimulus/750 ms post-stimulus). Epochs were randomly deleted until the number of target and non-target epochs were balanced. Approximately twenty artifact free epochs were randomly chosen from average 120 artifact free non-target epochs and average 22 artifact free target epochs for each subject for all blocks (Table 1).

Table 1. Average number of artifact free epochs for each stimulus in each block

	Mean epoch artifact free epochs (SD)		
Stimulus	*Block 1*	*Block 2*	*Block 3*
Target	21,5 (7,44)	22,42 (5,76)	22 (6,90)
Non-target	123,42 (52,40)	121,83 (45,87)	118,17 (44)

2.7 Time-Frequency Decomposition

Wavelet convolution in frequency domain was applied to the EEG data for time-frequency decomposition (Cohen, and Donner, 2013). Matlab 2021b functions were used to apply this transformation procedure with custom scripts. This wavelet convolution was conducted to transform raw EEG signal to theta (4 – 8 Hz) frequency at Fz, Cz, Pz, and Oz regions of interest (ROI). Primarily, each participant’s all artifact free epochs were concatenated for each participant as if they consist of a continuous signal.   Complex wavelets were generated by:

$$\psi(t) = (e^{2\pi i f/t})(e^{-t^2/2\sigma^2}) \tag{1}$$

$$\sigma = \frac{n}{2\pi f} \tag{2}$$

Where t is time, f is frequency, σ^2 scales the gaussian window of the complex wavelets according to n is the number of wavelet cycles. Frequencies ranged from 4 to 8 Hz in .25 steps. Number of wavelet cycles were n = 6. The energy of complex wavelets was normalized to one unit. Using the built-in Fast Fourier transform, the signals and complex wavelets were transformed into frequency domain. (fft.m function in MATLAB; Frigo, and Johnson, 1998). For vector x and n sampling points, the fast Fourier transform (FFT) is defined by:

$$y_k = \sum_{j=1}^{n} \left(\omega_n^{(j-1)(k-1)} x_j \right) \tag{3}$$

Where *i* is the imaginary unit and $\omega = e^{-2\pi i/n}$ is one of n complex roots of unity. The signal's power spectrum and the complex wavelets that resulted were then multiplied. The result of this multiplication was converted to time domain using Matlab 2021b's built-in inverse FFT (iFFT) technique. iFFT is defined by:

$$x_j = \sum_{k=1}^{n} \left(\omega_n^{(j-1)(k-1)} y_k \right) \tag{4}$$

Then, for each participant at each time point, frequency-band specific power *A* will be determined and averaged over trials in each condition using:

$$A(t) = \sum_{k=1}^{n} |Z(t)_k|^2 \tag{5}$$

Where Z represents the complex signal, t represents the time, and n represents the total number of trials a participant has completed in each condition.

For all participants, center frequency was 5.5 Hz, and %95 of its activity will be between 3.7 and 7.3 Hz. This range was chosen because it reflected activity in the wide theta band and was defined as two standard deviations of the wavelet in the frequency domain.

2.8 Data Analyses

In the first step, data was separated 3 blocks and artifacts in target and non-target stimuli were rejected within (-250 – 900 ms) time window. Then data was segmented 1 second epochs (-250 – 750 ms) and filtered according to the common theta frequency band (4 – 8 Hz). Within the frequency limitations of the used filters, digital filtering gives visual representations of time courses of oscillatory components. The advantages of digital filters are that they do not induce the phase changes that electrical filters do.

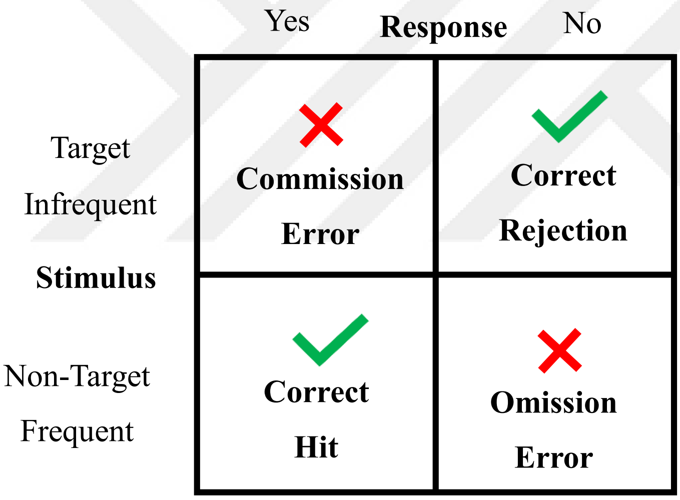
2.9 Statistical Analysis

2.9.1 Comparison of Turkish and German Participants

Behavioral and physiological data comparison in Turkish and German participants was analyzed with The Mann–Whitney test which is the non-parametric version of independent t-test because of the inequality in the number of participants in Turkish (5 subjects) and German (8 subjects) sample. All non-parametric test was interpreted from exact method which is best for small sample size groups. The behavioral data is based on the classical parameters of signal detection theory which are Correct Hit, Correct Rejection, Error of Commission, and Error of Omission (Figure 39). Reaction time (RT) to non-target stimuli was calculated from Correct Hit data within 200-930 ms time window. Physiological data digitally filtered according to the common frequency band of theta (4-8Hz) using Fast Fourier Transformation (FFT). Maximum peak-to-peak amplitude and maximum ITC value after the stimulus occurrence (0-750) was calculated from the filtered and averaged data for target and non-target trials separately at each electrode locations (Fz, Cz, Pz, and Oz). So, the significance vale was divided four which is the number condition in electrode variable (p = .05/n of tests).

2.9.2 Behavioral Data Analyses

Turkish and German data were combined into a single data. One-way repeated measures ANOVA (if the data distributes normally) or its non-parametric counterpart the Friedman's test was used to compare the differences between three blocks in all participants according to the results of the The Mann–Whitney test analysis (German-Turkish comparison).



Stimulus	**Response**	
	Yes	No
Target Infrequent	✗ **Commission Error**	✓ **Correct Rejection**
Non-Target Frequent	✓ **Correct Hit**	✗ **Omission Error**

Figure 39. Schematic representation of behavioral data in SART experiment

2.9.3 Physiological Data Analyses

Turkish and German physiological data was combined, and physiological analyses were conducted across thirteen participants. Theta frequency band and maximum ITC values were separately analyzed for target and non-targets on averaged data using Two-way repeated measures ANOVA using 3 blocks (Block 1, Block 2, and Block 3) x 4 electrode location (Fz, Cz, Pz, and Oz). For violation of the assumption of sphericity, Greenhouse-Geisser adjustment was applied to all main and interaction effects to the degrees of freedom where needed. Effect sizes were calculated using r values $(\surd F(1,df_R)/\ F(1,df_R)+df_R)$ were reported as estimations of effect size of main and interaction effects. In addition, four sets of planned comparisons were carried out to look at the changes in theta activity and ITC values between each block and each electrode. Findings of planned comparisons were provided instead of post-hoc comparisons where predicted results were also determined to be significant.

CHAPTER 3: RESULTS

3.1. Behavioral Results

3.1.1 The Comparision of Behavioral Data from German and Turkish Subjects

Before start the all data analyzes, behavioral data of Turkish and German participants were analyzed with The Mann–Whitney (because of the unequal samples size) to detect results that may arise from the nationality difference and to determine the type of analysis to be performed. Results of the Mann-Whitney test shows the difference on correct hit, and correct rejection (Figure 40), but no difference was found on error of commission, error of omission and reaction time (RT) between Turkish and German participants (Figure 41). Results of the Mann-Witney test showed that Turkish participants were significantly higher than German participants in correct hit (*Mdn* = 646; *Mdn* = 451.5; $U = 0.00$, $z = -2.93$, $p < .01$), and correct rejection (*Mdn* =87; *Mdn* =72; $U = 0.50$, $z = -2.86$, $p < .01$) respectively (Figure 40). However, no difference was found between Turkish and German participants in number of errors of commission (*Mdn* = 18; *Mdn* = 21.5; $U = 28$, $z = 1.18$, $p = .28$), error of omission (*Mdn* = 5; *Mdn* = 17; $U = 27$, $z = 1.03$, $p = .35$) and reaction time (*Mdn* = .417; *Mdn* = .434; $U = 21$, $z = .15$, $p = 1.0$) respectively (Figure 41).

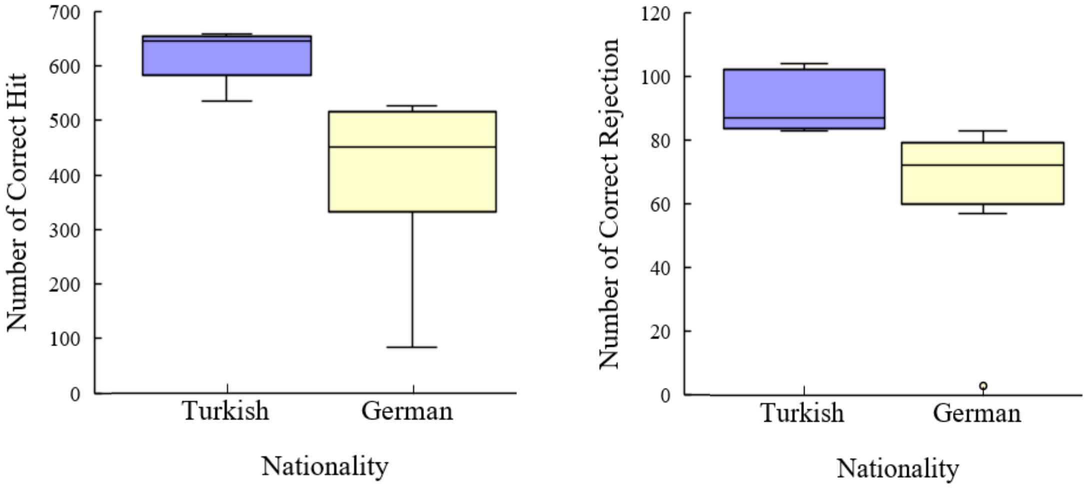


Figure 40. Box plot of Mann-Witney test for Correct Hit and Rejection in Turkish and German Participants

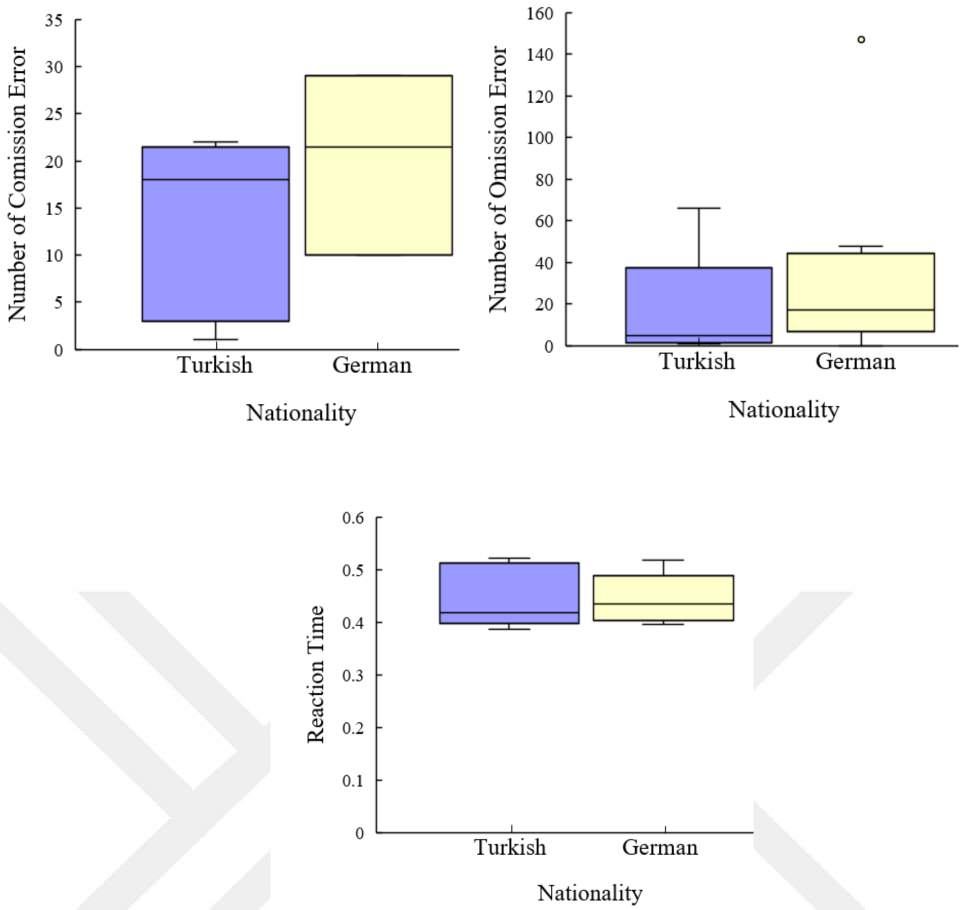


Figure 41. Box plot of Mann-Witney test for Commission Error, Omission Error, and Reaction Time in Turkish and German Participants

3.1.2 Behavioral Data Results in Three Blocks

In the second part of analysis behavioral data from Turkey and Germany were integrated into a single dataset. It was decided to perform non-parametric analysis on correct hit, and correct rejection data which has significant difference between Turkish and German sample. One-way repeated measures ANOVA was chosen for the error of commission, error of omission and reaction time data because of similar results between Turkish and German participants. However only reaction time data was distributed normally for all blocks, so reaction times in non-target trials was analyzed by the means of One-way repeated measures ANOVA time (block 1-2-3) as within subject's factor. Number of errors of commission for block 1, $D(13) = .25$, $p = .03$, and errors of omission for block 1 $D(13) = .33$, $p = .000$; and block 2 data, $D(13) = .31$, $p = .001$ were significantly different from normal; so, they were also analyzed with non-parametric test.

Correct hit, correct rejection, errors of commission, and errors of omission data was analyzed with the Friedman's test which is nonparametric counterpart of one-way repated measures ANOVA to examine the differences between 3 blocks. Results of the analyses showed that the participants did not significantly change over the three blocks, $\chi^2(2) = 0.78$, $p = .68$; $\chi^2(2) = 1.14$, $p = .57$; $\chi^2(2) = 1.22$, $p = .54$; $\chi^2(2) = 3.59$, $p = .17$ respectively (Figure 42). One-way repeated measures ANOVA was conducted to see the effect of block on reaction time to non-target stimlus (Block 1, Block 2, Block 3). Mauchly's test indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 0.68$, $p = .70$ and results show that the reaction time was not significantly affected by blocks, $F(2,24) = 0.97$, $p = .40$ (Figure 43).

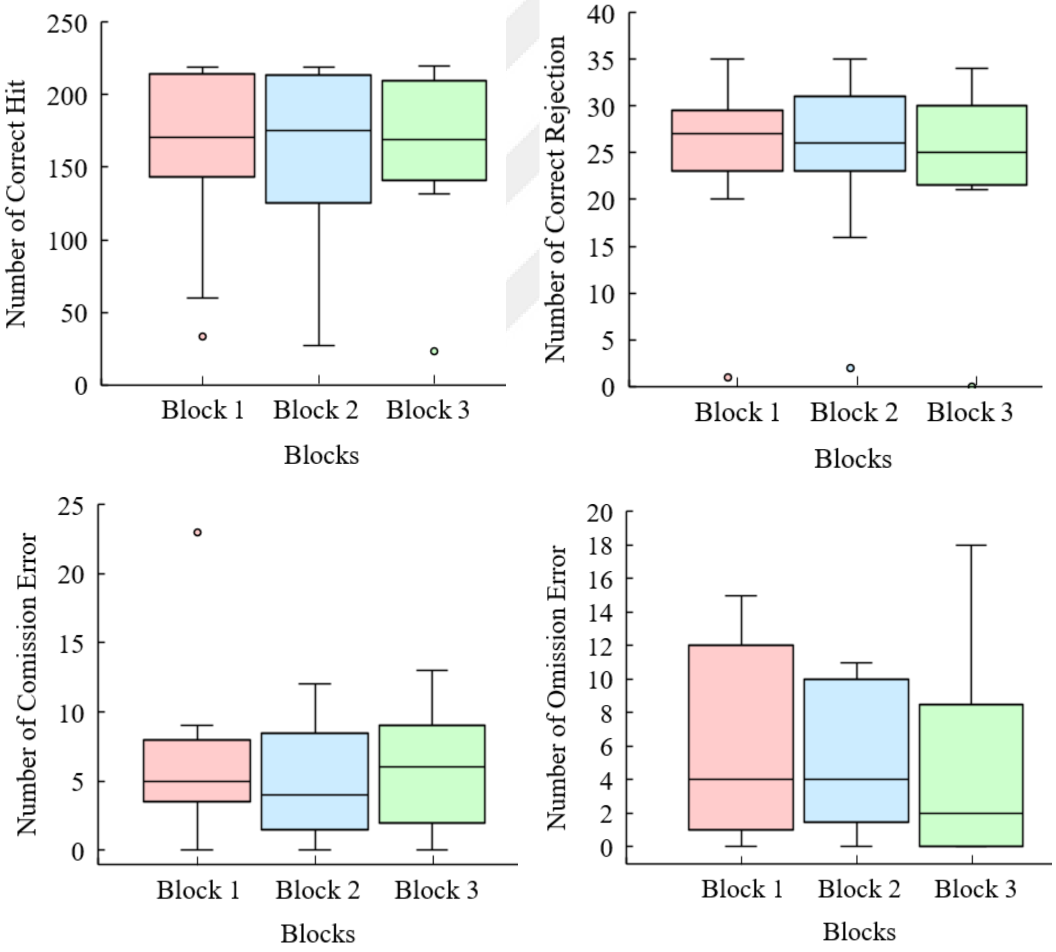


Figure 42. Box plot of the Friedman's test for Correct Hit, Correct Rejection, Commission Error, Omission Error in three blocks

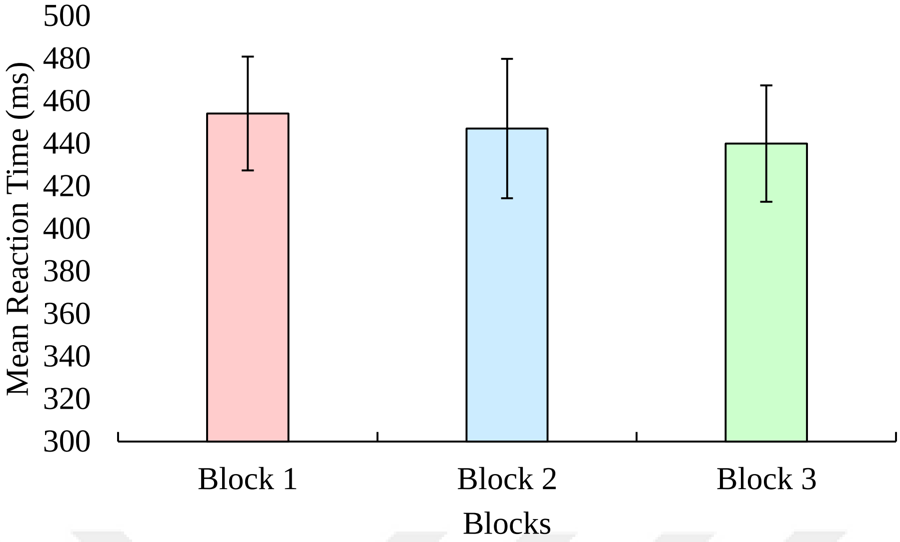


Figure 43. Mean (with 95% CI) reaction time of the participants by blocks

3.2. Electrophysiological Results

3.2.1 The Comparision of EEG Data from German and Turkish Subjects

Electrophysiological data of Turkish and German participants were also analyzed with The Mann–Whitney (because of the unequal samples size) to check is there any difference between Turkish and German participants. Physiological data composed of maximum peak-to-peak amplitude and maximum ITC values for target and non-target trials separately at each electrode locations (Fz, Cz, Pz, and Oz).

Results of the Mann-Whitney test shows no nationality (Turkish and German) difference on theta values for target Fz (*Mdn* = 6.67; *Mdn* = 7.29; *U* = 24, *z* = .59, *p* = .62), Cz (*Mdn* = 7.19; *Mdn* = 8.56; *U* = 32, *z* = 1.76, *p* = .09), Pz (Mdn = 6.03; Mdn = 7.11; U = 26, z = .88, p = .44), and Oz (*Mdn* = 4.75; *Mdn* = 4.12; *U* = 17, *z* = -.44, *p* = .72) (Figure 44). Likewise, theta values for non-target Fz (*Mdn* = 6.42; *Mdn* = 6.37; *U* = 20, *z* = 1.00, *p* = 1.00), Cz (*Mdn* = 6.93; *Mdn* = 6.96; *U* = 18, *z* = .77, *p* = .83), Pz (*Mdn* = 4.54; *Mdn* = 4.44; *U* = 18, *z* = .77, *p* = .83), and Oz (*Mdn* = 3.76; *Mdn* = 3.29; *U* = 15, *z* = -.73, *p* = .52) shows no significant difference between Turkish and German participants (Figure 45).

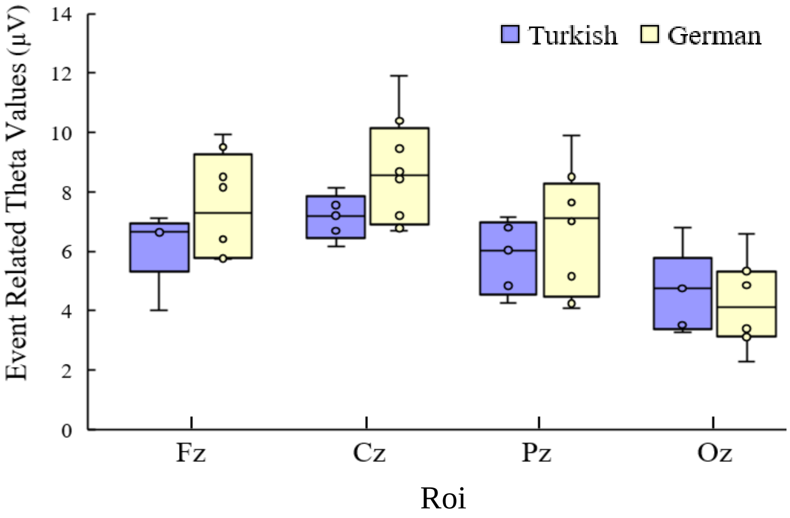


Figure 44. Box plot of Mann-Witney test for Event Related Theta values (µV) on target stimuli on each electrode at Turkish and German Participants (13 participants).

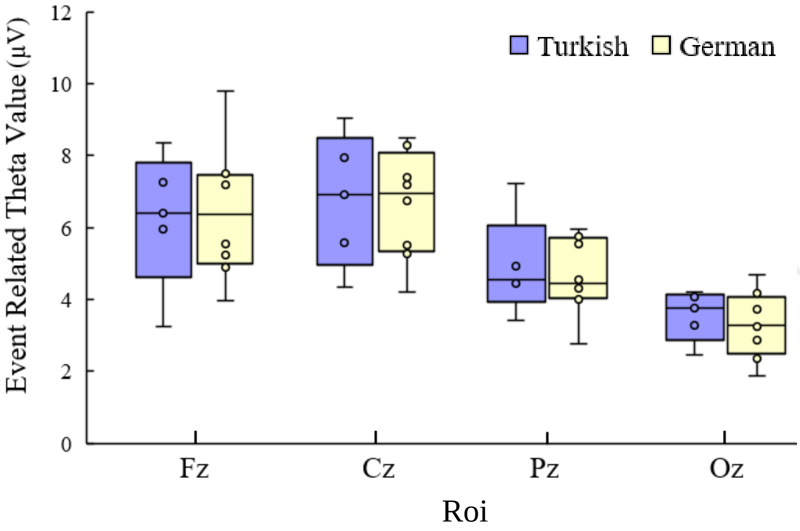


Figure 45. Box plot of Mann-Witney test for Event Related Theta values (µV) on non-target stimuli on each electrode at Turkish and German Participants (13 participants)

Similarly, there is no significant difference between Turkish and German values for ITC theta values for both target Fz (*Mdn* = 0.23; *Mdn* = 0.28; *U* = 24, *z* = 0.59, *p* = .62), Cz (*Mdn* = 0.33; *Mdn* = 0.26; *U* = 11, *z* = -1.32, *p* = .22), Pz (*Mdn* = 0.23; *Mdn* = 0.27; *U* = 26, *z* = .88, *p* = .44), Oz (*Mdn* = 0.23; *Mdn* = 0.25; *U* = 25, *z* = .46, *p* = .52) (Figure 46), and non-target Fz (*Mdn* = 0.27; *Mdn* = 0.26; *U* = 17, *z* = -0.44, *p* = .72), Cz (*Mdn* = 0.29; *Mdn* = 0.27; U = 20, *z* = .00, *p* = 1.00), Pz (*Mdn* = 0.28; *Mdn* = 0.26; *U* = 20, *z* = .00, *p* = 1.00), Oz (*Mdn* = 0.22; *Mdn* = 0.22; *U* = 19, *z* = -.15, *p* = .94) (Figure 47).

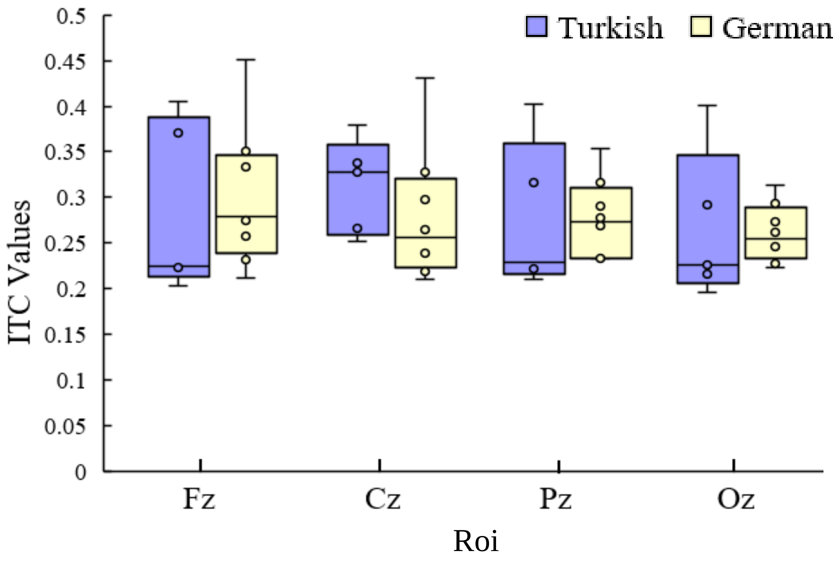


Figure 46. Box plot of Mann-Witney test for ITC Theta values (μV) on target stimuli on each electrode at Turkish and German Participants (13 participants)

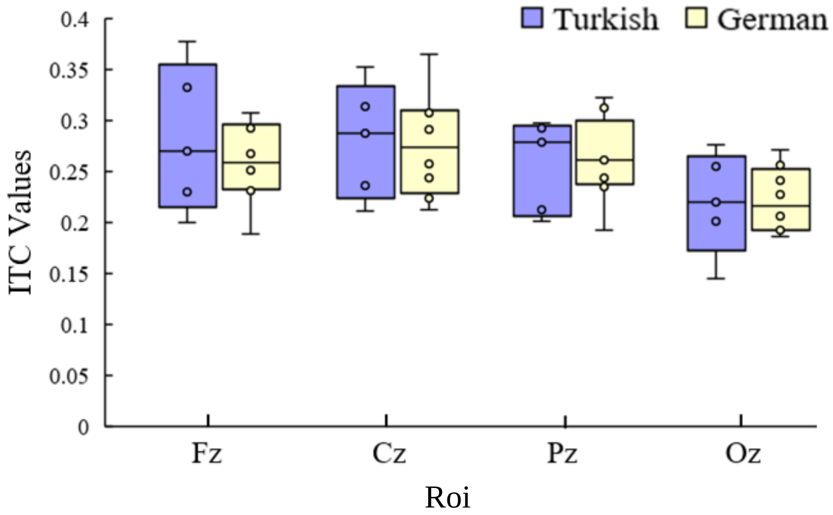


Figure 47. Box plot of Mann-Witney test for ITC Theta values (μV) on non-target stimuli on each electrode at Turkish and German Participants (13 participants)

In total four Mann–Whitney test (Target Theta, Non-target Theta, Target ITC, Non-Target ITC) was conducted for each electrode position (Fz, Cz, Pz, Oz). Because for each analyze, within variable had four condition, so significant value was accepted as p = .13 (p =.05/n of tests).

Results of Mann–Whitney test for physiological data showed no difference between Turkish and German participants which allowed us to analyze the data of all participants as a single data. Theta filtered data and ITC (Theta) values (distributed normally for all blocks and electrodes) were separately analyzed for targets and non-targets using a two-way repeated measures analysis of variance with three blocks (block1, block2, block3) x 4 electrode locations (Fz, Cz, Pz, Oz).

3.2.2 Event Related Theta Responses on Target Stimuli

Effect of block and electrode location on event related theta responses for target trials was invested with two-way repeated measures ANOVA. Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of electrode, $\chi^2(5) = 23.00$, $p < .001$. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .56$ for the main effect of electrode). There was no significant main effect of block on event related theta responses, $F(2, 24) = .19$, $p = .83$ (Figure 48). However, there was a significant main effect of the type of electrode on event related theta responses, $F(1.68, 20.10) = 29.32$, $p < .001$ (Figure 49). Contrasts revealed that event related theta responses on Cz, $F(1, 12) = 24.16$, $p < .001$, r = .82 were significantly higher and on Oz, $F(1, 12) = 22.64$, $p < .001$, $r = .81$, were significantly lower than Fz electrode. Nevertheless, there was no significant interaction effect between the type of electrode and block, $F(6, 72) = .96$, $p = .46$ (Figure 50) which can be seen visually in electrophysiological results (Figure 51).

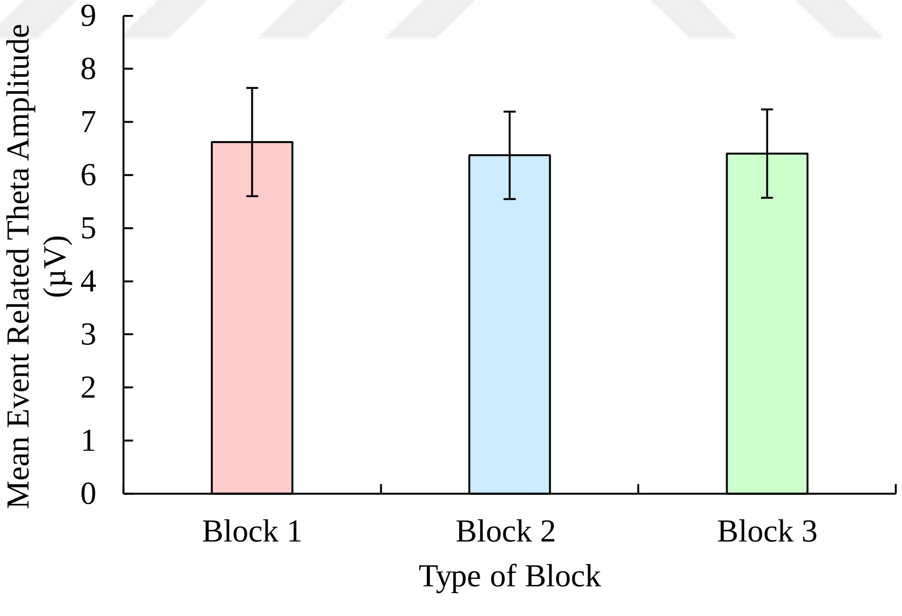


Figure 48. Mean Event Related Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of block

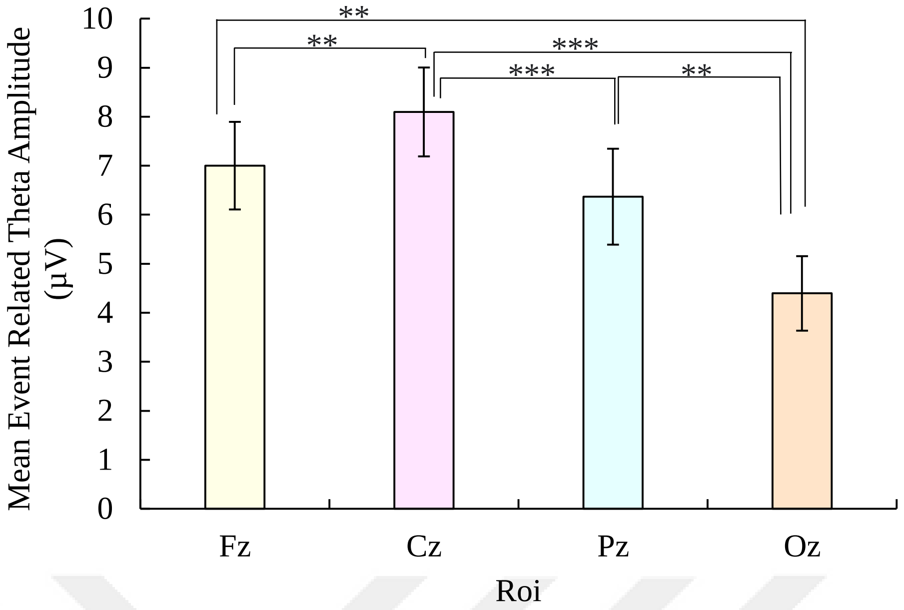


Figure 49. Mean Event Related Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of electrode. *s denote significance at * p < 0.05, **p < 0.01, ***p < 0.001

3.2.3 Event Related Theta Responses on Non-Target Stimuli

This time, effect of block and electrode location on event related theta responses was invested for non-target stimuli. Mauchly’s test indicated that the assumption of sphericity had been violated for the main effects of electrode, $\chi^2(5) = 12.34$, $p < .05$, and block and electrode interaction $\chi^2(20) = 32.70$, $p < .05$. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .61$ for the main effect of electrode and .56 for the interaction effect of electrode-block). On event-related theta responses, there was no significant main effect of block $F(2, 24) = 1.63$, $p = .22$ (Figure 52). However, the type of electrode has a significant main effect on event-related theta responses., $F(1.82,21.86) = 33.80$, $p < .001$, r = .78 (Figure 53). Contrasts revealed that event related theta responses on Pz, $F(1, 12) = 16.19$, $p < .01$, r = .76, and on Oz, $F(1, 12) = 38.53$, $p < .001$, $r = .87$, were significantly lower than Fz electrode. But again, there was no significant interaction effect between electrode type and block, $F(3.35,40.21) = .85$, $p = .54$ (Figure 54) and also results can easily be seen from electrophysiological view of non-target evenet related theta oscillations (Figure 55).

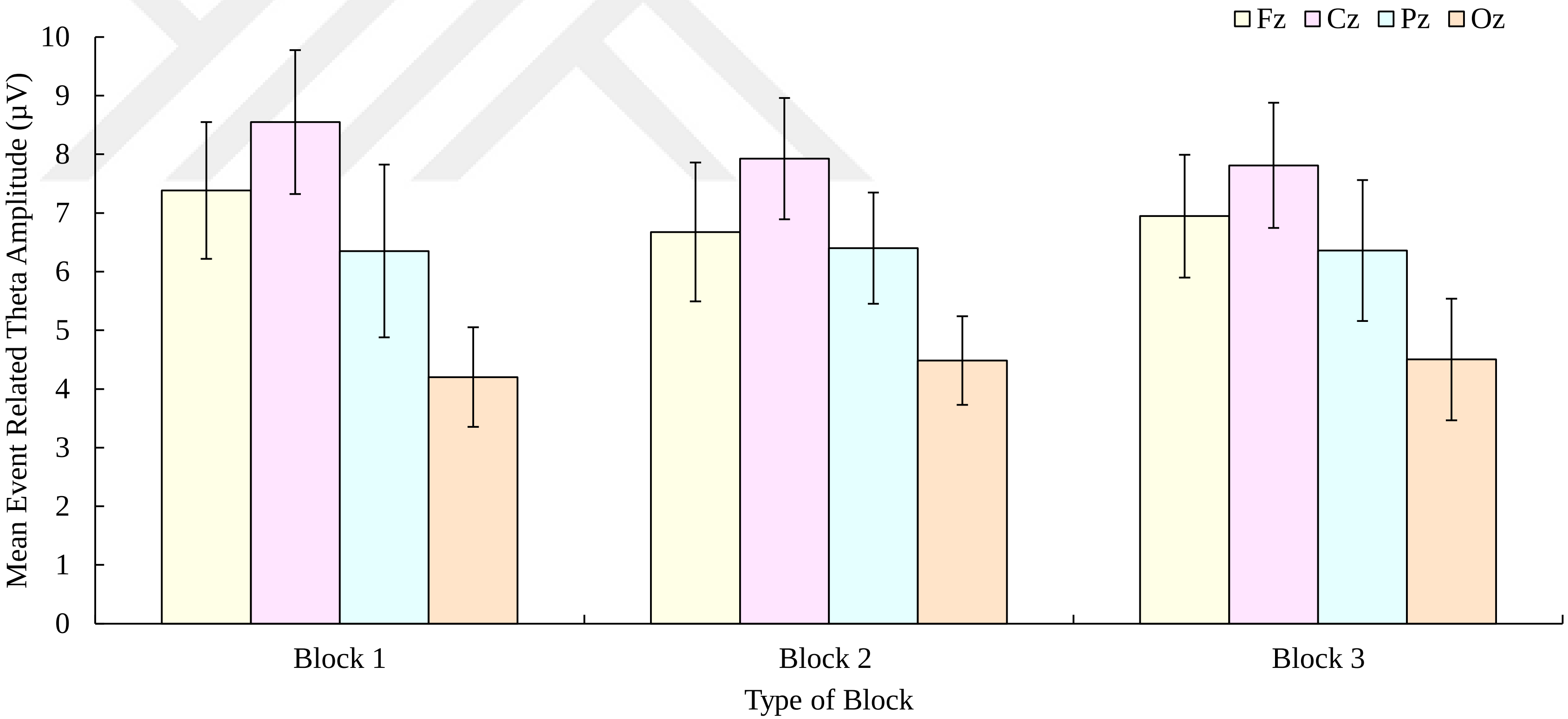


Figure 50. Mean Event Related Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of block in each electrode.

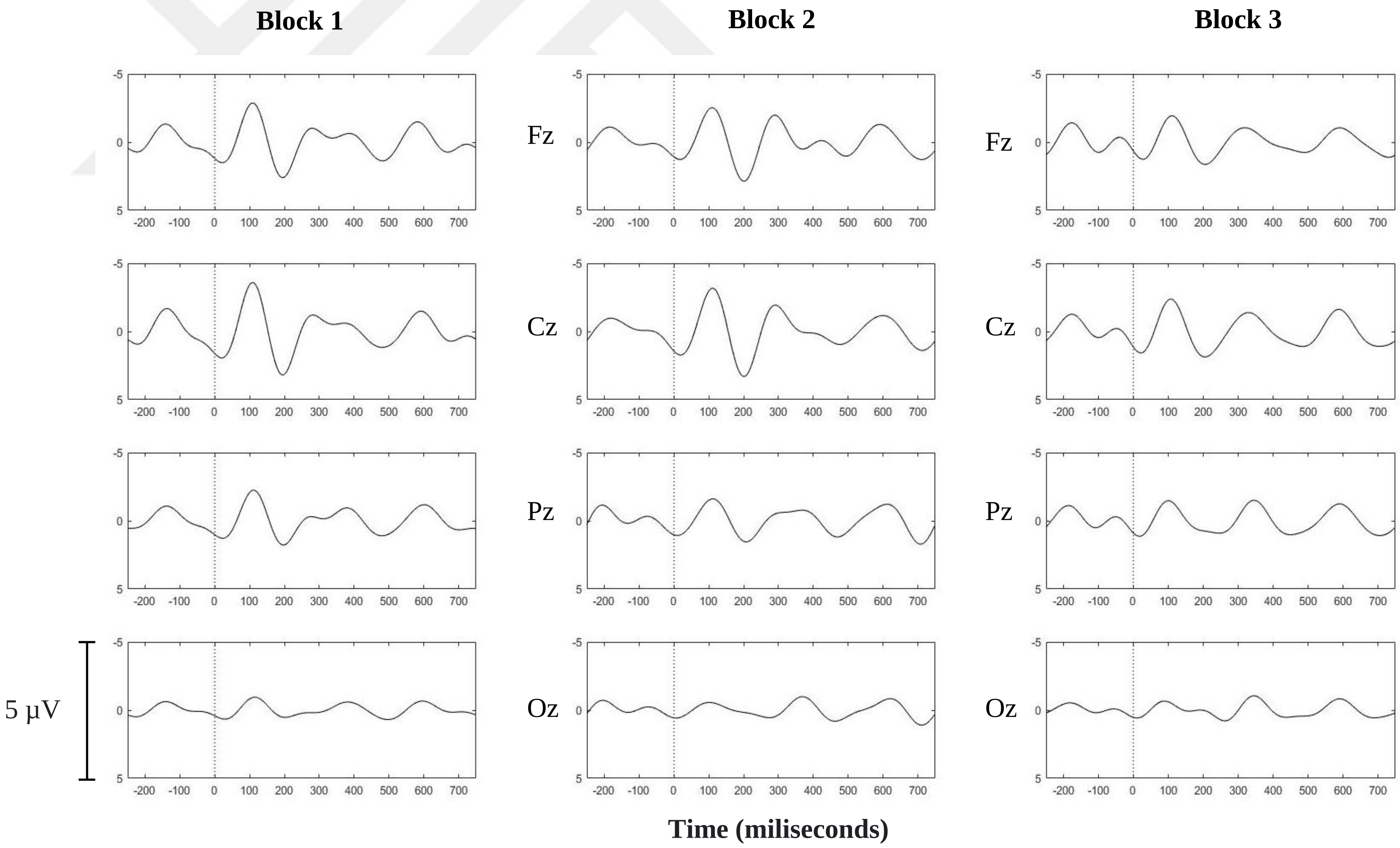


Figure 51. Grand averages of event-related theta oscillations in Fz, Cz, Pz, Oz electrodes during target-detection at three blocks

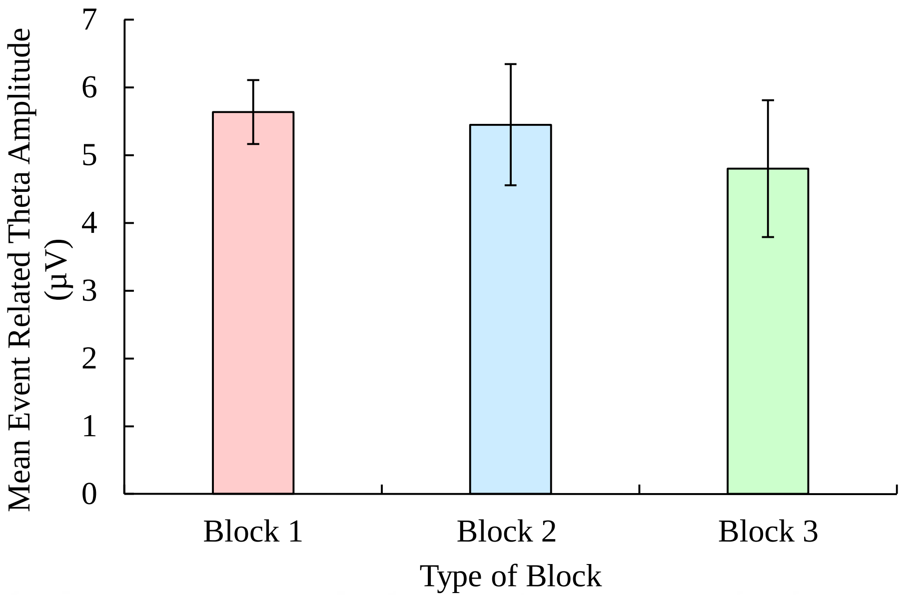


Figure 52. Mean Event Related Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of block.

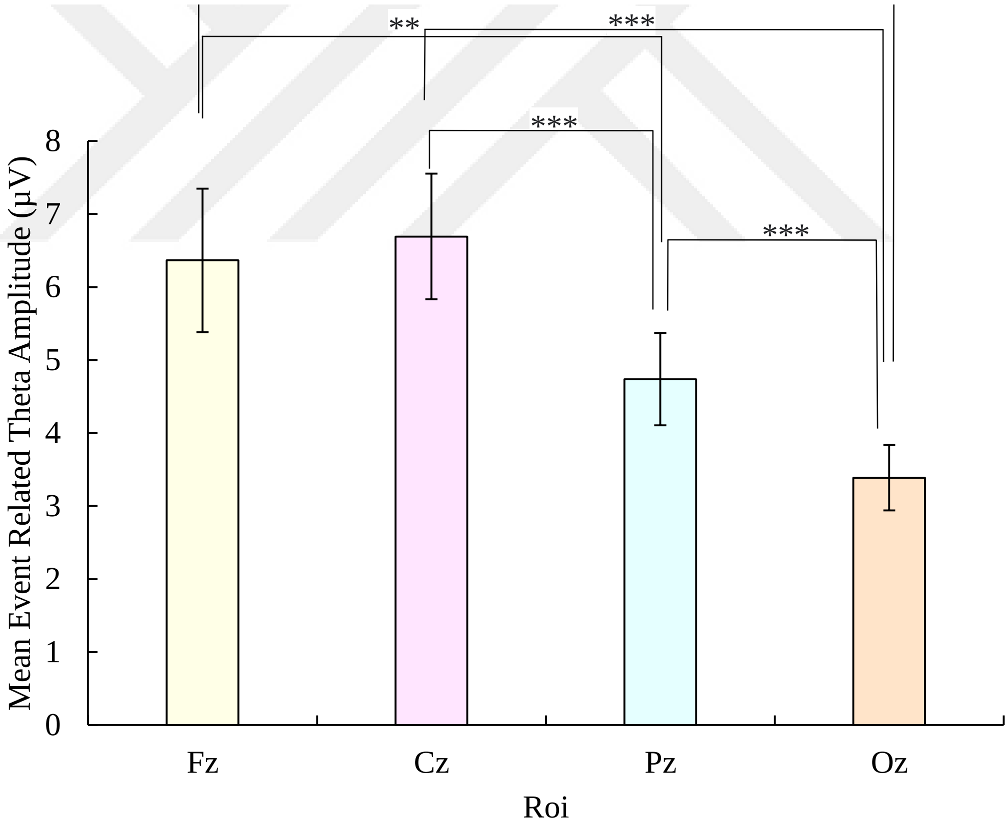


Figure 53. Mean Event Related Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of electrode

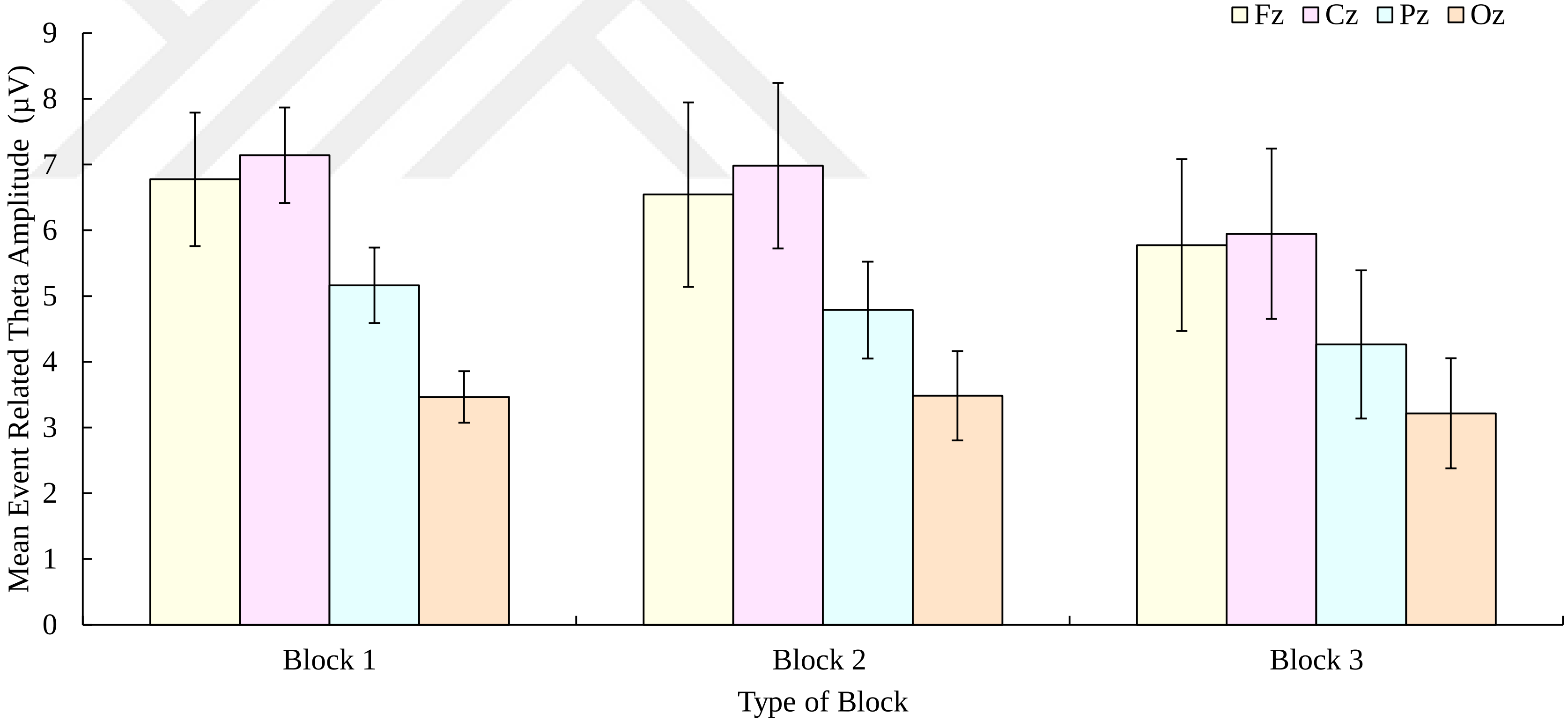


Figure 54. Mean Event Related Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of block in each electrode

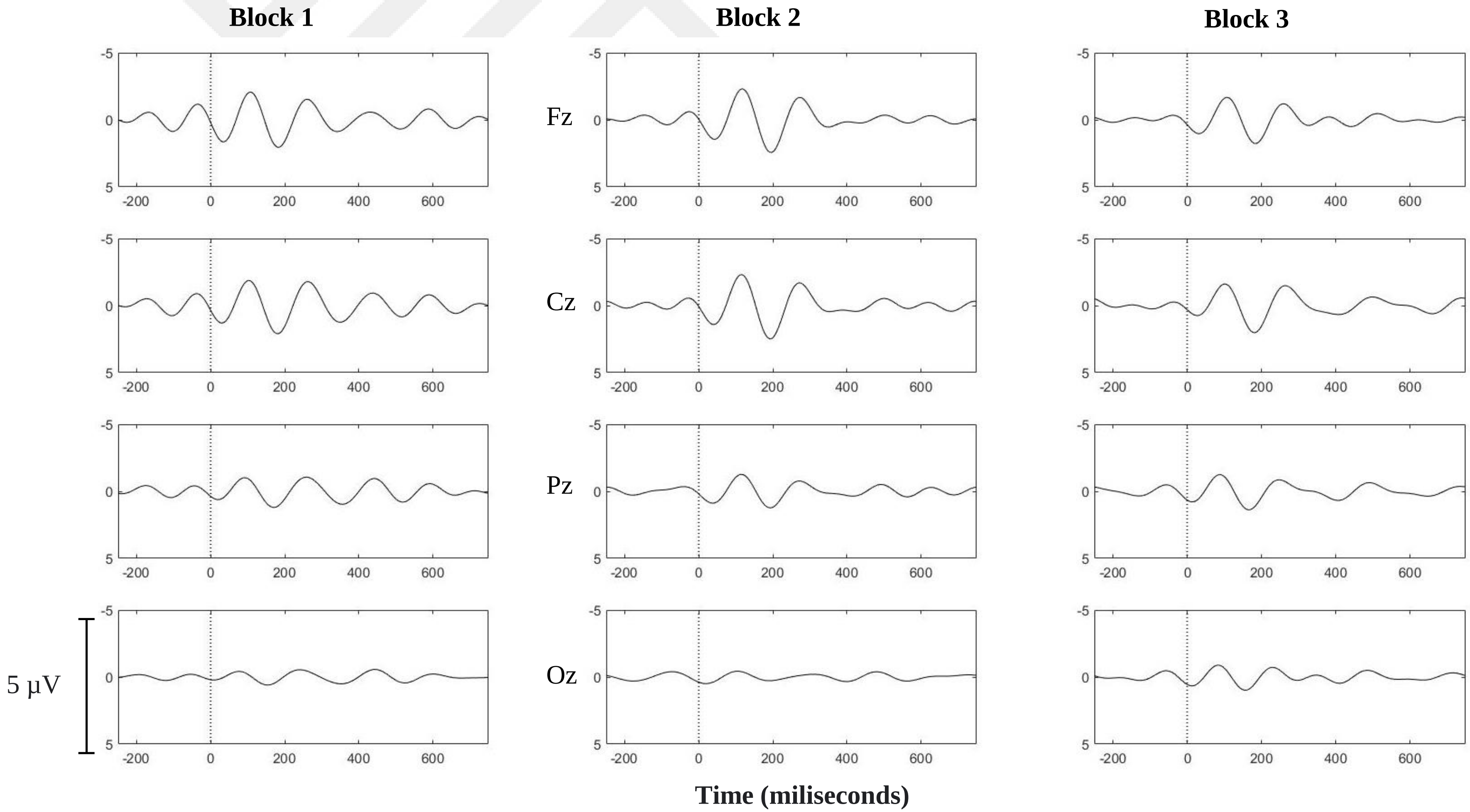


Figure 55. Grand averages of event-related theta oscillations in Fz, Cz, Pz, Oz electrodes during non-target stimuli at three block

3.2.4 Theta ITC values on Target Stimuli

Two-way repeated measures ANOVA were used to investigate the effect of block and electrode position on theta ITC values for target trials. Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of electrode, $\chi^2(5) = 17.53$, $p < .01$. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .55$ for the main effect of electrode). There was no significant main effect of block, $F(2, 24) = .25$, $p = .78$ (Figure 56), main effect of electrode, $F(1.65, 19.85) = 1.63$, $p = .20$ (Figure 57), and interaction effect between the type of electrode and block, $F(6, 72) = .71$, $p = .64$ on theta ITC values (Figure 58). The reflection of these results on can be seen in the time-frequency domain on target stimuli (Figure 59).

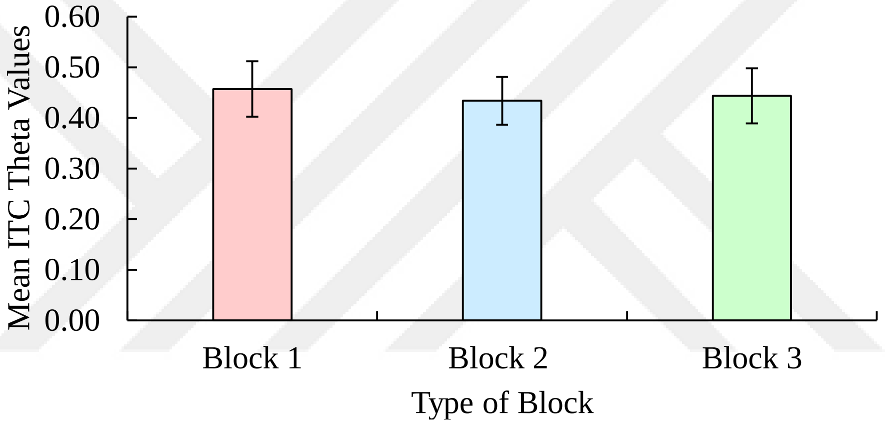


Figure 56. Mean ITC Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of block.

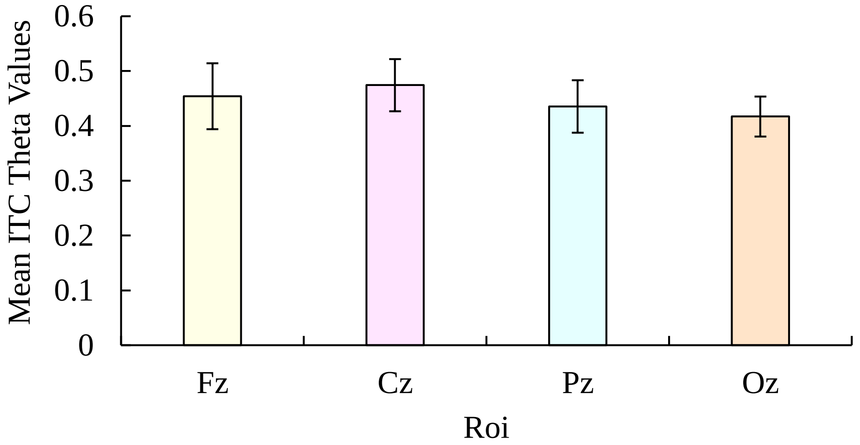


Figure 57. Mean ITC Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of electrode

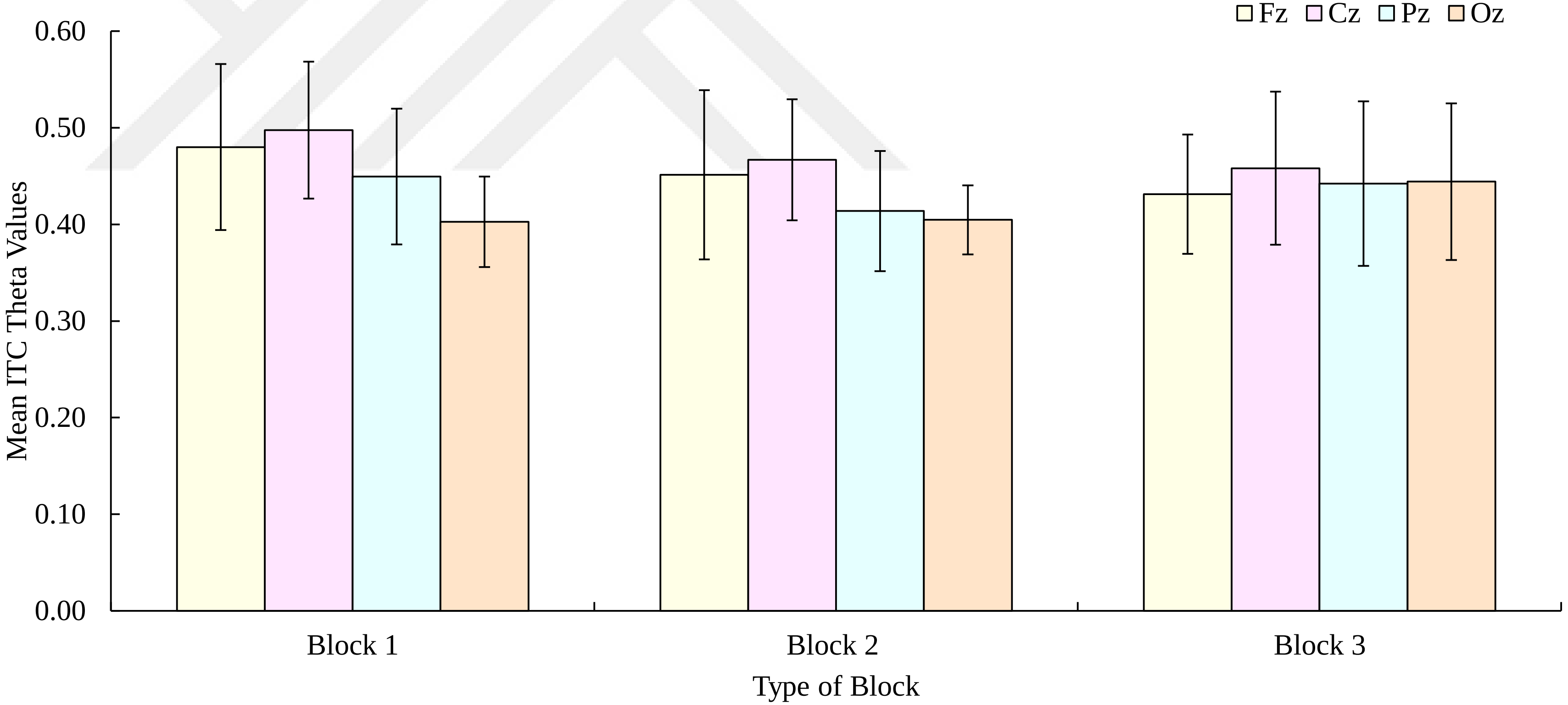


Figure 58. Mean ITC Theta Values of 13 participants for target stimuli (with adjusted 95% CIs) by type of block in each electrode.

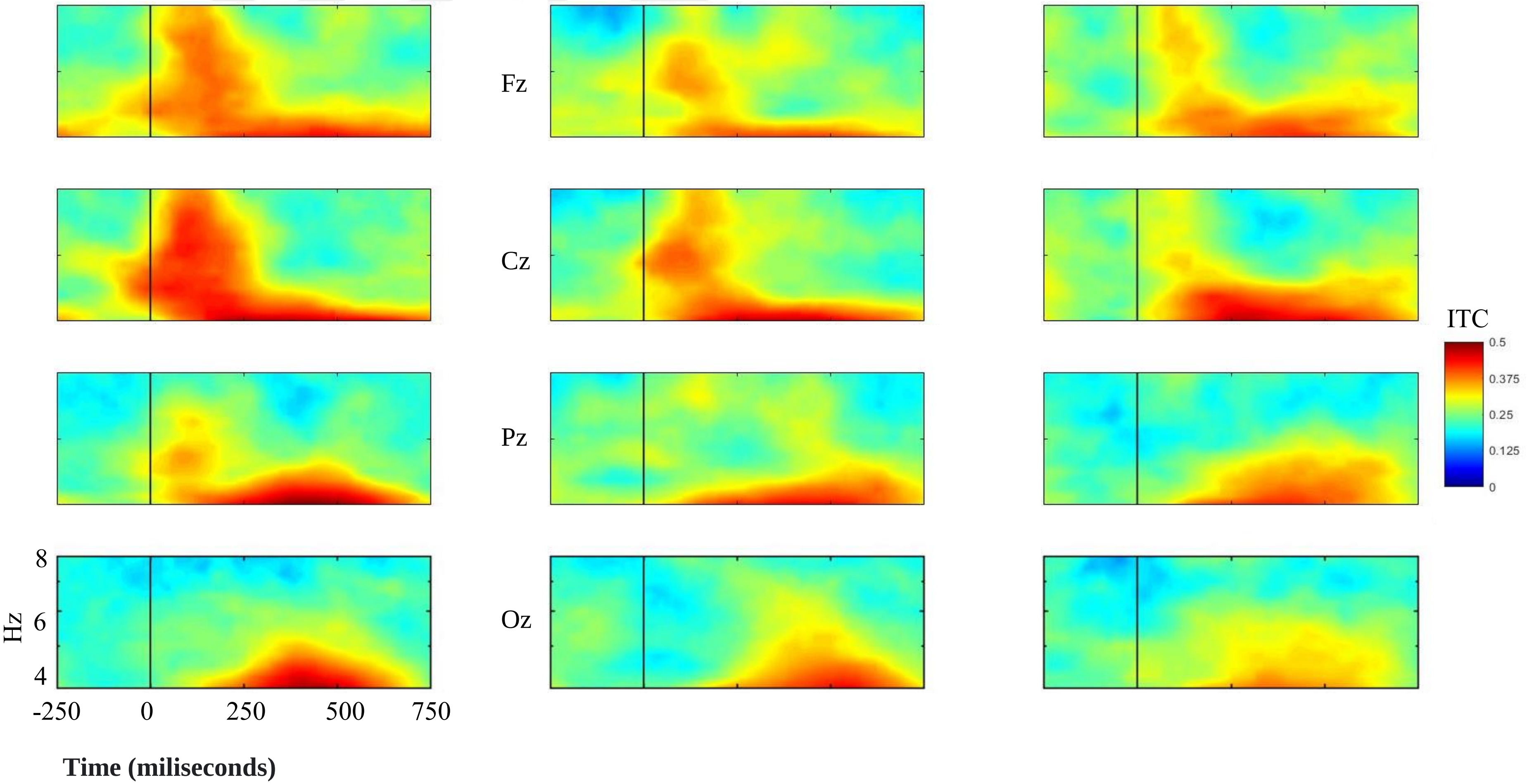


Figure 59. Grand averages of ITC at 3 blocks for target stimlus of auditory SART experiment (13 participants)

3.2.5 Theta ITC values on Non-Target Stimuli

Same procedure was applied for non-target stimuli on theta ITC values for block and electrode position. Mauchly's test indicated that the assumption of sphericity had been violated for block and electrode interaction $\chi^2(20) = 34.87$, $p < .05$. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity (.50 for the interaction effect of electrode-block). On theta ITC values, there was a significant main effect of block $F(2, 24) = 3.55$, $p < .05$, r = .36 (Figure 60), and electrode $F(3, 36) = 5.80$, $p < .01$, r = .37 (Figure 61), however there was no interaction effect between block and electrode type, $F(2.97, 35.63) = 2.17$, $p = .11$ (Figure 62). Contrasts revealed that theta ITC values on block 2, $F(1, 12) = 8.80$, $p < .01$, r = .65, were significantly higher than block 3. Furthermore, theta ITC values on Oz, $F(1, 12) = 5.57$, $p < .05$, $r = .56$, were significantly lower than Cz electrode. These differences can easily be seen in EEG graph at time-frequency domain for non-target stimuli (Figure 63).

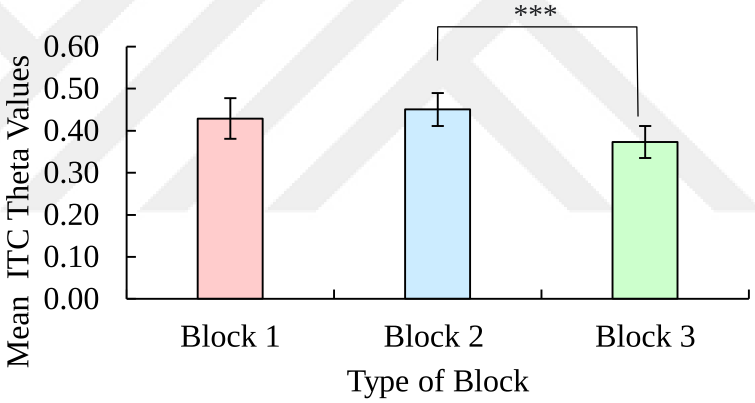


Figure 60. Mean ITC Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of block.

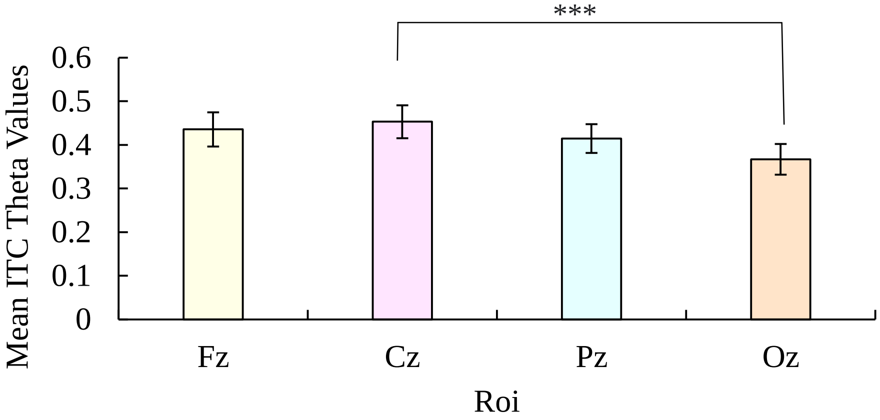


Figure 61. Mean ITC Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of electrode

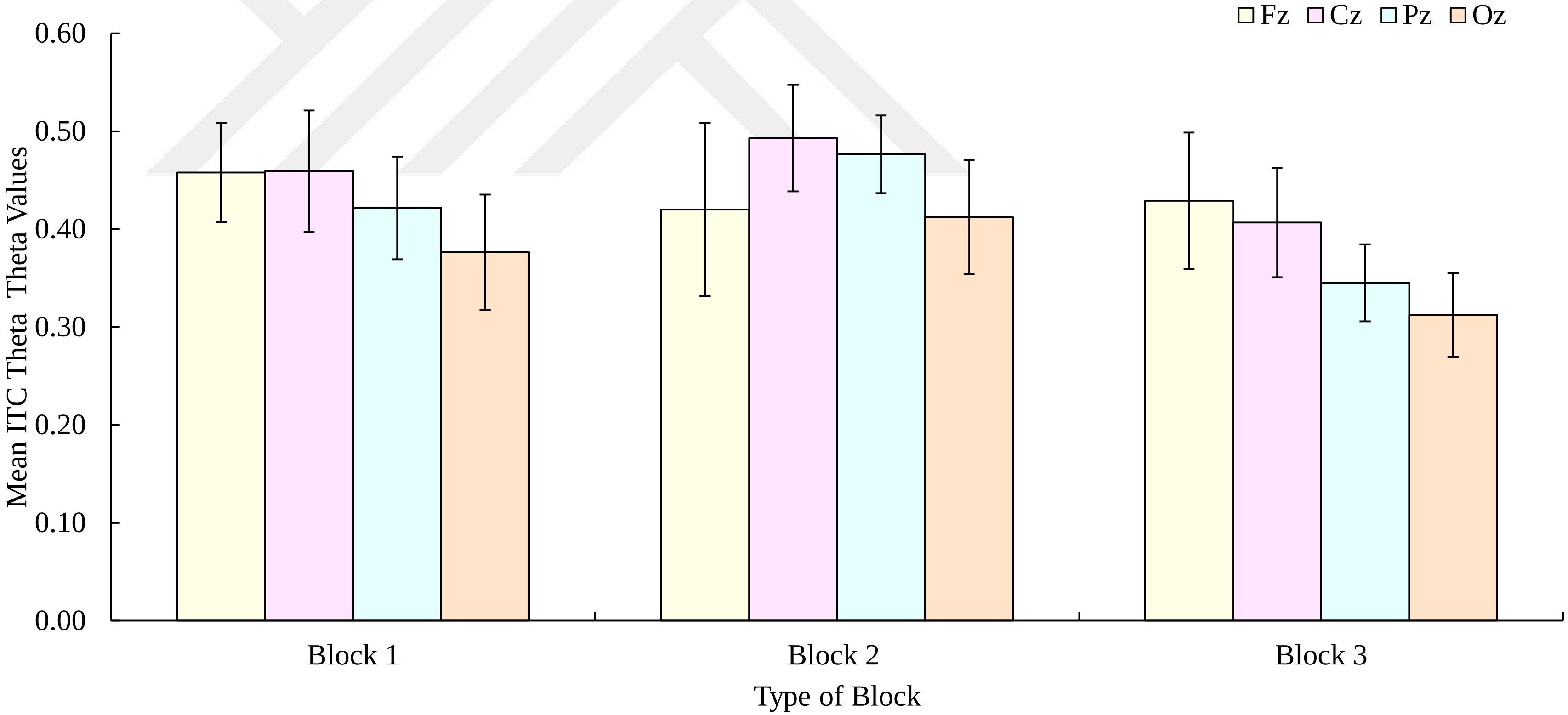


Figure 62. Mean ITC Theta Values of 13 participants for non-target stimuli (with adjusted 95% CIs) by type of block in each electrode

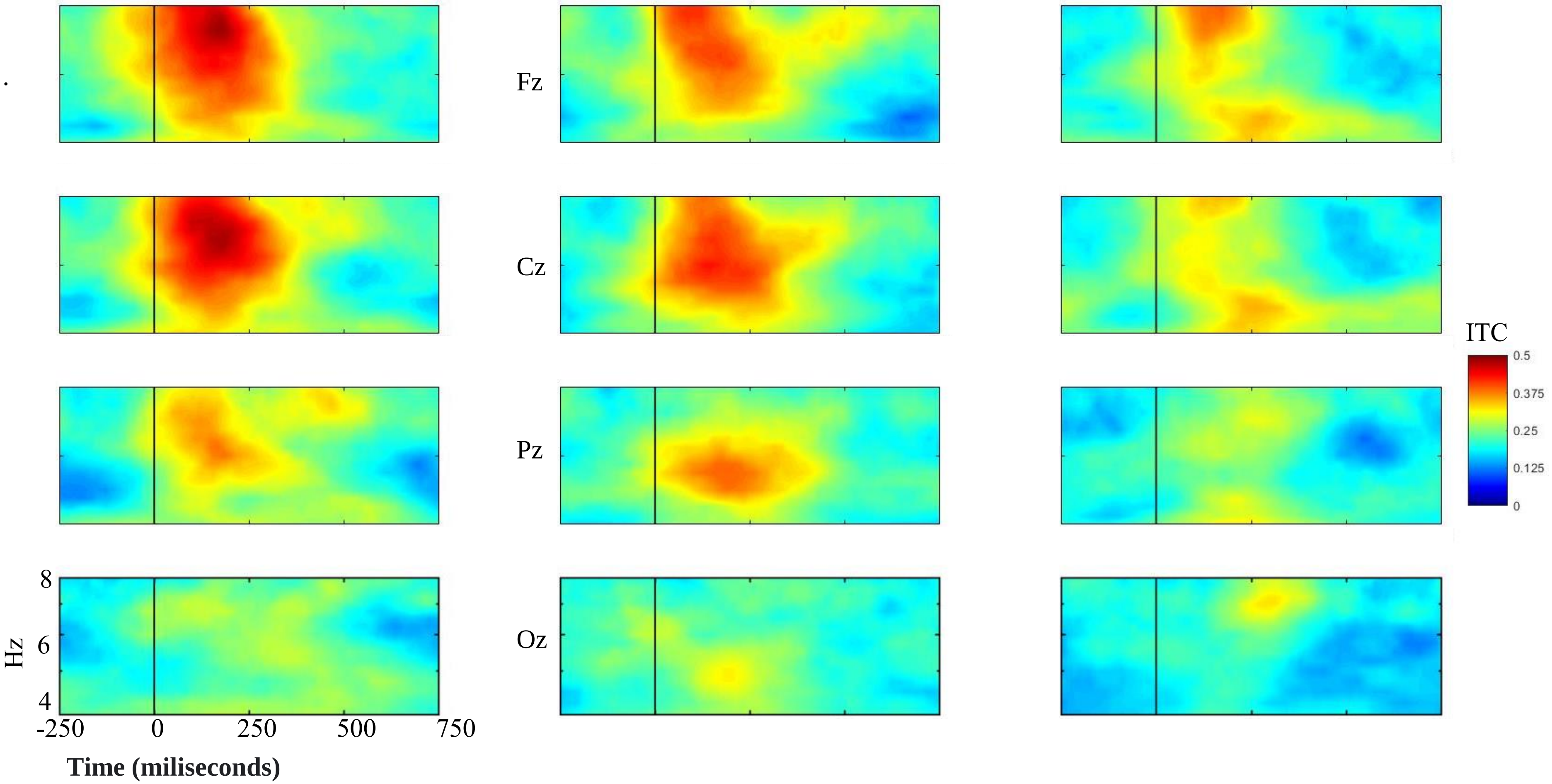


Figure 63. Grand averages of ITC at 3 blocks for non-target stimlus of auditory SART experiment (13 participants)

3.2.6 General Overview to Electrophysiological Results

Results of electrophysiological data showed that block has only significant effect on non-target theta ITC values. Theta ITC values decreases from beginning to end of the experiment. Location of the electrode has significant difference on event related theta oscillations (both target and non-target) and non-target theta ITC values. However, block and location have no significant effect on any data (Table 2).

Table 2. Summary of analyses of variance (3 Block: Block 1, Block 2, Block 3 x 4 electrode locations: Fz, Cz, Pz, Oz) performed separately for target and non-target stimuli on the mean amplitude theta oscillations, and maximum peak-to-peak theta ITC values.

F-ratio (*df*)	*Event Related Theta Oscillation*		*Theta ITC values*	
Stimuli	Target	Non-target	Target	Non-target
Block (2,24)	-	-	-	3.55*
Location (3,36)	29.32***	33.80***	-	5.80**
B x L (6,72)	-	-	-	-

Note 1. *s denote significance at * $p < 0.05$, **$p < 0.01$, ***$p < 0.001$

CHAPTER 4: DISCUSSION

This thesis investigated the relationship between theta oscillation and time during a sustained attention to response task. Behavioral results and results of event related theta and theta ITC values was discussed separately for target and non-target stimulus in terms of blocks and electrode location. Event related theta and theta ITC values were examined to understand brain activities associated with sustained attention.

There were significant differences in region of electrode at event related theta responses on both target and non-target stimulus and non-target theta ITC values. Maximum theta response is seen at the central electrode then frontal, parietal, and occipital respectively on both target and non-target stimulus. However, no significant difference was shown in target ITC values among electrodes which is important information in terms of function of ITC. Effect of block was only seen in non-target ITC values that can be because of learning process.

4.1. Behavioral Findings

Sustained attention to response task (SART) was used to examine outcomes of task and interpret these outcomes in terms of the attentional mechanisms. In the first part, Turkish and German participants were compared to see is there any possible difference between Turkish and German participants which can lead to biased results in analyses of combined data.

Behavioral results showed that no significant changes in correct hit, correct rejection, commission error, omission error rates, and reaction time across three blocks. Longer experimental periods may be required to effectively study attention.

4.1.1 The Comparision of Behavioral Data from German and Turkish Subjects

In the first part, Turkish and German participants were compared. Results showed that Turkish people significantly more correct hit and correct rejection than German participants and no difference was found in reaction time, omission, and commission errors. The difference in correct hit (pressing frequent non-target stimulus) and correct rejection (not pressing infrequent target stimulus) difference can be because of the age difference between Turkish (M_{age}=26, SD_{age}= 4) and German participants (M_{age}=32, SD_{age}= 4). One of the research groups who study with auditory oddball task found that older group has significantly less target detection than younger groups but not found any significant difference on reaction time (Iragui et al., 1993). Therefore, such a difference may have occurred between Turkish and German correct hit and correct rejection data, due to the fact that young people are better at perceiving the target stimulus. Due to the difference between Turkish and German data, nonparametric analysis was preferred to these two data (Correct Hit and Correct Rejection) while looking the effect of block.

However, there is no significant group difference between Turkish and German participants on their reaction time, omission, and commission Errors. Most of the study could not find any age-related difference on these variables (Brache et al., 2010; Carriere et al., 2010; Iragui et al., 1993; Mani et al., 2005; Schmiedt-Fehr and Başar-Eroğlu, 2011). For this reason, there may not have been a significant difference in these variables between Turkish and German participants. Other reasons for similar results between Turkish and German participants in omission and commission error may be due to the low probability of making a mistake. Participant most of the time pressing the button for non-target stimulus so forgetting to press frequent non-target stimulus (omission error) can be rarely. Similarly, the reason for commission error can be because of the physical structure of experiment. Participant has very low chance for commission error because of it appears rarely. Even though we cannot know exactly why these errors and reaction time are similar in Turkish and German participant, non-significant results in reaction time, omission and commission error give us a chance to combine and analyze them with parametric design.

4.1.2 Results Across Three Blocks

Correct hit and correct rejection were analyzed with non-parametric design due to the difference between the current Turkish and German data. Then data was analyzed to examine the difference between blocks. Even though correct hit number dipped in second block and reached highest number at the last block, there were no significant change found between blocks. Other researchers found decreased hit rate with time (Bunce, 2001; Deaton and Parasuraman, 1993), however when the research with similar age group like our study is examined, and they found more hit rate at block 3 than block 1 (Parasuraman et al., 1989). Change in the number of hit across blocks can be more successful with the experiments with longer durations. For example, one of the experiments which lasts sixty minutes used auditory vigilance task and showed decreased hit rate with time (Paus et al., 1997).

Correct rejection (not pressing infrequent target stimulus) number also was not affected by time. Although number of correct rejections decreased sharply in third block this decrease is not meaningful. Total number of possible correct rejection is 35 in each block which is quite small number to compare results. Longer experimental periods can be more successful while detecting number of correct rejection changes between blocks.

Commission error variable was also applied non-parametric design because of the normality problem. No difference was found between blocks in number of commission error even though it dipped in second block and increased again in third block. One of the research groups found significant increase in commission error across blocks in young subjects but significant decrease in older group (Staub et al., 2015), and also found decreased commission error regardless of the effect of age (Staub et al., 2014). Another group also studies with different age group and found that decreased commission error rate over the blocks regardless of effect of age (Parasuraman et al., 1989). However, one of the study investigates the effect of time and uses auditory SART; and found no significant difference on commission error across blocks (Roebuck et al., 2015). Commission error means pressing to the infrequent target stimulus, and due to the nature of the experiment there were small (infrequent) number of target stimulus, so comparing commission error across block with small number can give us non-significant result. More participants or longer experimental design can show the possible difference between blocks during the sustained attention task (Parasuraman et al., 1989; Staub et al., 2014; Staub et al., 2015).

Like commission error variable omission error variable was also applied non-parametric because data was not distributed normally. Results of the analyses showed that although we saw a decreasing pattern in omission error number across blocks, this decrease did not show a significant difference while comparing three blocks. These results are in line with previous studies with same age range that show no difference between blocks (Staub et al., 2015), but some studies found increased omission error with time (Roebuck et al., 2015) and from block 2 block 3 (Staub et al., 2014).

Only normally distributed data was reaction time data in our study. So one-way repeated measures ANOVA was applied to see the difference between blocks. Even though reaction time decreased gradually with time this reduction was not significant. This non-significant decrease in reaction time may be because of the learning the task. One of the studies which has nearly same age range and used visual SART paradigm also found non significant change in reaction time change across blocks (Staub et al., 2015). Some groups observed that the reaction time increased over time (Paus et al., 1997; Roebuck et al., 2015; Staub et al., 2014), while others observed that it decreased (Brache et al., 2010).

Most importantly all these studies had nearly least 40 participants and longer duration for the task (average 30 minutes). Whereas we had only 13 participants in total and our experiment lasted 15 minutes. These two factors could completely change the effect of block on these variables. Additionally, our results showed that using the same sustained attention to response task leads to consistent results even in small difference between Turkish and German age and in different countries.

4.2 Electrophysiological Findings

Results of electrophysiological data in SART (sustained attention to response task) was investigated to analyze and interpret them in terms of attentional processes. Same procedure also applied before combined the Turkish and German data to determine whether there were any differences between them that may lead to skewed results in combined data analysis. No difference found between Turkish and German participants and data was combined into a single data and showed normal distribution for all conditions. Then maximum peak-to-peak amplitude and maximum ITC values were analyzed in each block and location.

Electrophysiological results showed that target event related theta oscillation didn’t change significantly between blocks but changed significantly at different electrode ROIs. This was also true for non-target event related theta oscillation. However, target theta ITC values showed no significant change neither in block nor in

ROIs. In contrast, non-target theta ITC values were changed significantly both across the block and location (Figure 64).

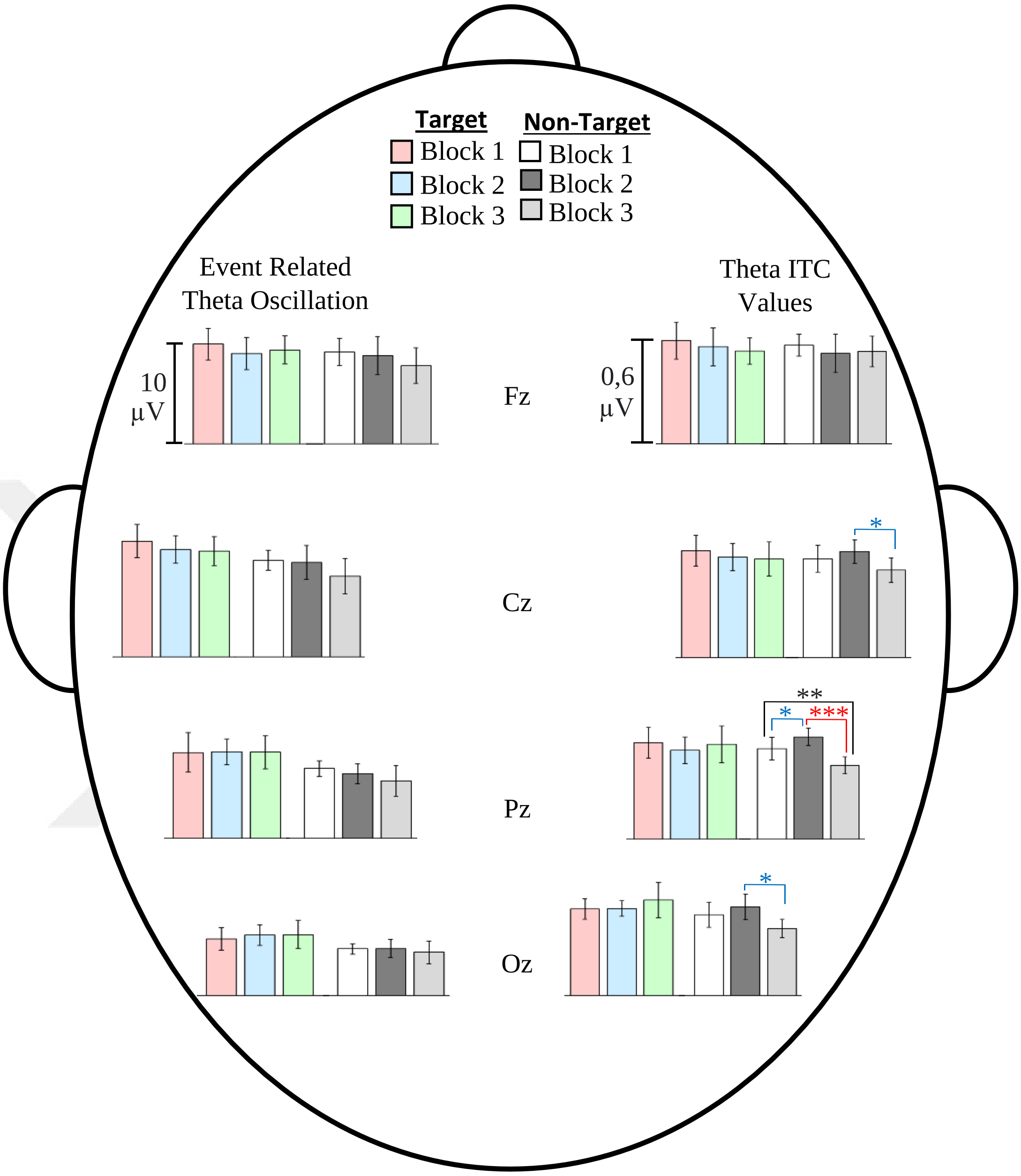


Figure 64. Mean Theta ITC (Right) and Event Related Theta values (Left) for target (colour bars) and non-target stimuli (Black and White bars) (with adjusted 95% CIs) by type of electrode in each block. *s denote significance at * $p < 0.05$, **$p < 0.01$, ***$p < 0.001$

4.2.1 The Comparision of EEG Data from German and Turkish Subjects

Non-parametric analyses were applied to the electrophysiological data to compare any possible difference between Turkish and German participants. Results showed no significant difference on event related theta and theta ITC values for both target and non-target stimuli. These results are quite logical because seeing a difference in the electrical responses of the brain according to nationality would require us to see a difference in different nationality in EEG studies conducted all over the world. Differences in behavioral outcomes may differ in such a small sample by age and educational status, however, although studies show that electrophysiological results may also vary according to age (Yordanova et al., 2004; Schmiedt-Fehr, Mathes, and Başar-Eroğlu, 2009; Schmiedt-Fehr, and Başar-Eroğlu, 2011), the age difference in our sample is not large enough to reveal such a difference. In addition, while behavioral data is obtained from a total of 765 trials (220 non-target, 35 target in each block), our physiological data are much more because electrophysiological data is obtained from millions of data and averaged 20 sweeps for each block. As a result, in the next stages of electrophysiological analysis, Turkish and German data were combined, and the data were analyzed for electrode and block effect.

4.2.2 Event Related Theta Oscillations

Event related theta oscillations was analyzed with two-way repeated measures ANOVA to see the main and interaction effect of blocks and electrodes in target and non-target stimulus. Results showed that even though there was no significant difference between block both for target and non-target stimuli, electrode location affected the event related theta oscillation significantly.

When looking at focused and sustained attention, theta oscillations are quite important (Başar-Eroğlu and Demiralp, 2001) while examining the forms of attentional process (Karakaş, Erzengin and Başar, 2000). Because event related theta oscillations nearly 300 ms after stimulus onset can also be interpreted as selective attention (Başar-Eroğlu et al., 1992). Even though block had non-significant effect on theta oscillation, the smallest theta oscillation was seen at second block for target and third block for non-target stimuli. Same pattern is also seen in the number of correct hits like target theta oscillation and number of correct rejections for non-target theta oscillation. Increase of theta signify a rise in cognitive effort (Arnau et al., 2021), so decrease in second block for the target stimuli can be interpreted as the decrease in cognitive effort which also reflects to the behavioral data by decreased correct hit number in second block. Theta activity starts to increase in the third block again like increased number of hit in third block. We know that expectancies and planned action increases event-related theta (Başar-Eroğlu and Demiralp, 2001; Demiralp et al., 1994), so this increase in the third block can be related to increased expectation to infrequent target (increased theta) relatively, noticing the non-target stimulus more easily (increased number of correct hit) due to the increase in expectation of target stimulus stimuli. However, the gradual decrease both in non-target theta and correct rejection can be based on the learning process. Correct rejection numbers in target stimuli and theta activity in non-target stimuli decreased continuously towards the end of the experiment. That can be interpreted as the participant's ability to easily distinguish between target and non-target stimulus during the experiment, as a result of this, cognitive effort decreased in non-target stimuli.

In our study, there is a significant difference between the electrodes, especially the increase in the fronto-central regions. Previous studies showed that event related theta oscillations are related to the cognitive process (Başar, 1980; Klimesch et al., 1994; Miller, 1991) and it has an important role in integrating information and communicating between different brain regions (Başar et al., 2001; Başar-Eroğlu and Demiralp, 2001; Kirk and Mackay, 2003; Sarnthein et al., 1998). The event-related theta activity was significantly higher at central region than all other regions in both target and non-target stimulus. In addition, second highest theta activity was seen at frontal region for both target and non-target stimuli. It is known that the increase in frontal theta changes according to the level of expectation and the intensity of selective attention, especially in oddball (Başar-Eroğlu and Demiralp, 2001) and omitted stimulus tasks (Demiralp et al., 1994). The increase in the frontal theta also interpreted as cognitive and anticipatory control during learning process or high demand contexts (Başar et al., 2001; Başar-Eroğlu et al., 2001). Furthermore, fronto-central theta enhancement (280-500 ms) was also affected by task difficulty (Schmiedt et al., 2005) and the increased frontal midline theta activity has been identified as a correlate of executive control (Cavanagh and Frank, 2014). Sustained attention tasks that require inhibitory control and long-term attention (e.g. GNG, CPT) were shown to elicit increased mid-frontal theta activity during the response inhibition (Kirmizi-Alsan et al., 2006; Barry, 2009; Yamanaka and Yamamoto, 2010). Therefore, increased fronto-central activity shown with the auditory version SART that was applied in this experiment is in line with previous literature.

4.2.3 Theta ITC Values

Event-related activity is defined as reactions to sensory and cognitive events (Başar et al., 2001) So, studying different types of attentional processes (Karakaş, Erzengin and Başar, 2000), and examining the event related theta oscillations (Başar-Eroğlu and Demiralp, 2001) in terms of how responses are locked to time (ITC) can present us an essential view while measuring the attention. Theta ITC values was analyzed with two-way repeated measures ANOVA to see the main and interaction effect of blocks and electrodes in target and non-target stimulus. Results showed that no significant change was found neither in block nor in electrode side for target stimuli. However, block and electrode sides was changed significantly in non-target ITC values.

Results showed that there was no significant main effect of block for target however there is a significant main effect of block for non-target stimuli. The non-significant block effect on target trials means that withholding the response to the target stimuli induces consistent theta responses across all the experimental blocks. This continuous time-locked theta activity can be regarded as a permanent selective attention which is extended theta oscillations after the stimulus presentation (Başar-Eroğlu et al., 1992) persists throughout the experiment. This time locked continuous theta activity also shows us the existence of event related theta activity in each block. So, this event related theta oscillations which was elicited in both humans and cats by the fourth (last in the sequence) auditory stimulus showed that theta oscillations play a function in focused attention (Başar-Eroğlu and Başar, 1991; Demiralp and Başar, 1992; Demiralp et al., 1994). It is known that selective attention enables task-related perception, cognition and response (Anderson, Reder and Lebiere, 1996) and this selective attention on a selected stimulus over a long period of time is named as sustained attention or alertness (Driver, 2001; Oken, Salinsky and Elsas, 2006). So, these time-locked theta responses, during sustained attention to response task, can be interpreted as continuous sustained attention to target stimuli throughout the experiment.

However, there is a significant difference between block 2 and block 3 in non-target stimuli. Theta ITC values increases non significantly from first block to the second block and decreases sharply at the third block. This means that theta activity is seen at the same time after stimulus presentation at the second block but towards the end of the experiment, theta activities start to respond at different times, and this reflects as smaller theta ITC to the results. Differences in theta responses is related to the different levels of attention, so different forms of attention can affect the amplitude and duration of theta (Posner and Rothbart, 2007). Increased theta ITC was found in deviant stimuli while in a classical oddball paragm which requires selective attention in long-term (Ko et al., 2012). Based on this information, we can interpret the high time-locked theta activity in block 2 as an increase in selective attention to understand the difference between target and non-target tone. Towards the end of the experiment probably differentiating the target and non-target stimuli became easier because of the learning and smaller time-locked theta response in third block. The importance of the theta response to attentional processing is explained by a substantial body of research using a system of cognitive processes which emphasis the relationship between attention and short-term memory (Başar-Eroğlu et al., 1992; Demiralp and Başar, 1992; Karakaş, 1997; Yordanova and Kolev, 1998; Klimesch, 1999). This decreased theta ITC activity can be explained with model of orienting response (OR) which is a reflex is seen both human and animals can be defined as immediate response to the even small changes in the environment (Sokolov, 1963). This model clarifies facilitatory and inhibitory attention within the context of OR and suggests that repetitive stimuli create memory traces in the hippocampus. OR is activated when a new stimulus that does not fit this neuronal model (facilitatory effect). However, the activity of stimulus which matches the neuronal trace (frequent non-target stimuli) can be ignored as a result of habituated detectors in hippocampus (inhibitory effect) and reflects to electrophysiological results as a decreased activation. Therefore, this result can be interpreted as ignored stimuli which matches with the neuronal trace causes decreased theta response at different times.

Although the effect of electrode on theta ITC has same pattern in both target and non-target stimuli, the difference between electrodes were significant only in the non-target stimulus. In both stimuli, the strongest theta activity appears in the central region and continues in the form of the frontal, parietal, and occipital which is supporting our expectations like other studies using oddball (Barry, 2009; Başar-Eroğlu et al., 2009; Kirmizi-Alsan et al., 2006; Yamanaka and Yamamoto, 2010). Increased theta activity in the frontal region has been previously shown by a study which found increased theta oscillations in the frontal area while paying attention to photographs of participants’grandmother compared to unknown faces (Başar et al., 2007). It is also known that theta activity in the frontal area increases in complex events and bimodal sensory stimulation (Başar, 1999). Another finding supporting the bimodal sensory stimulation finding is a study used the auditory, visual and audiovisual stimuli in oddball paradigm and discovered that theta ITC activity is particularly prominent in the fronto-central region in response to audiovisual inputs (Keller et al.,2017). Based on this, it can be interpreted that the high time locked theta activity seen in the frontal region is due to increased attention to target and non-target stimuli and increased complexity due to a long duration of task.

The relationship between theta and hippocampus may also guide us while interpreting the strong activation in the fronto-central area. Theta oscillation which is especially related with the encoding phase of episodic memory, was recorded during the learning of words that can subsequently be recalled (Klimesch et al., 1996). Also strong theta synchronization was showed during encoding process (Klimesch, 1999) which is stronger in performers with an excellent memory (Doppelmayr et al., 1998). Although the cognitive functions of midline theta are not fully known yet, studies on hippocampus and theta in animals have shown us an increase in phase-locked fronto-central theta activity (Mitchell et al, 2008). Even though the relationship between theta and hippocampus is important, theta activity is not only limited to the hippocampus. Hippocampus is just the part of the theta system which spread to the prefrontal, parieto-temporo-occipital, and limbic cortices (Mundy-Castle, 1951; Walter et al, 1984; Westphal et al, 1990). This complex connection with other brain areas can be explained by cortico-hippocampal interplay model (Miller 1991) which clarify the distributed theta network and its function in associative cognitive performance. An auditory evoked potential study with cats showed that theta activity distributed over a network system which is comprising of hippocampus, reticular formation, neocortical and subcortical centers (Başar et al, 1975). The resonance in the theta frequency band allows these structures to communicate with one another (Miller 1991). Consequently, a strong theta response in the phase-locked fronto-midline after the stimulus in a task which requires long-term focus and affect cognitive performance can be interpreted as a theta response which occurs during the encoding process distributed over a network system like hippocampus and other subcortical centers.

4.4 Limitations

First of all, data collection could not be carried out due to the pandemic in between 2020-2021, consequently it was decided to carry out the thesis process with the raw dataset which was recorded at the University of Bremen, Bremen, Germany by Prof. Dr. Canan Başar-Eroğlu and her team. Universities were reopened with the discovery of COVID-19 vaccines in the fall of 2021 and data collection started in the spring term of 2022 at Izmir University of Economics, due to the precautions because of the being at the beginning of the vaccination studies and the waiting for the missing devices required for carrying out the experiments in the laboratory. As a result, it was decided to combine the data collected in Turkey and Germany and continue the analysis in that way. Because of the limited time the data collection process in Turkey was short-lived and data was collected from ten participants whose five of them had to been eliminated due to artifacts. For these reasons, the second limitation of this study can be called sampling size. So more individuals should be included in future studies.

4.5 Conclusion

This study contributed to the literature by examining the behavioral effect of time on auditory sustained attention for the first time. There was no significant difference in behavioral results due to the small number of participants considering the time effect. The changes in attention has been investigated based on new analytical methods such as event related theta response and inter-trial coherence (ITC) with respect to time and brain regions in the SART which requires long-term attention the first time.

Event related theta oscillations and theta ITC values were analyzed separately as target and non-target stimulus. Electrophysiological results showed that event related theta oscillations that represent selective attention didn’t change significantly across the time (Block 1, 2,3) for the target stimuli. The non-significant falls and rises between the blocks along with behavioral results have been interpreted and associated with cognitive effort and attention. The significant difference between electrodes for both target and non-target stimuli showed increased fronto-midline theta response which can be associated with anticipation and the intensity of selective attention. This strong frontal midline theta activity which is known to be parallel to executive control also occurs in inhibition control was examined in the SART and showed consistency with the literature.

Theta ITC values showed no significant change for target stimuli in block and electrode but showed significant changes for non-target stimuli in both block and electrode. Unchanging time-locked theta activity between blocks was interpreted as selective attention throughout the experiment for the target stimuli. However, after theta ITC showed the highest theta activity in second blocks, it showed a sharp decrease in the third block which can be interpreted as increased selective attention in the second block to distinguish between target and non-target stimuli and a decrease in the third block due to learning the difference between target and non-target stimuli. Electrodes showed the same pattern with highest activity in central, frontal, parietal, occipital respectively in both target and non-target. But this difference is significant only in non-target stimuli. The increased theta activity in the frontal area is associated with increasing focus to target and non-target stimuli, as well as increased complexity due to the extended duration of task. Furthermore, the phase-locked theta activity was interpreted in terms of memory processes and the cortico-hippocampal interaction model.

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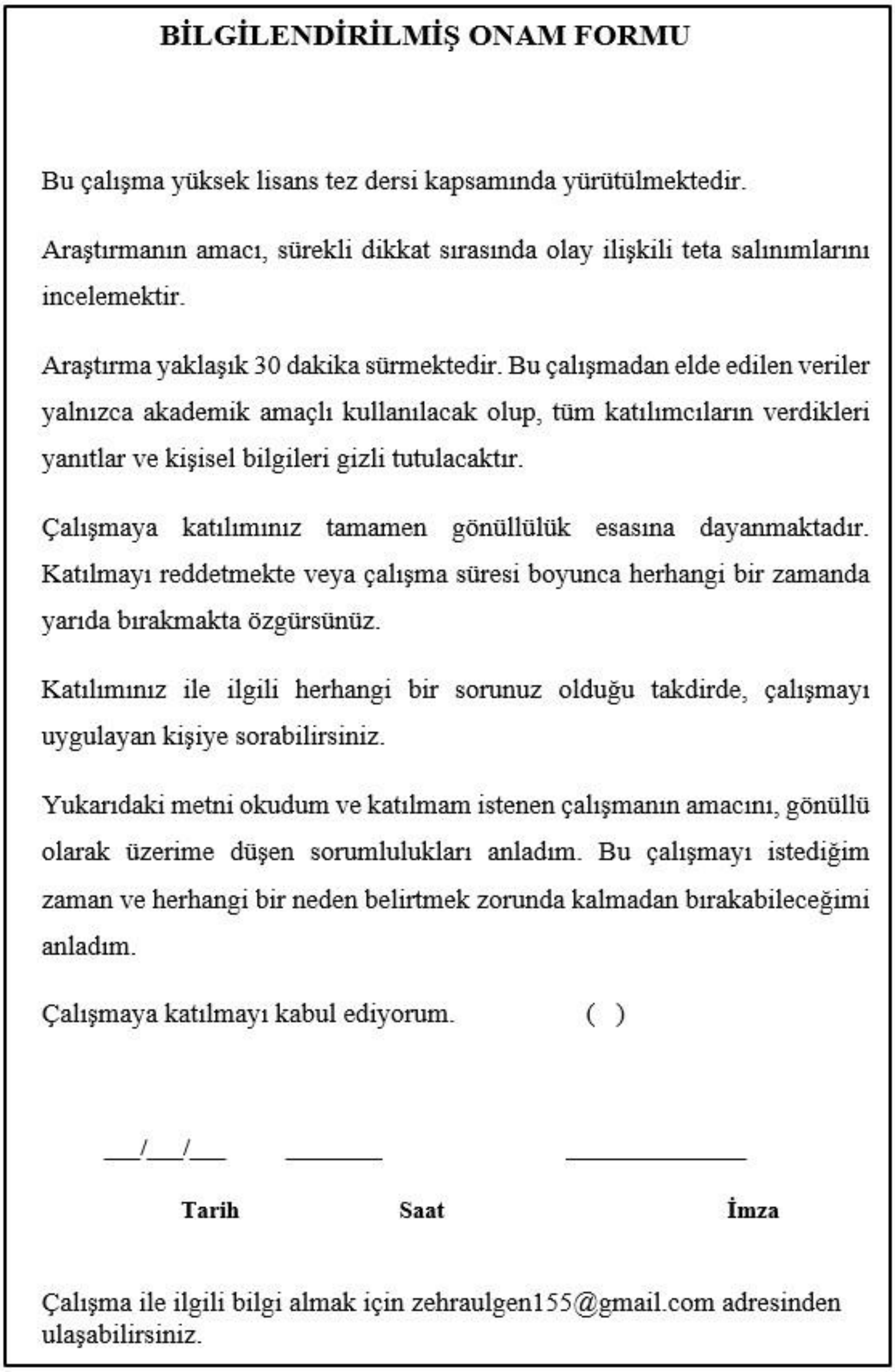
APPENDICES

Appendix A – Informed Consent Form



BİLGİLENDİRİLMİŞ ONAM FORMU

Bu çalışma yüksek lisans tez dersi kapsamında yürütülmektedir.

Araştırmanın amacı, sürekli dikkat sırasında olay ilişkili teta salınımlarını incelemektir.

Araştırma yaklaşık 30 dakika sürmektedir. Bu çalışmadan elde edilen veriler yalnızca akademik amaçlı kullanılacak olup, tüm katılımcıların verdikleri yanıtlar ve kişisel bilgileri gizli tutulacaktır.

Çalışmaya katılımınız tamamen gönüllülük esasına dayanmaktadır. Katılmayı reddetmekte veya çalışma süresi boyunca herhangi bir zamanda yarıda bırakmakta özgürsünüz.

Katılımınız ile ilgili herhangi bir sorunuz olduğu takdirde, çalışmayı uygulayan kişiye sorabilirsiniz.

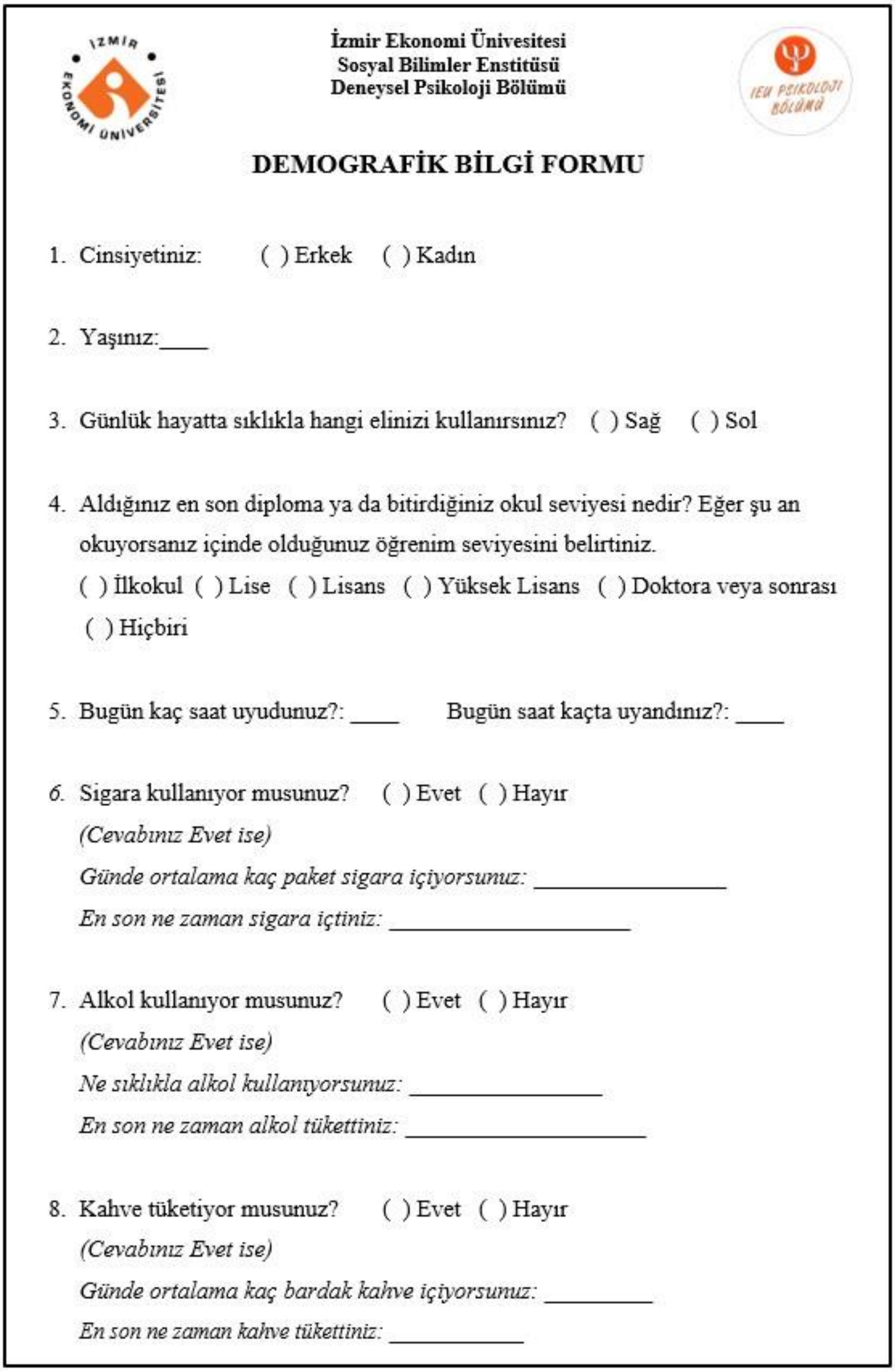
Yukarıdaki metni okudum ve katılmam istenen çalışmanın amacını, gönüllü olarak üzerime düşen sorumlulukları anladım. Bu çalışmayı istediğim zaman ve herhangi bir neden belirtmek zorunda kalmadan bırakabileceğimi anladım.

Çalışmaya katılmayı kabul ediyorum. ( )

___/___/___	________	______________
Tarih	**Saat**	**İmza**

Çalışma ile ilgili bilgi almak için zehraulgen155@gmail.com adresinden ulaşabilirsiniz.

Appendix B – Demographic Information Form



İzmir Ekonomi Üniversitesi
Sosyal Bilimler Enstitüsü
Deneysel Psikoloji Bölümü

DEMOGRAFİK BİLGİ FORMU

1. Cinsiyetiniz: ( ) Erkek ( ) Kadın

2. Yaşınız:____

3. Günlük hayatta sıklıkla hangi elinizi kullanırsınız? ( ) Sağ ( ) Sol

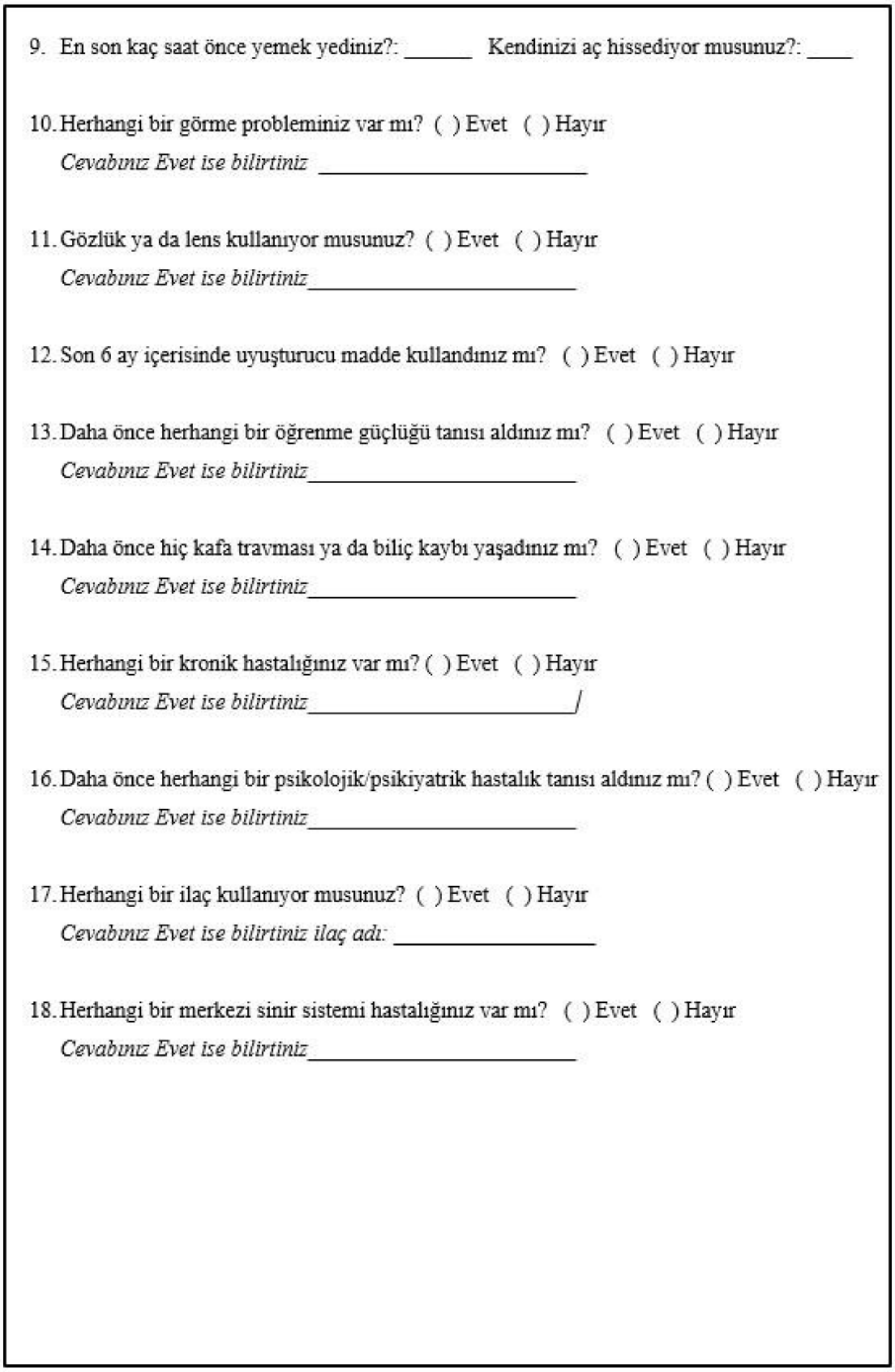
4. Aldığınız en son diploma ya da bitirdiğiniz okul seviyesi nedir? Eğer şu an okuyorsanız içinde olduğunuz öğrenim seviyesini belirtiniz.
   ( ) İlkokul ( ) Lise ( ) Lisans ( ) Yüksek Lisans ( ) Doktora veya sonrası
   ( ) Hiçbiri

5. Bugün kaç saat uyudunuz?: ____ Bugün saat kaçta uyandınız?: ____

6. Sigara kullanıyor musunuz? ( ) Evet ( ) Hayır
   (Cevabınız Evet ise)
   Günde ortalama kaç paket sigara içiyorsunuz: ________________
   En son ne zaman sigara içtiniz: ____________________

7. Alkol kullanıyor musunuz? ( ) Evet ( ) Hayır
   (Cevabınız Evet ise)
   Ne sıklıkla alkol kullanıyorsunuz: ________________
   En son ne zaman alkol tükettiniz: ____________________

8. Kahve tüketiyor musunuz? ( ) Evet ( ) Hayır
   (Cevabınız Evet ise)
   Günde ortalama kaç bardak kahve içiyorsunuz: _________
   En son ne zaman kahve tükettiniz: ___________



9. En son kaç saat önce yemek yediniz?: ______ Kendinizi aç hissediyor musunuz?: ____

10. Herhangi bir görme probleminiz var mı? ( ) Evet ( ) Hayır
    Cevabınız Evet ise bilirtiniz ________________________

11. Gözlük ya da lens kullanıyor musunuz? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________

12. Son 6 ay içerisinde uyuşturucu madde kullandınız mı? ( ) Evet ( ) Hayır

13. Daha önce herhangi bir öğrenme güçlüğü tanısı aldınız mı? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________

14. Daha önce hiç kafa travması ya da biliç kaybı yaşadınız mı? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________

15. Herhangi bir kronik hastalığınız var mı? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________/

16. Daha önce herhangi bir psikolojik/psikiyatrik hastalık tanısı aldınız mı? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________

17. Herhangi bir ilaç kullanıyor musunuz? ( ) Evet ( ) Hayır
    Cevabınız Evet ise bilirtiniz ilaç adı: __________________

18. Herhangi bir merkezi sinir sistemi hastalığınız var mı? ( ) Evet ( ) Hayır
    *Cevabınız Evet ise bilirtiniz*________________________