Design, Implementation and Evaluation of P300-Based Brain-Computer Interface Speller and Lie Detector

by

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A Thesis submitted to the Faculty of Graduate Studies of

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Department of Electrical and Computer Engineering

University of Manitoba

Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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Abstract

In this study, we designed, implemented and evaluated two P300-based Brain-Computer Interface applications; P300-based speller and P300-based lie detector. These applications are completely non-invasive and do not require any complex training. The main objective of the P300-based speller is to spell characters via the brain. The most well-known P300-based speller was designed by Donchin and Farwell. It is believed that the accuracy of their paradigm is affected by several perceptual phenomena as the main source of errors. To develop a better P300 speller, we formulated and implemented a proposed speller paradigm by reducing the influence of these phenomena and considering P300 characteristics. Using ten different subjects who voluntarily participated in, a number of experiments were conducted to confirm the better performance of the designed paradigm. In this study, we also designed new paradigms to simulate the P300-based lie detector as much as feasible. However, our results were neither a confirmation nor a refutation of this application. We only proved that the reliability of the P300-based lie detector extremely depends on the choice of the stimuli.

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Nomenclature of Chapter 1

V_m: The voltage of a neuron cell	Page 2
φ_i: Potential of inner surface of a neuron cell	2
φ_o: Potential of outer surface of a neuron cell	2
EEG: Electroencephalogram (or brainwaves or brain signal)	2
Hz: The SI base unit of frequency	3, 4
REM: Rapid Eye Movement	3
ERP: Event Related Potential (brain reaction following presentation of a stimulus)	8
*N400:*ERP response to unexpected linguistic stimuli	8
P300: ERP response to unexpected stimuli	8
ISI: Inter-Stimulus Interval (time interval between two sequent stimuli)	13
TTI: Target-to-Target Interval (time interval between two sequent targets)	13
NSL: Non-target Sequence Length	13
RSVP: Rapid Serial Visual Presentation	15
AB: Attentional Blink (confusion between the target and subsequent target)	15
RB: Repetition blindness (failure in detection of repeated stimulus)	16
IC: Illusory conjunction (a stimulus perceived as having features of another one)	16
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BCI: Brain Computer Interface	19
DF paradigm: A speller paradigm designed by Donchin and Farwell	21

Chapter 1 Introduction

1.1. Brain Signal

In this section, we mainly focus on the brain signal and its behavior. However, prior to discuss brain activities it would be more appropriate to start with some definitions about the human body's communication system from the physiological point of view.

In the human body, nervous system is responsible for controlling and coordinating crucial organs activities by gathering information from the inside and outside of the body, carrying the collected data to the brain and spinal cord, processing them, and sending them back to the organs as a response. The nervous system is mainly composed of two types of cells: Glia and Neuron or nerve cells. Glias provide support and protection for neurons whereas neurons' job is to process and transmit information. Neurons as well as muscle cells are excitable, i.e. they can produce electrochemical impulses and conduct them. In fact, neurons are electrically active cells and the core components of the brain. The voltage V_m of an excitable cell is defined as (φ_i -φ_o) where φ_i and φ_o are the potential at the inner and outer surface of the cell respectively [1]. This definition is completely independent of the source of the potential and whether the voltage is constant, periodic, or non-periodic [1]. This electrical activity of neurons can be recorded and measured using an electronic conductor called "electrode". Electrical activity of the brain could be measured by placing electrodes on the surface of the scalp. The result will be an electrical signal called "Electroencephalogram" or "EEG". EEG is also referred as brainwaves or brain signal and usually is described in terms of frequency bands. There are four major types of EEG activity: Alpha, Beta, Theta and Delta (Table 1.1).

Activity type	*Frequency range*
Delta	Up to 4 Hz
Theta	4 to 8 Hz
Alpha	8 to 12 Hz
Beta	Above 12 Hz

Table 1.1. EEG activities' frequency range

EEG activities are continuous rhythmic sinusoidal varying in specific rang of frequency (Fig. 1.1).

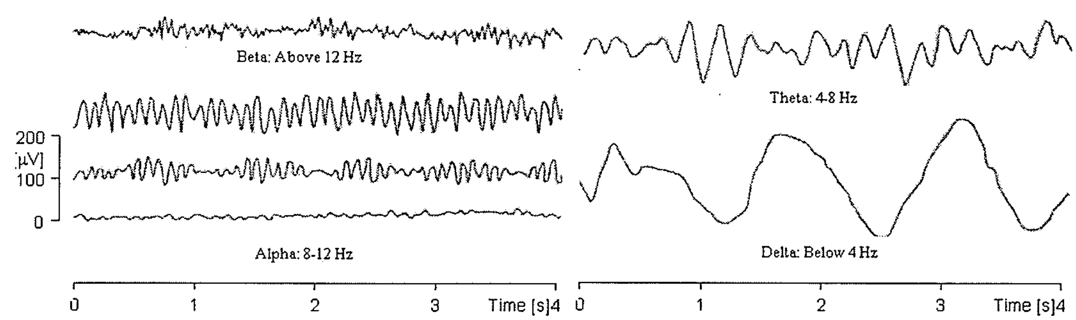

Fig. 1.1. Different EEG activities [1]

Delta wave is the frequency range up to 4 Hz and is associated with deep sleep and reflects an unconscious mind. High amplitude and low frequency is two characteristics of the delta waves. Theta wave is the frequency range from 4 Hz to 8 Hz and reflects the state between wakefulness and sleep which can be seen during some hypnagogic states such as light sleep and hypnosis and also in connection with emotional feeling, creativity and daydreaming. Alpha wave is the frequency range from 8 Hz to 12 Hz and is associated with a relaxed alert state of consciousness. Alpha rhythms are best detected with the eyes closed. Beta wave is the frequency range above 12 Hz with low amplitude which is often correlated with judgment, decision making, anxious thinking and active concentration. Consequently, the EEG is related to the level of consciousness. The more the activity, the higher the frequency and the lower the amplitude. Fig. 1.2 demonstrates the EEG activities during different phase of sleep. Note that "Rapid Eye Movement" or "REM" is a certain phase of sleep that person dreams. In this phase subject has active movement of the eyes. In addition, the brain activities stop completely and irreversibly when "Cerebral death" is occurred.

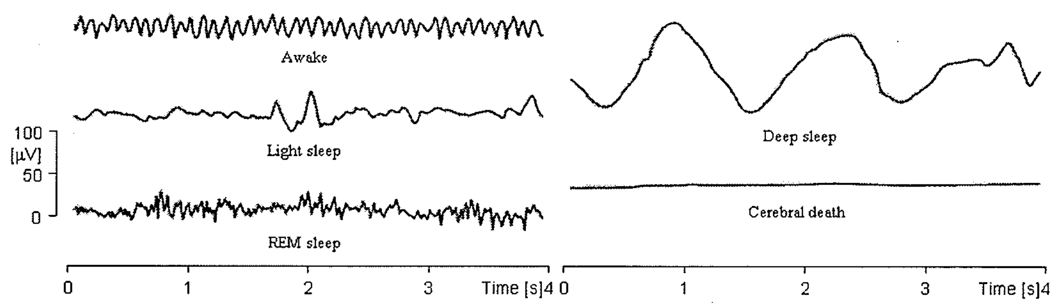

Fig. 1.2. EEG activity during different phase of sleep [1]

As it was mentioned, EEG is the measurement of the brain's electrical activity using number of electrodes. If electrodes are placed on the scalp, the signal is called surface EEG which is considered in this study. For reducing the impedance and precise measurement, a conductive gel is usually applied over the area under the electrodes.

The location of each electrode is determined by a widely used method called the 10-20 system [2]. This system is called 10-20 due to the fact that the distances between adjacent electrodes are either 10% or 20% of the entire distance from front to back or from right to left of the skull [2] (Fig. 1.3 and Fig. 1.4). Two reference nodes are required for locating these points on the scalp: *Nasion,* which is the intersection of the frontal and two nasal bones of the human skull, the area between the eyes, just superior to the bridge of the nose; and *Inion*, which is the most prominent projection of the occipital bone at the lower rear part of the skull.

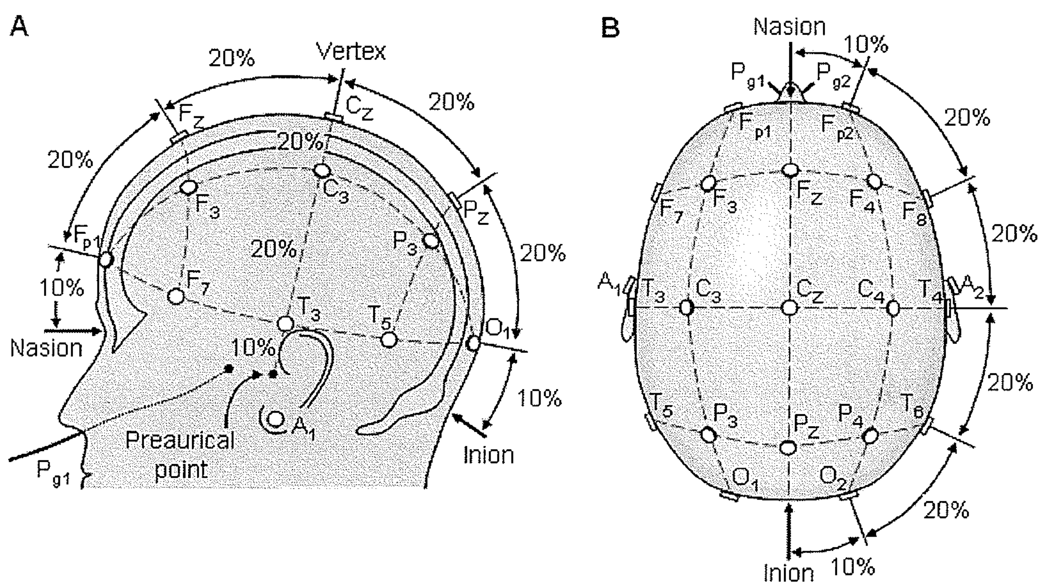

Fig. 1.3. Side view (A) and top view (B) of 10-20 system electrodes' location [1]

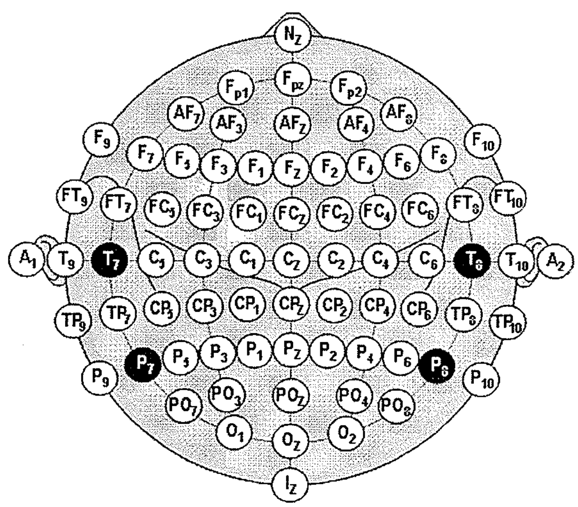

Fig. 1.4. Location of electrodes without considering the actual distances [1]

Furthermore, each electrode is connected to a differential amplifier. Each differential amplifier is designated to the two electrodes and amplifies the voltage between them. The amplitude of the output voltage is normally about 1000 to 100000 times more than the input. Note that the amplitude of the EEG is about 10 μV to 100 μV when measured on the scalp [3], and is about 1-2 mV when measured from implanted electrodes [1]. After amplification and filtering the result will be displayed on a computer screen. The electrodes' configuration could be one of the following montages: "Common Reference", "Average Reference", "Bipolar" and "Laplacian" [4].

In common reference derivation reference electrode is the one that typically placed somewhere along the scalp midline. It could also be attached to the mastoids area or even to the earlobes or noise tip. In this composition, first input of amplifiers is connected to the different recording electrodes and second one is hooked up to the reference electrode [4]. Fig. 1.5 illustrates how the voltage of one channel (Pz) is measured in common reference derivation.

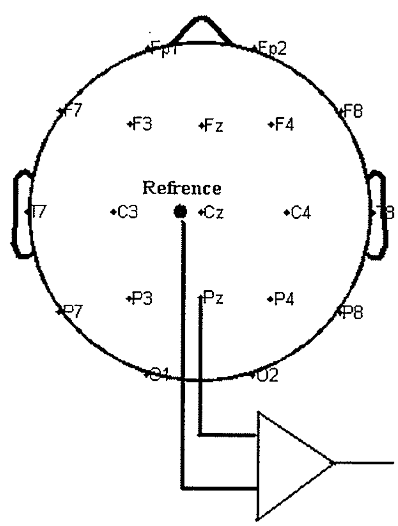

Fig. 1.5. Measuring the potential of Pz in Common reference derivation

In common reference derivation, in case if the reference node is replaced by the mean potential of all electrodes, it is a new composition called "Average Reference Derivation" or "Common Average Reference Derivation". Note that for finding the average value, most of the EEG systems let us to select desired electrodes.

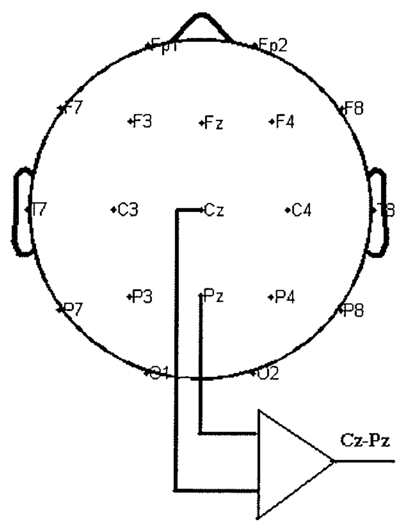

Fig. 1.6. Measuring the difference potential between Cz and Pz in Bipolar derivation

Moreover, if the number of available channels is limited "Bipolar Derivation" (Fig. 1.6 – 1.7) is being used for better demonstration of EEG activities. In this method the electrodes are connected in series to an equivalent number of amplifiers. Each amplifier measures the potential difference between a pair of electrodes. For example, amplifier *"A"* measures the difference between channels *1* and *2*; amplifier *"B"* measures the difference between channels *2* and *3* and so on. Fig. 1.7 illustrates the "Unipolar" (common/average reference) and "Bipolar" measurements.

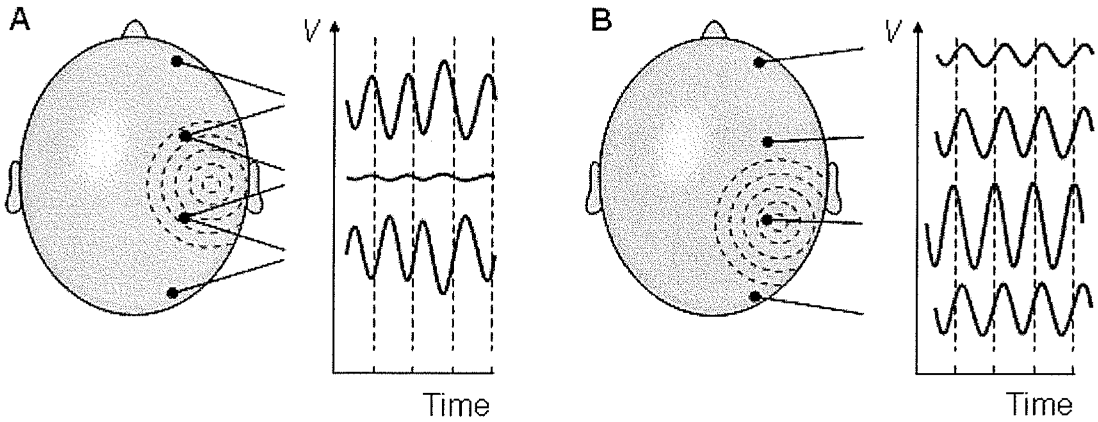

Fig. 1.7. (A) Bipolar and (B) Unipolar measurements [1]

In Laplacian montage, the difference between an electrode and a weighted average of the surrounding electrodes is being used.

1.2. Event Related Potential and P300

The brain response to an internal or external stimulus is called Event Related Potential (ERP) which is the brain reaction following presentation of a stimulus. ERPs are detectable and measurable using EEG signal. However, their detection requires several signal processing steps because they are not usually visible in the EEG signal. Their amplitude tends to be low and varies from less than one microvolt to several micro-volts. There are some different types of ERPs elicited by various types of stimuli. Two well-known ERP responses are N400 and P300; N400 is a response to unexpected linguistic stimuli [1] and the most essential ERP response - known as P300 or simply P3 (Fig. 1.8) - is elicited by unexpected stimulus [6]. In fact, it is believed that the "P300 is involved with the process of memory modification or learning and things appear to be learned if, and only if, they are surprising" [7].

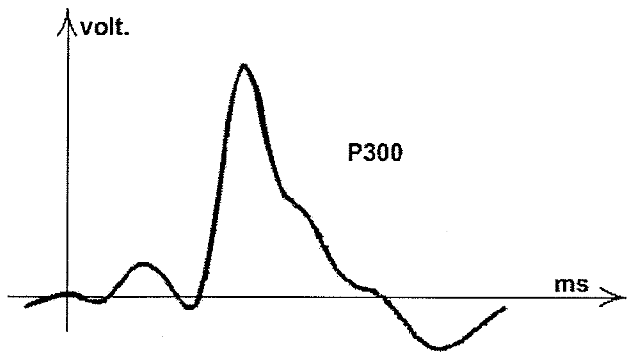

Fig. 1.8. The P300 wave

The P300 is a positive peak about 300 ms extracted from 'oddball paradigm'. In an oddball paradigm the subject is typically presented with a sequence of events that can be categorized into two classes such that one of them is rarely presented [8]. From the subject's point of view, these infrequent stimuli, somehow, are meaningful and surprising. Hence, their appearance will elicit ERP responses characterized by a P300 component. This paradigm can be a series of standard stimuli such as letters, pictures, sounds or symbols. These stimuli, however, can be auditory (e.g. sounds) or visual (e.g. pictures) and so their responses are called auditory P300 and visual P300 respectively.

It has been reported in many articles that P300 could be an assessment in recognition of some diseases such as Alzheimer's [9], [11], Parkinson's [12], Depression [13] and Schizophrenia [14].

1.3. P300 Amplitude and Latency

The P300 is evaluated by measuring its amplitude and latency (Fig. 1.9). Amplitude is defined as the voltage difference between a baseline and the largest positive peak of the ERP waveform within a window called latency. Latency is defined as the time from stimulus onset to the point of maximum positive amplitude in millisecond [9].

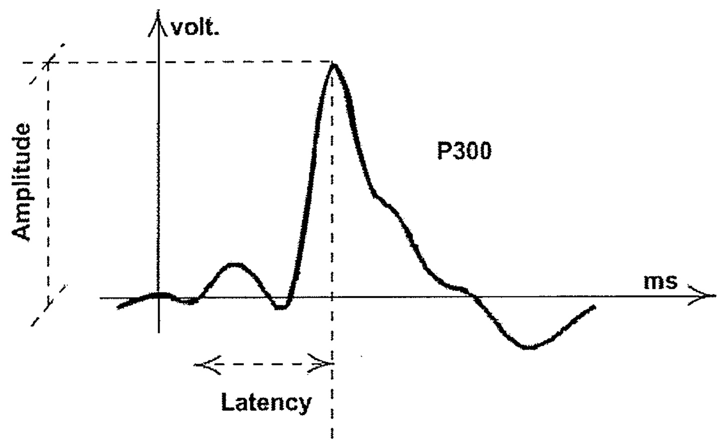

Fig. 1.9. P300 amplitude and latency

From the neurological point of view, there is a direct relationship between P300 amplitude and the amount of attentional resources devoted to a given task [10]. P300 latency, on the other hand, shows the processing time required before a response is generated; therefore, as it's also supported by results, P300 latency increases as cognitive capability decreases [45]. Regular P300 amplitude is about 5~15 μV and its latency is about 250~500 ms [45]. However, significant portion of regular P300 variation is caused by factors associated with the subject's level of "physiologic state" (Table 1.2) regardless of the fact that dissimilarity of P300 amplitude/latency can be decreased by maintaining the identical recording conditions for all subjects [15]. P300 inconsistency within and between subjects can be diminished by lessening the effect of these factors. Therefore, its measurement sensitivity can be increased significantly [16].

It is quite interesting to know the P300 amplitude and latency could be also affected by several non-neurological phenomena such as probability of target stimulus, inter-stimulus interval, habituation, attentional blink, repetition blindness and so forth. In the following sections, it has been tried to explain those ones that we should bear them in mind during designing P300 applications.

Factor	Amplitude	Latency	Comment
Natural			
Circadian:	Indirect	Indirect	Circadian body changes affect P300 measures
Body temperature	No	Yes	Increased temperature decreased latency
Heart rate	No	Yes	Faster heart rate, decreased latency
Food intake	Yes	Some	Amplitude increases, latency shorter
Activity time	Yes	Some	Food interacts with activity preference time
Ultradian	Some	Yes	90-min latency cycles
Seasonal	Yes	No	Seasons with light, increased amplitude
Menstrual	No	No	Neutral stimuli; no effects
Induces			
Exercise:	Indirect	Direct	Affects overall arousal level
Tonic	Yes	Yes	Increases amplitude, decreases latency
Chronic	No	Yes	Decreased latency; variable results across studies
Fatigue	Yes	Yes	Decreased amplitude, increased latency
Drugs (Common)	Yes	Yes	Specific drug, arousal level. Tonic/chronic use
Caffeine	Some	Yes	Amplitude increases if subject is fatigues; latency decreases
Nicotine	Small	Yes	Weak amplitude effects; latency decreases
Alcohol:			
Acute	Yes	Yes	Amplitude decreases, latency increases
Chronic	No	No	Social drinking; No parameters important
Alcoholism risk	Yes	No	At risk: Smaller amplitudes with visual tasks
Constitutional			
Age:	Yes	Yes	Modality, task, response parameters important
Children	Yes	Yes	Amplitude increases, latency decreases
Adults	Yes	Yes	Amplitude decreases, latency increases
Intelligence	Yes	Yes	Amplitude from complex tasks smaller for more intelligent,
Handedness	Yes	Yes	Amplitude: L > R for frontocentral sites, latency: L < R for
Sex	Small	Small	Amplitude: F > M, latency F < M
Personality	Yes	No	Amplitude: Introverts < extroverts
Genetic	Yes	Yes	Amplitude and latency genetically determined

Table 1.2. P300 amplitude and latency biologic determinants [16]

1.3.1. Probability of Target Stimulus

The most essential factor influences the P300 amplitude is the probability with which a stimulus is presented. The relationship between them is fairly straight forward: the more frequently the stimulus is presented, the smaller the amplitude and vice versa [17], [40]. In 1990, John Polich reviewed the relationship between target stimulus probability and inter-stimulus interval on the P300 (Fig. 1.10) [19]. He stated that "P300 amplitude decreased with increases in target stimulus probability for inter-stimulus intervals ranging from 2.0-3.0 seconds (short interval between stimuli), but exhibited no difference for longer inter-stimulus intervals of about 4.0-10.0 seconds (long interval between stimuli)". As a result, when the time between stimuli in our presentation is relatively short, P300 amplitude could be influenced by the probability of stimuli in such a way that just has been explained.

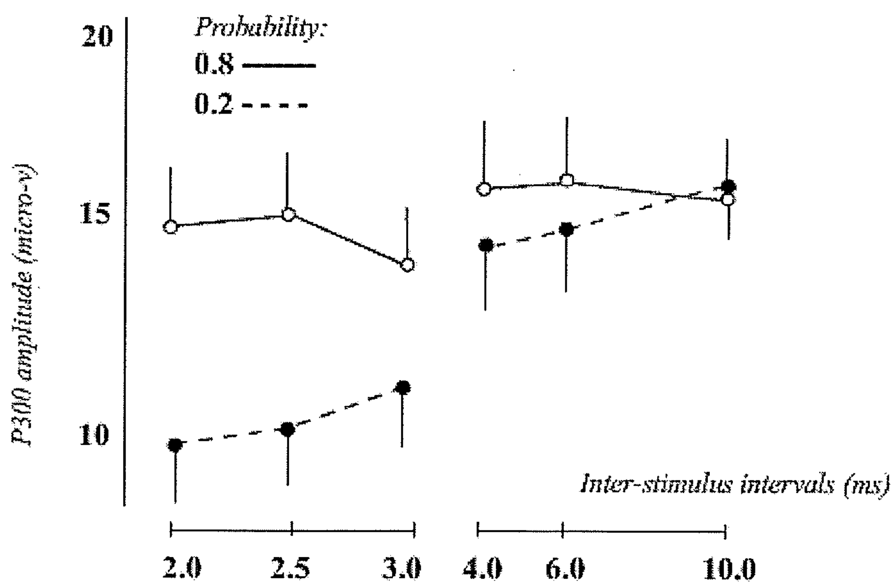

Fig. 1.10. The relationship between probability and inter-stimulus interval [19]

1.3.2. Time Intervals

Even though stimulus probability is an important determinant of P300, time intervals between stimulus events are also the big issue in P300-based systems. For instance the time interval between two sequent stimuli or "Inter-Stimulus Interval" (ISI) and the time interval between two sequent targets or "Target-to-Target Interval" (TTI) are very crucial in designing the P300-based applications. P300 amplitude also can be influenced by "Non-target Sequence Length" (NSL). These three properties, i.e. ISI, TTI and NSL, have been discussed in many articles [18], [19], and [20]. It has been claimed that long ISI (but not very long) gives the system enough time to recover from very recent ERP production [18], [19]. On the other hand, very long ISI (6 sec or longer) wanes the effect of target stimulus probability on P300 amplitude [19]. He also has reported that increases in ISI (as long as it's less than 6 sec) produce reliable increases in P300 amplitude [18]. As seen in Fig. 1.11, 4-sec ISI shows better results compare to 2-sec and 1-sec.

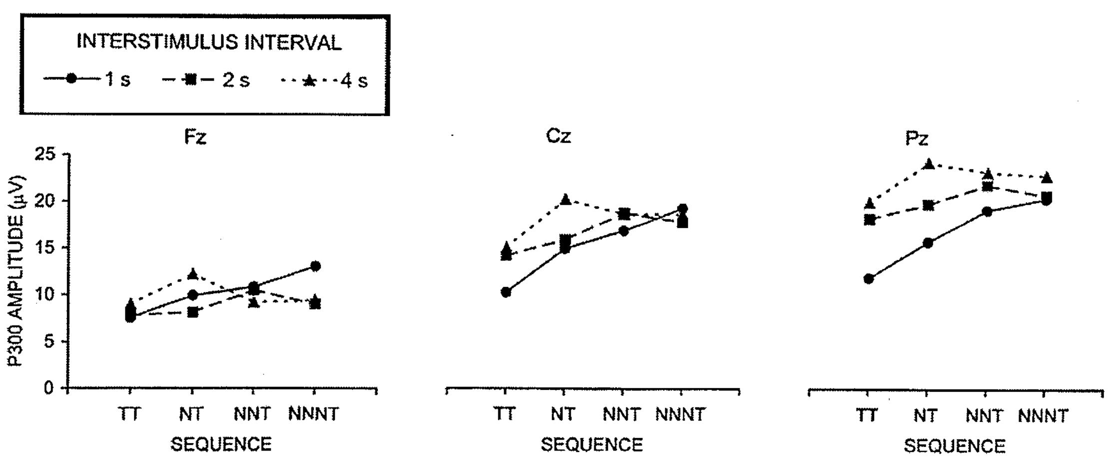

Fig. 1.11. P3 amplitude as a function of stimulus (N = Non-target, T = Target) [18]

Increasing the ISI, however, may increase the TTI as well. Polich has proved that P300 amplitude is curvilinearly related to TTI [18]. Increasing the TTI up to 6-8 sec boosts the P300 amplitude but further increases have no effect (Fig. 1.12).

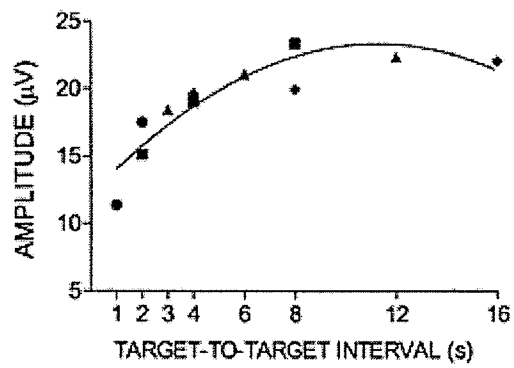

Fig. 1.12. P3 amplitude as a function of TTI for each stimulus [18]

In addition, P300 latency could be affected by NSL. Increasing the NSL demonstrates a consistent decrease in P300 latency [18].

1.3.3. Habituation and Novelty

Habituation, in psychology, is referred to a "decrease in the strength of a behavioral response occurs when an initially novel eliciting stimulus is repeatedly presented" [19]. In fact, habituation is caused by repetition of a stimulus and reduces the behavioral response probability progressively. In 1993, Ivey and Schmidt showed that repetition of stimulation decreases P300 amplitude logarithmically [21]. Fig. 1.13 clearly shows how P300 amplitude and latency change in response to visual stimuli at three different scalp recording sites. P300 amplitude decreased across trial blocks especially at Fz and Cz electrode sites [22]. However, P300 latency did not change with trial block.

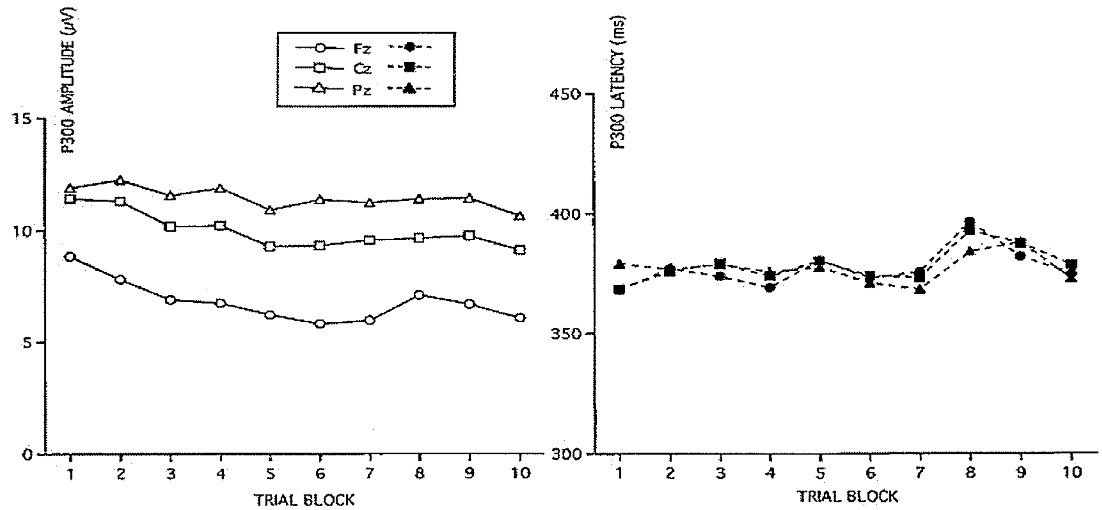

Fig. 1.13. P300 amplitude and latency from each electrode as a function of the trial block [22]

Polich et al. proved that the visual stimulus P300 amplitude habituates within the active oddball task, but only when short inter-block-intervals (time duration between each two blocks) and many trial blocks are used [22].

1.3.4. Psychological Phenomena

The Rapid Serial Visual Presentation (*RSVP*) is a technique of presenting stimuli such that each stimulus is displayed for a short time in sequential order. In this presentation, attentional blink (*AB*) and repetition blindness (*RB*) may impair the tracking process if the subject is supposed to follow the target stimulus. These psychological phenomena may happen in P300-based application where, in most cases, the users are asked to follow one type of stimuli as the target. Consequently, either the system doesn't spot the P300 or detects it in response to the wrong stimulus.

In an RSVP series, AB is produced by perceptual confusion between the target (T1) and subsequent target (T2) if the time interval is less than 500 ms [23]; therefore the subject may not be able to identify the second target. Moreover, RB is failure in detection of repeated stimulus (letter, digit, color [24] or picture [26]) in an RSVP. Illusory conjunction (*IC*) is another possible issue in response to an RSVP task. It potentially can evoke a pseudo-P300. IC may happen if between two stimuli with different features one of them perceived as having one or more features of the other one [25].

1.4. P300 Scalp Topography

P300 scalp distribution is the change in P300 amplitude across the midline recording sites (Fz, Cz and Pz) [27]. As it is shown in Fig. 1.14 and 1.15, the P300 response to the both auditory and visual modalities increases from frontal lobe toward parietal region and achieves its maximum value at Pz. It eventually decreases at the occipital recording sites [28]. However, it's believed that the P300 scalp distributions in auditory and visual modalities are similar to a certain extent.

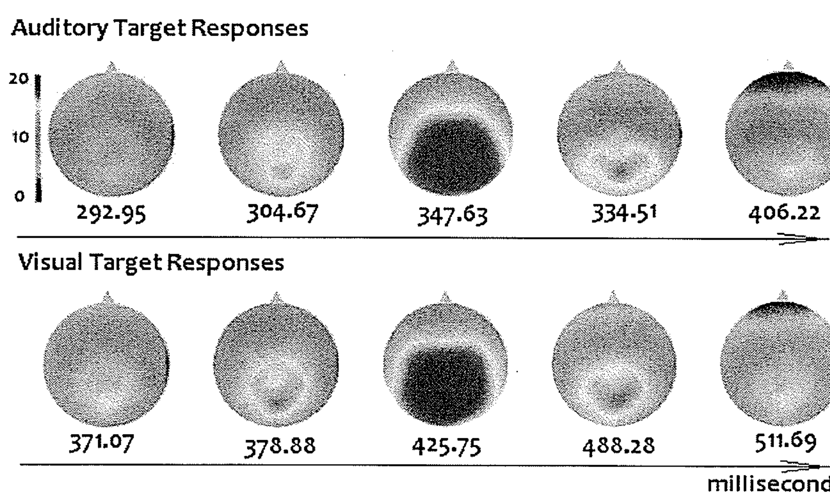

Fig. 1.14. Scalp distribution at five points after P300 elicitation. (Top: Auditory, Bottom: Visual) [28]

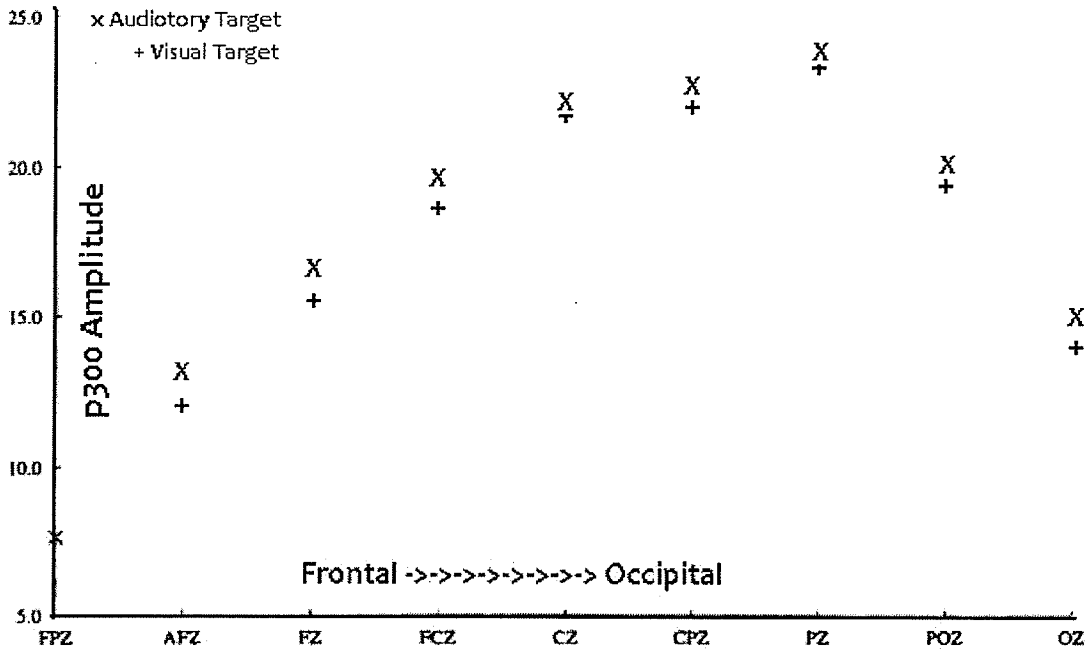

Fig. 1.15. Scalp distribution from frontal channels to occipital (Auditory and visual) [28]

1.5. P3a and P3b

In the typical P300-based experiments three different types of paradigms are being used; 1) single-stimulus, 2) oddball, and 3) three-stimulus paradigm. The single-stimulus paradigm includes one type of stimuli called target (Fig. 1.16., A). In a typical oddball paradigm, the subject is normally presented with target and standard (or irrelevant) stimuli (Fig. 1.16., B). The three-stimulus paradigm consists of target, standard and distracter (Fig. 1.16., C). Distracters are also referred as probes or novels.

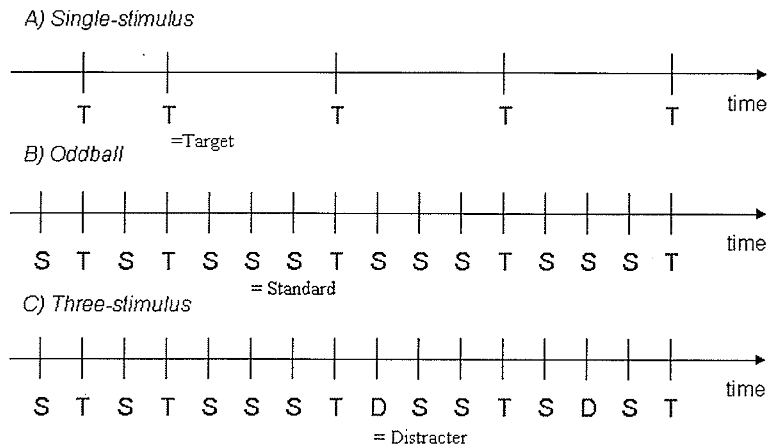

Fig. 1.16. Different types of paradigms: A: Single-stimulus, B: Oddball, C: three-stimulus

Novel stimuli in a three-stimulus paradigm are presented infrequently and produce a P300 component that is large over the frontal/central area and is different from the typical parietal maximum P300 (Fig. 1.18) [29]. This 'novelty' P300 is called the P3a which is totally different from the P300 in response to the target stimulus (P3b) (Fig. 1.17). Furthermore, P3a's peak is bifurcated (Fig. 1.17) with shorter latency compare to P3b (Fig. 1.18). It also habituates relatively faster [29].

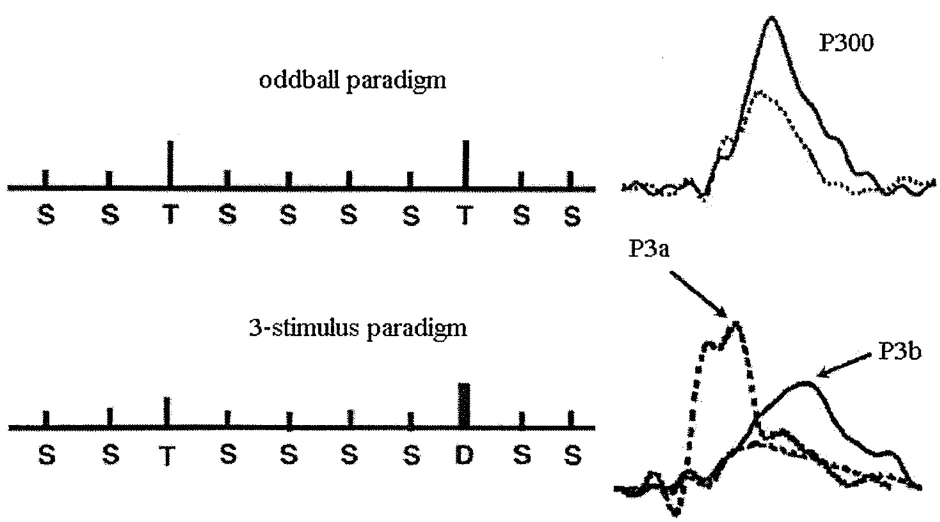

Fig. 1.17. P300 responses in an Oddball and a three-stimulus paradigm [30]

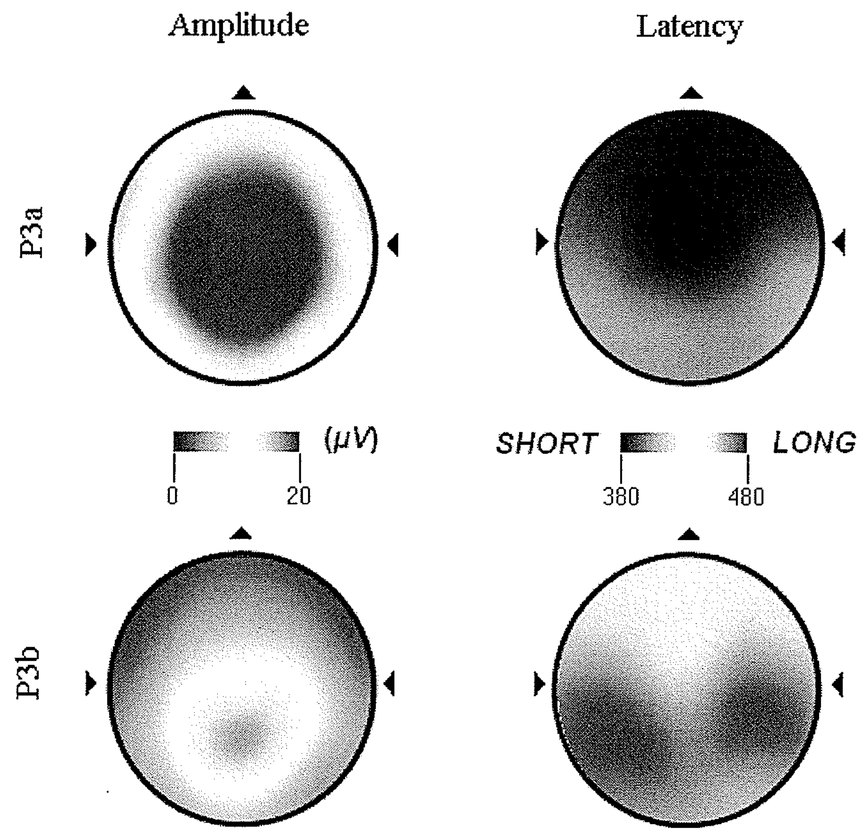

Fig. 1.18. Amplitude and latency of P3a and P3b in a three-stimulus paradigm [31]

1.6. Brain Computer Interface

A Brain Computer Interface (BCI) allows a user to communicate with the external world by creating a direct channel between a brain and computer [32]. In BCI, users can send the commands without using their muscles or brain's normal output pathways of peripheral nerves [32]. There are some different BCIs based on the electrophysiological signals: slow cortical potentials, P300, mu and beta rhythms, and cortical neuronal action potentials [32]. In the following section we discuss some of the BCIs based on P300.

1.7. P300 Applications

In this section, two different P300 applications are discussed; P300-based speller paradigms and P300-based lie detector. P300-based speller paradigm has been designed for physically disabled people to input a text document into computer. Moreover, P300-based lie detector is another P300 application in criminal investigations. Even though it has been claimed that this system is absolutely reliable but our results show it needs more investigation to be accurately developed.

1.7.1. Speller Paradigms

Falling on the neck or back, or any other movement of the spinal cord can result in spinal cord injury which is a disturbance of the spinal cord. Typically, the people who become spinal cord injured will loss of feeling in certain parts of their body. In good cases a victim might only suffer loss of hand or foot function; however, it is possible to be full body paralysis. Refer to the National Spinal Cord Injury Association (NSCI) approximately 250,000 – 400,000 individuals in the United States have spinal cord injuries. The people who endure from this type of disability have difficulties to communicate and need a real-time method to express their wishes in an efficient mode. It is possible using BCI systems such as brain-based word processors. Since they cannot move some parts or whole of their body, these systems are practical if they do not require any corporal activity or physical reaction from the patient. In addition of spinal cord, BCI can help people suffer from Cerebral palsy, Muscular Dystrophy, Multiple Sclerosis (MS), Spina Bifida, Amyotrophic Lateral Sclerosis (ALS), Essential tremor (ET) and so on. BCI is a good candidate to improve the quality of life of these types of patients since there is no body movement involved.

As it was mentioned in section 1.2., the P300 is believed to be elicited by an unexpected stimulus in an oddball paradigm when the subject is dynamically engaged in the task of detecting the "target" among a stream of standard stimuli. In 1988, Lawrence A. Farwell and Emanuel Donchin employed this unique feature of P300 and designed an oddball paradigm known as Donchin-Farwell speller paradigm or DF paradigm. Their speller made it possible to type letters and numbers using the brain signal.

1.7.1.1. Donchin – Farwell paradigm

Donchin and Farwell (DF) speller paradigm is a 6×6 matrix of letters and numbers [33] (Fig. 1.19) which has been a benchmark in P300-based BCI systems since past several years.

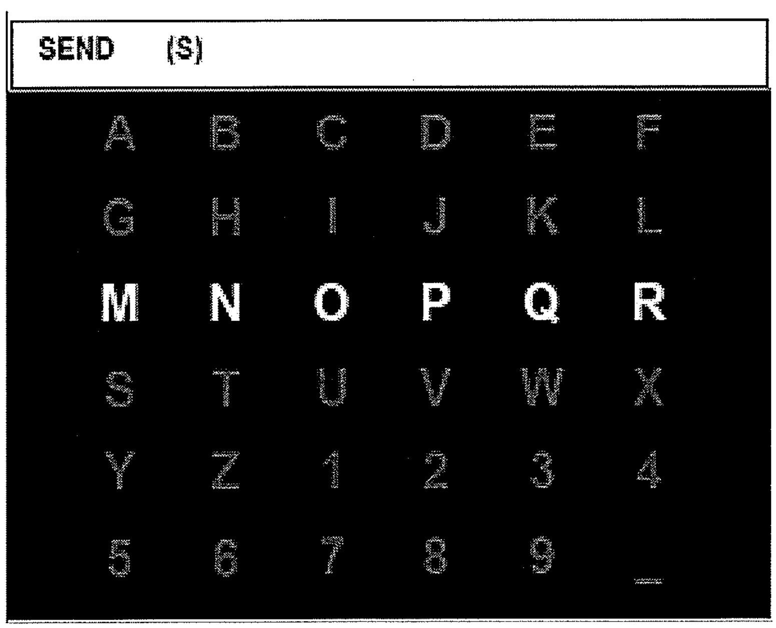

Fig. 1.19. Donchin-Farwell paradigm: 6x6 matrix of characters

In this method, among all of the letters and numbers, the subject is asked to get focused on the desired character. Meanwhile, all rows and columns are intensified randomly at very high speed (180 times in total: 100ms intensification of one row/column and 75ms blank time (i.e. same color for all rows and columns)) (Fig. 1.20). Two out of twelve intensifications will contain the desired character (one particular row and one particular column). Thus, we expect two P300 responses after twelve intensifications [33]. Furthermore, desired character will be detected by considering the time of P300 elicitation and comparing with original pattern and classification.

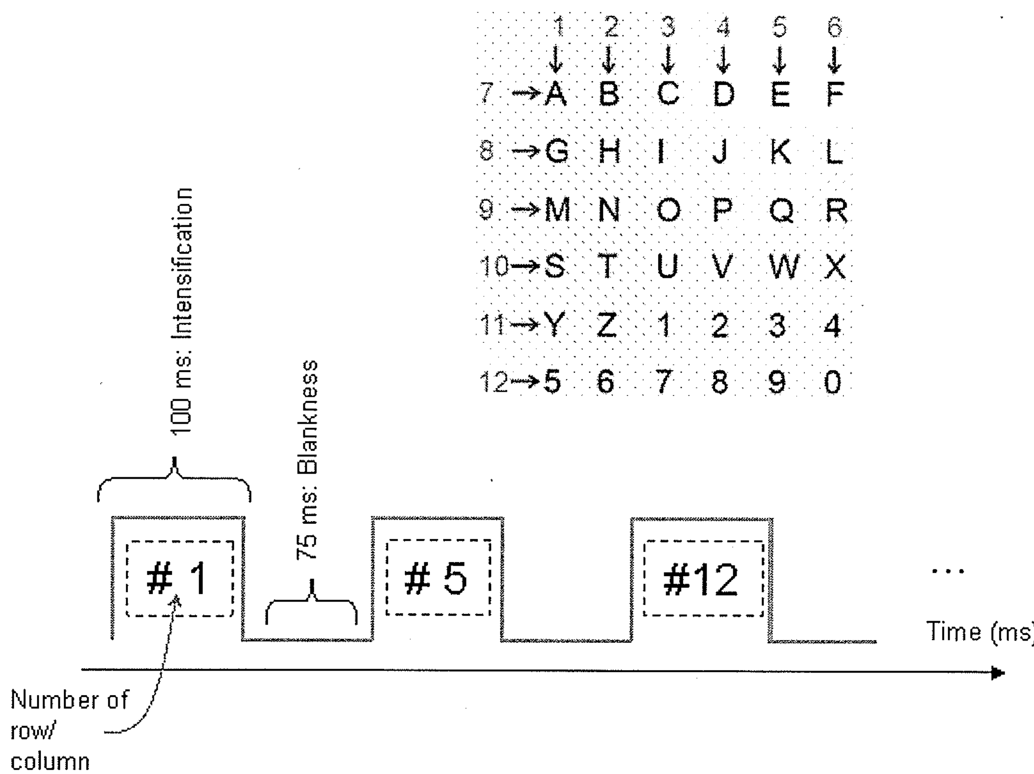

Fig. 1.20. Donchin-Farwell paradigm, an example of matrix intensification pattern

1.7.2. Lie Detectors

The fact that telling a lie has some physical side-effects has been considered to detect the liar for a long time. The best known device uses this phenomenon is "polygraph". A polygraph is a combination of medical devices used to measure and record several body activities such as blood pressure, heart rate, respiration and skin conductivity during a question-answer interview. After the experiment, the examiner compares the measured values with expected normal values to indicate the level of subject's honesty. Even though it has been claimed by "American Polygraph Association" that polygraph examination is a scientific test, there are some logical reasons illustrate its unreliability. For instance, what if the subjects show anxiety for some other reasons than lying or what if they somehow trained to beat the test by controlling their anxiety and produces no noticeable clue. Consequently, the polygraph test result is not always reliable and acceptable legally. For example, polygraphs are not considered reliable evidence in Canada, Europe and Australia. For this reason, during the past decade some new technologies have been studied and developed to bring the lie detection beyond the polygraph.

1.7.2.1. P300-based Lie Detector

In 1993, Lawrence A. Farwell introduced a new technique based on brain electrical activities to spot a liar [41]. His invention was based on the fact that P300 is elicited when the subject is confronted with particular stimulus that he/she has prior knowledge of. Certain stimuli, such as a crime scene or specific gun's picture, produce P300 if they look familiar to the subject [42]. This stimulus could be a word, phrase, or picture [42]. He defined three different types of stimuli in his method: Irrelevant, Target and Probe. The subject is given a list of specific stimuli called 'Target' and instructed to perform a task which is pressing a particular button in response. 'Irrelevant' stimuli are not relevant while 'Probes' are related to the situation under investigation. Probes elicit P300 if the subject is knowledgeable. On the other hand, they have the same effect as the irrelevants for a subject who is not knowledgeable about the situation [41]. Fig. 1.21 shows the difference between guilty and innocent's ERP response. Clearly, user's response to the Probe is very similar to the Targets when he/she is guilty and is almost the same as the Irrelevants when he/she is innocent.

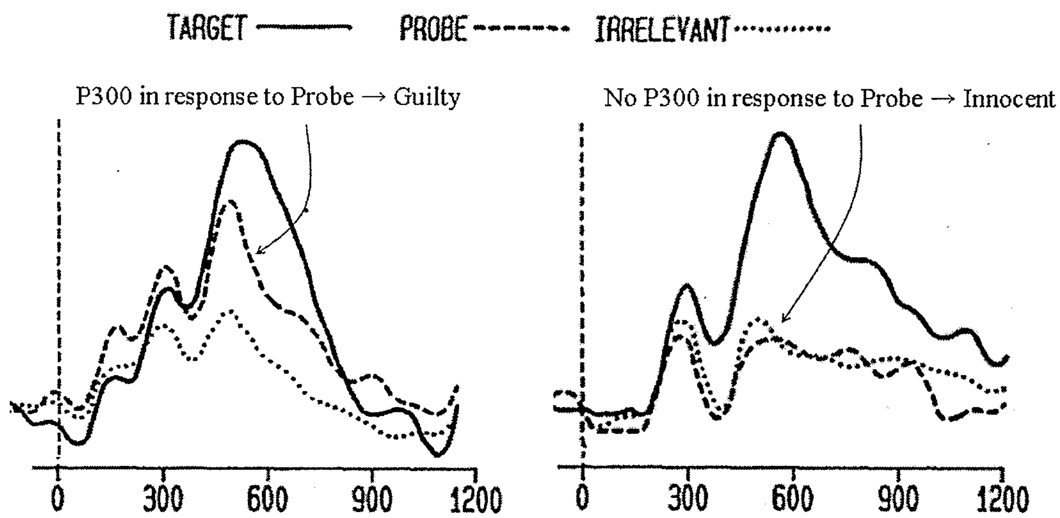

Fig. 1.21. ERP response of guilty (left) and innocent (right) subject [41]

In these figures, subjects generate P300 in response to the targets while irrelevants are neutral in both cases. Probe stimuli are the main key and evoke P300 if the subject is guilty and has the same effect as the irrelevant stimuli when the subject is innocent. Even though Farwell has claimed his technique is 100% accurate [42] it has never been subject to independent review.

1.7.3. Other applications

P300 could also be clinically useful. P300 amplitude and latency could be influenced by those brain disorders that affect the immediate memory such as Alzheimer's, HIV Dementia, Parkinson's, Supranuclear Palsy, Depression, Obsessive-Compulsive, Schizophrenia, Normal Aging, Dyslexia, Head Injury and Narcolepsy [43]. Patients of these types of illnesses may produce P300 with lower amplitude and/or longer latency [43].

Nomenclature of Chapter 2

Fz: An electrode channel placed on the middle line of the frontal lobe	Page 28
Cz: An electrode channel placed on the middle line of the central lobe	28
Pz: An electrode channel placed on the middle line of the parietal lobe	28
C3: An electrode channel placed on the left hemisphere of the central lobe	28
C4: An electrode channel placed on the right hemisphere of the central lobe	28
P: Probe stimuli	35
T: Target stimuli	35
I: Irrelevant stimuli	35
ICA: Independent Component Analysis	41
η: Summation of the signal values in 20ms interval around the peak	46

Chapter 2 Methods & Materials

The main focus of this chapter is to explain the experiments' design and implementation. In the following sections preparation processes including ethic approval and subject characteristics as well as experiment properties and procedures are described.

2.1. Experiment Design

2.1.1. Ethic Approval

An ethic approval was obtained in order to conduct experiments. Our protocol (#E2007:020) has received human ethics approval by the Education/Nursing Research Ethics Board, which is organized and operates according to the Tri-Council Policy Statement.

2.1.2. Subjects

Ten students (8 Males, 2 Females, Age range: 20-29) from University of Manitoba voluntarily participated in our experiments. Before each experiment the procedure was explained to the subjects and they signed the informed consent which was approved by the Education/Nursing Research Ethics Board. Subjects were seated on a chair in front of the screen and asked to be relaxed and avoid moving as much as possible during the experiments.

2.1.3. Data Acquisition

EEG activity was recorded across midline recording sites of *Fz*, *Cz* and *Pz* referenced to the left mastoid (Fig. 2.1) with a forehead ground using *Brain Products GmbH* EEG equipments. In lie detector application, data was collected through all of the above channels plus two more channels of *C3* and *C4* (Fig. 2.1). Electrodes' placement was based on the international 10-20 system (section 1.1). EEG data were sampled at 500 Hz and all impedances were kept below 10 kΩ.

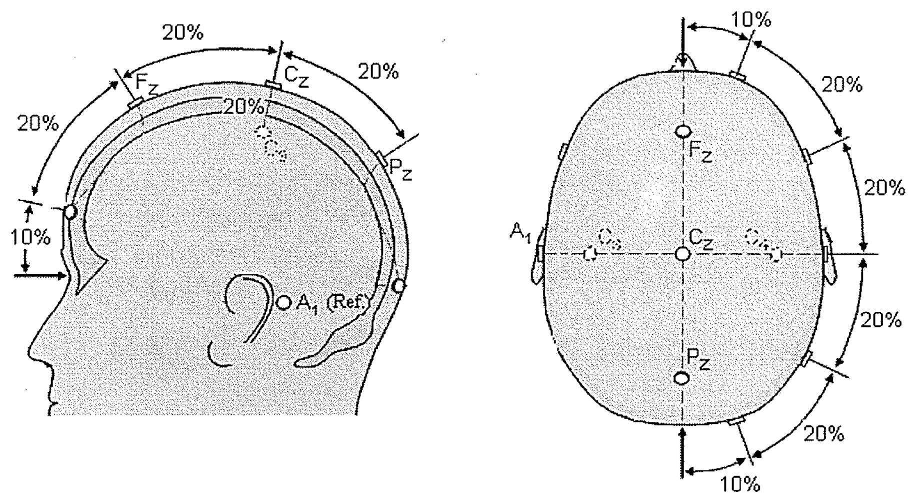

Fig. 2.1. EEG recording electrodes have been used in the experiments

2.1.4. Proposed Speller Paradigm

2.1.4.1. Objective

The paradigm designed by Donchin and Farwell (DF) has been a benchmark for the P300-based BCI and studied in the enormous number of articles [33]. On the other hand, some potential sources of errors have been observed in this paradigm [39]. Our motivation is to design a new P300 speller paradigm by considering the possible perceptual errors detected in the DF paradigm [35].

2.1.4.2. Paradigm Design

Unlike DF paradigm where characters are placed in rows and columns, in *7-region paradigm*, characters are split up into different groups and placed on different locations on the screen as you can see in Fig. 2.2 [35], [36]. In this paradigm, *Target group* means the set of characters which includes our target letter, number or symbol.

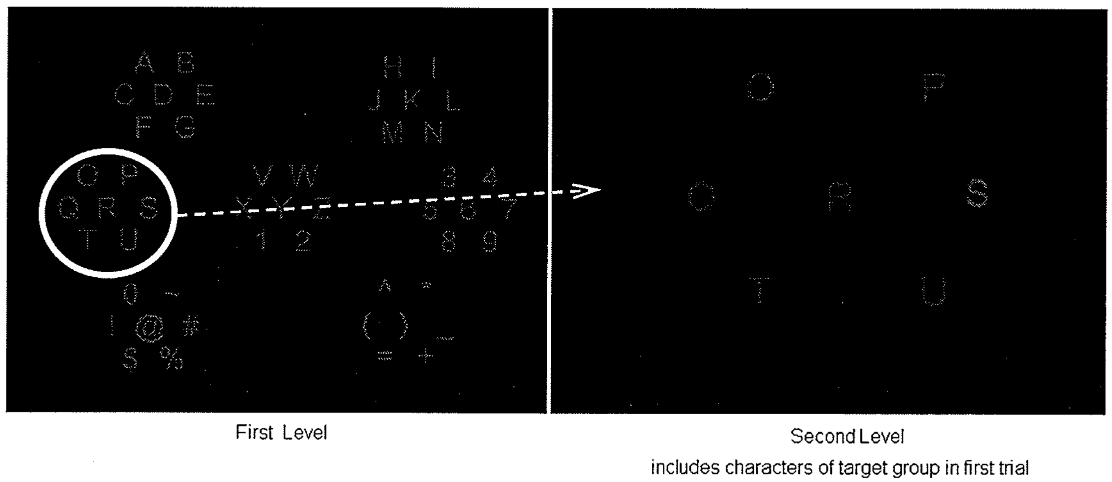

Fig. 2.2. First level for all possible characters and second level if the middle-left region is the target group

The whole experiment consists of $n\times2$ *levels* where n is the number of the target's character. Before each level begins, user has a few seconds to focus attention on the desired character. Thereafter, groups of characters *flash* in a random order similar to rows and columns in DF paradigm. Flashes are produced by changing the color of the characters from dark gray to white and from white back to dark gray. In an ideal case, these flashes must continue until the target being detected. In our case, however, the number of intensifications is limited to a specific value for every level. Same number of flashing has been used in this and DF paradigm for better comparison. Two levels are required for detecting one single character. During the first level all of the characters could be seen on the screen (Fig. 2.2). At the end of first level, the characters of the target group are broken apart into new seven regions such as each region presents one character (Fig. 2.2). Thereafter, second level starts in the same way of the first one and all characters flash randomly for a particular period of time. This time detection of the desired group is equal to detection of desired character.

Let's consider '*P*' as our target character. In the first level the target group is the one at the middle-left of the screen (Fig. 2.3). During the first level all of the groups are intensified in a random order.

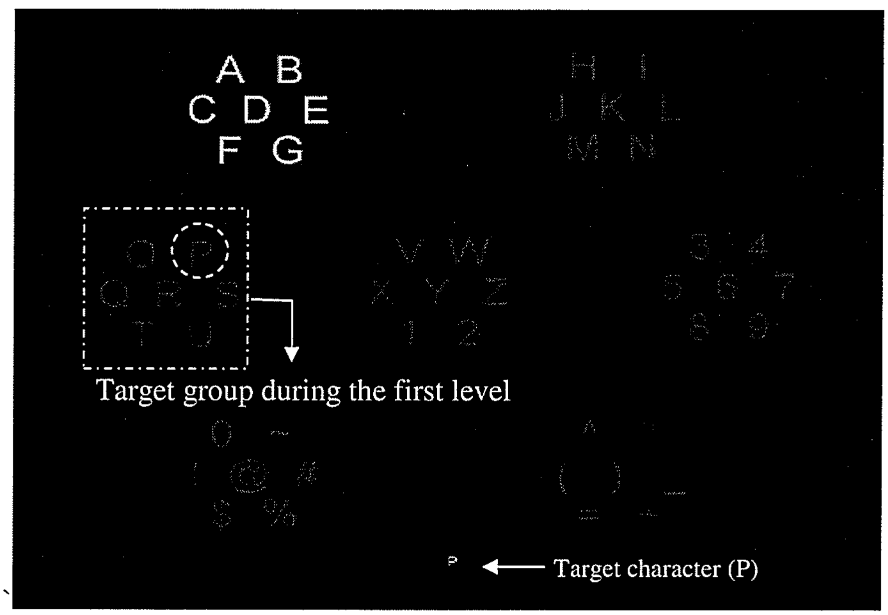

Fig. 2.3. Seven-Region Paradigm, Odd levels: 7 groups, each of them includes 7 characters

Subsequently, for the second level, each region will be replaced by one character from the target group (Fig. 2.4). In both levels, we expect a strong P300 wave at the moment that the target group flashes.

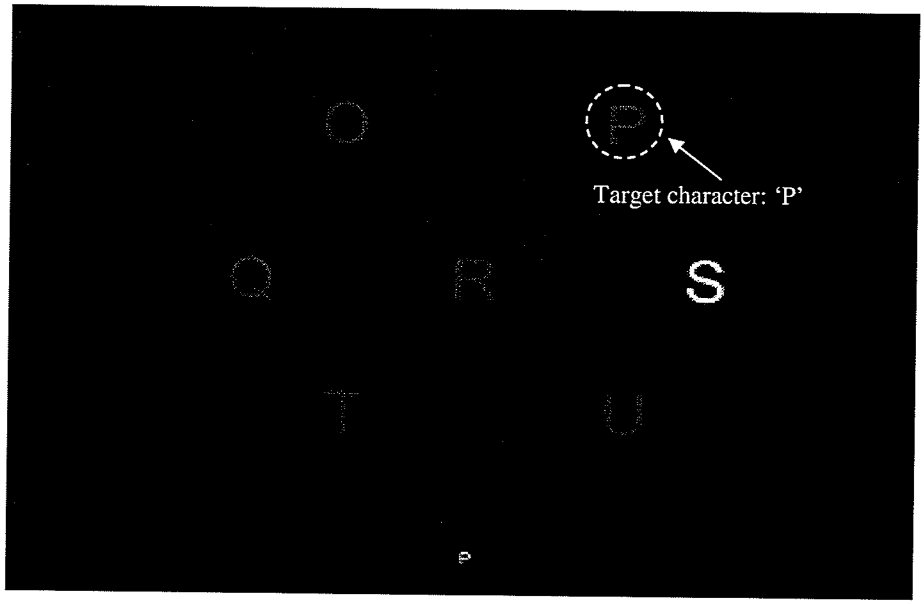

Fig. 2.4. Seven-Region Paradigm, even levels: 7 groups, each of them includes one character

In case of having more than one character as the target, this procedure repeats for $n \times 2$ levels where n is the number of the target's character. For instance, to spell the word '*P3A*', 6 levels are expected.

The procedure is illustrated in Fig. 2.5.

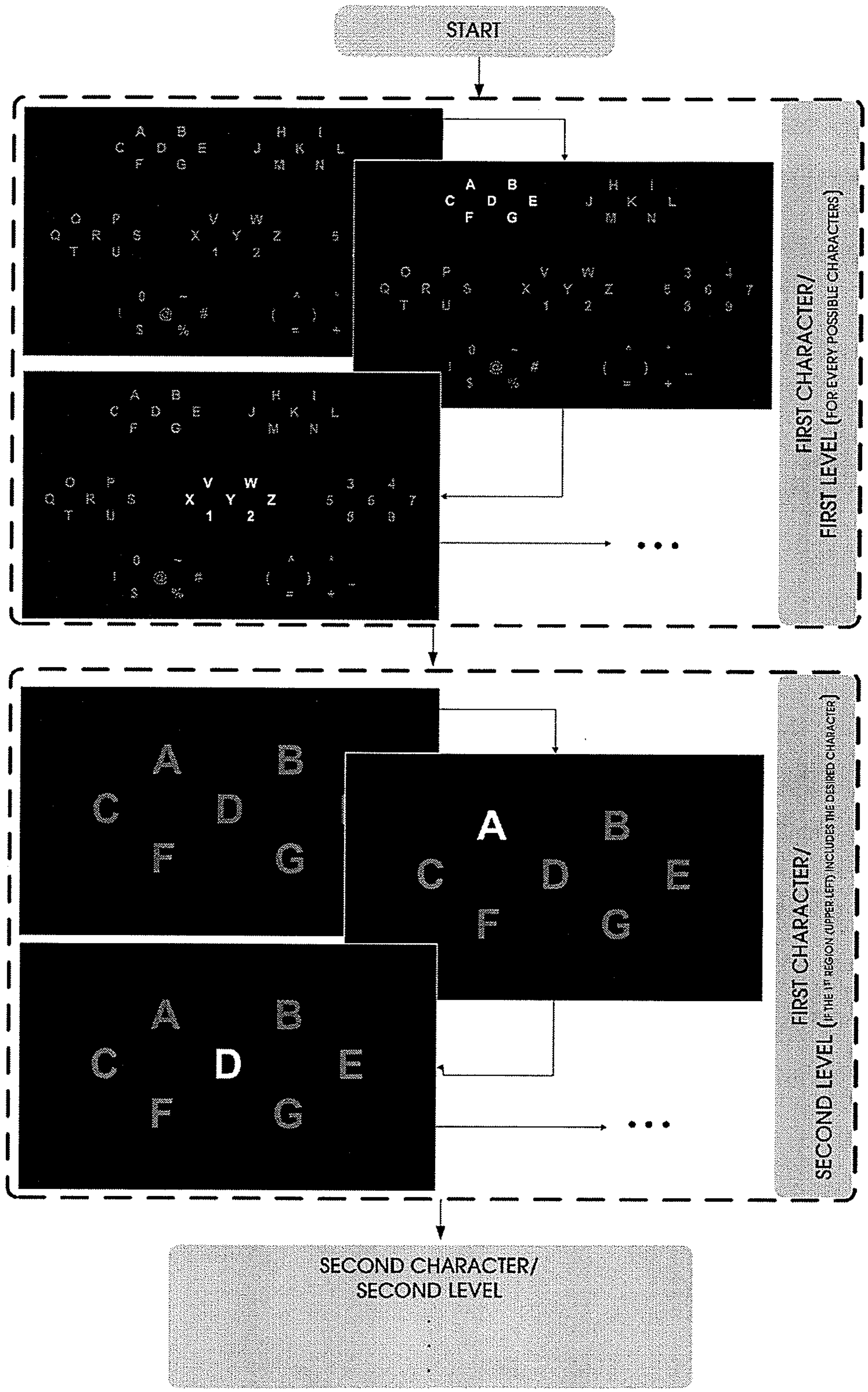

Fig. 2.5. The steps should have been taken to detect the target in 7-region paradigm

2.1.4.3. Discussion: Pros and Cons

It is believed that *Attentional Blink* (Section 1.3.4) happens in DF paradigm when a non-target row/column near the target attracts the user's attention [[35], [38]. In DF paradigm, it has been confirmed that flashing the adjacent rows/columns of the target's row/column is the main reason of wrong target detection [38]. The result of this study shows that 60% of the time among 35% of the cases that the target did not detected, the system detected adjacent row or column as the target. Fig. 2.6 shows the final result where D represents the percentage error of distance between target's row/column and detected character's row/column. Increasing the distance between target's group and other characters in 7-region paradigm might be helpful to avoid this possible source of error.

Furthermore, it has been proved that *Repetition Blindness* (Section 1.3.4) as well as Attentional Blink could take place when the target intensifies twice in less than 500ms and impair the P300 detection [35]. This error is avoidable if no characters flash twice in less than 500ms. For this purpose the flashing sequence should be organized while it doesn't follow a specific pattern.

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Fig. 2.6. D is the Percentage of error, represents the distance between target and detected row/column [38]

Habituation (Section 1.3.3) was another factor could affect P300's amplitude. User might be habituated in both paradigms but it's clear that it will be faster in DF paradigm because of the structure consistency compare to 7-region paradigm where the characters are relocated from level to level. *Probability* (Section 1.3.1) is one of the main factor affect P300 elicitation. In DF paradigm, a target takes place in the sequence of stimuli when its row *OR* its column flashes. Therefore, the target stimulus probability is equal to the probability of flashing one row or one column, i.e. $\frac{1}{12} + \frac{1}{12} = \frac{1}{6}$. In 7-region paradigm, on the other hand, the probability of target stimulus is equal to $\frac{1}{7}$. Consequently, the probability of target stimulus in 7-region is less than DF which generates the higher P300 amplitude. In addition, 7-region provides more characters (49) compare to the DF paradigm (36). Moreover, using 7-region paradigm, characters could be placed in any of seven locations on the screen (see Appendix A). This feature might be useful if the probability of letters' arrangements is considered in selection of character's spatial location on the screen. As an example, it's better to avoid placing the letters 'Q' and 'Z' in the same region because the probability of having these two letters in a word is very small. For the same reason, the letters 'T' and 'H' should be placed in a same region. By this means, the user can spell the desired word with a minimum movement which is very vital for the paralyzed people.

In spite of these advantages, the DF paradigm is relatively faster than the 7-region paradigm. 180 flashes are required for detecting one character in the DF speller paradigm while it is equal to 210 in the 7-region. Moreover, in the DF paradigm, 2sec. is considered before flashing sequence starts. During this period users must locate and focus on the desired character. In the 7-region, however, another 2 sec. is required between first and second level which comes to 4 sec. for one character. Therefore, $(180\times 175ms = 31.5s) + 2\sec = 33.5\sec$ ($1.79\ {}^{\text{char}}\!/_{\text{min}}$) is the total time required for detecting one character in the DF paradigm and $(210\times 175ms = 36.75s) + 4\sec = 40.75\sec$ ($1.42\ {}^{\text{char}}\!/_{\text{min}}$) is the total time required for detecting one character in the 7-region paradigm.

However, the focus of this study is more on the improving the accuracy of speller paradigms than anything else.

2.1.5. Lie Detector Paradigm

2.1.5.1. Objective

In this section, we propose a model for P300-based lie detector (section 1.6.2.1). In this design, the influence of probes on innocent people in P300-based lie detector is simulated and studied.

2.1.5.2. Design

Three different stimuli have been used in this application: Probe (*P*), Target (*T*) and Irrelevant (*I*). Subjects must respond to the targets while no task is defined in response to the irrelevants and probes. Therefore, we expect to observe P300 in response to the targets in all of the channels. Irrelevant stimuli are not relevant to the situation and have neutral effect. In contrary, probes are totally related to the situation under analysis. They are somehow selected to have the same influence on EEG data as irrelevant if the subject has no information about the crime or elicit P300 if the subject is knowledgeable [41] (Fig. 2.7).

Every experiment started by pressing the space bar after describing the task that subject should perform during the test. The task was simply counting the number of targets in their head. Afterwards, the subject was presented with these three stimuli. The number and order of stimuli were same for all the experiments but it looked random to user. Overall, 100 probes, 100 targets and 500 irrelevants were shown to the subject. Presentation of each stimulus, no matter of their type, was 200ms on the black background after 200ms blank screen.

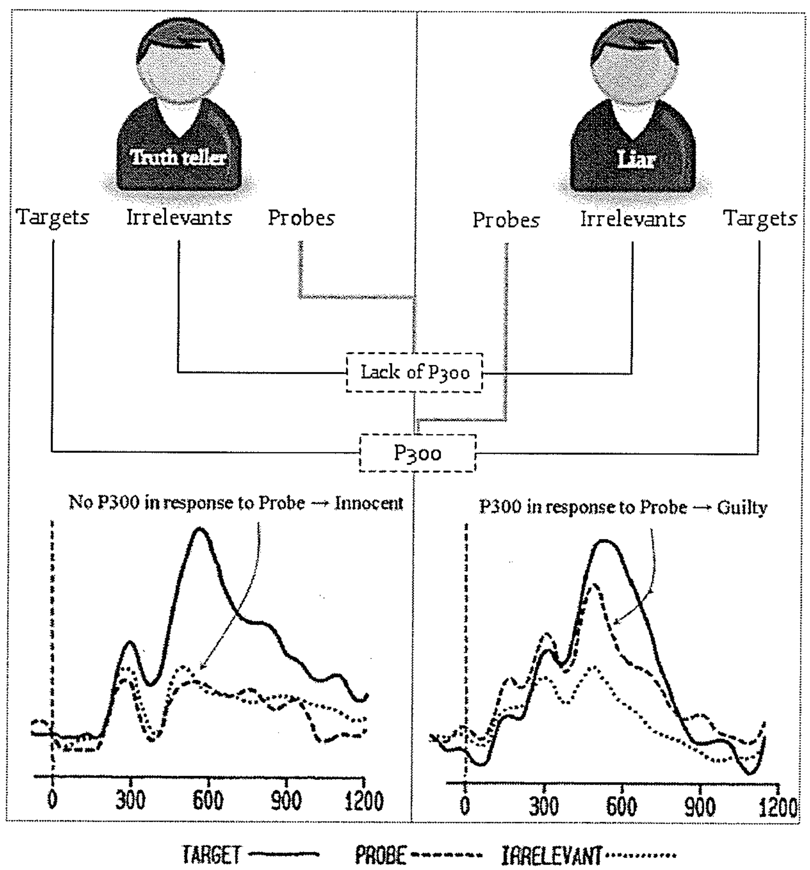


Fig. 2.7. Liar's and truth-teller's response to the PTI

Three different types of pictures were selected as stimuli. Two different collections of particular images were used as targets and irrelevants. We were looking for the specific type of stimulus as the probe to evoke P300. For this reason, we chose the user's own picture (or familiar names) without letting him know in advance [46]. Meanwhile, the subject's brain signals are recorded and transferred to the computer for further analysis. The test was carried on up to the time which the last image in sequence appeared on the screen.

As it discussed in Section 2.1.4.2, it's possible to mark the signal by triggering the LPT port as soon as any stimulus appeared on the monitor. Subsequently, these markers were used to find the P300 in response to the *P-T-I*s individually.

2.1.5.2.1. Design: Proposed Paradigms

The objective of these series of experiments is to find out the influence of Probes on innocent subjects. We try to show how unexpected infrequent stimuli could evoke a strong P300 wave in EEG signal when the subjects have no prior knowledge about the stimuli. This proves that Farwell's assumption about the probes is not very realistic.

For this purpose, we designed four different types of experiments which are described in Table 2.1 and depicted in Fig. 2.8. During these experiments, the user should follow the task which was tapping the finger as any Target appears on the screen. Thus, depends on difficulty of the task, the experiments were categorized as easy or hard. Recognizing letter *B* from letter *A* is classified as *Easy* and big circle from small circle as *Hard.* Results confirm that users may generate P300 even if they don't have any information about the stimuli in advance.

Experiment			Irrelevant	Target	**Probe**
1	Easy		‘A’	‘B’	**‘C’**
2	Easy		‘A’	‘B’	**Distracter**
3		Hard	Circle (Small)	Circle (Big)	**Triangle**
4		Hard	Circle (Small)	Circle (Big)	**Distracter**

Table 2.1. Easy/Hard experiment with and without a distracter as Probe

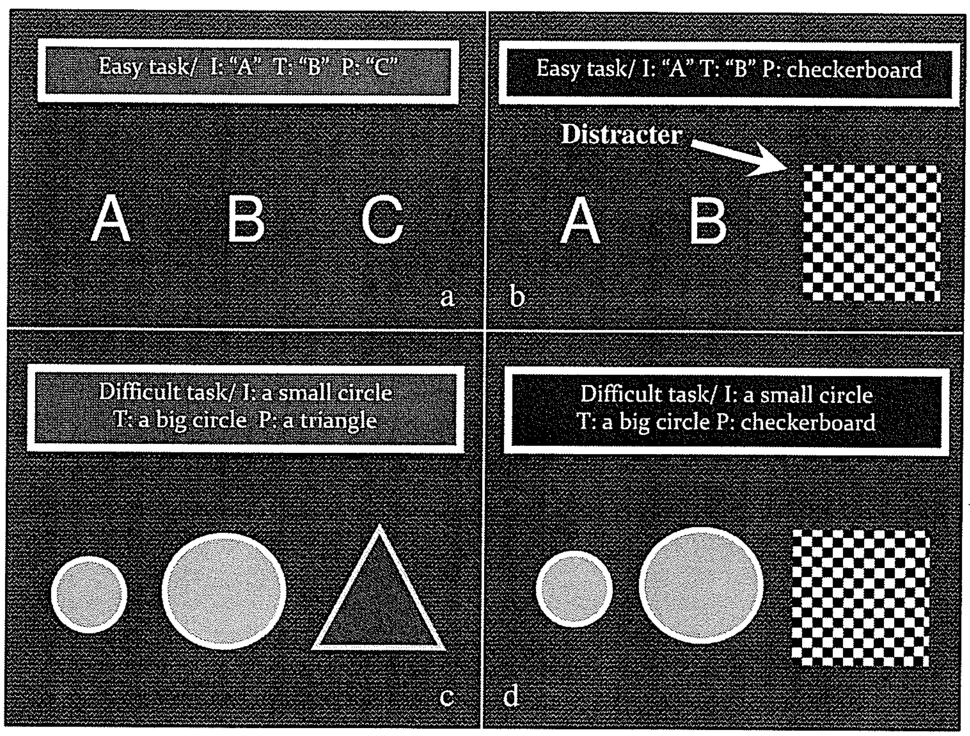


Fig. 2.8. (a) Easy/without distracter (b) Easy/with distracter
(c) Difficult/without distracter (d) Difficult/with distracter

2.1.5.3. Discussion

Farwell claimed that his P300-based lie detector offers 100% accuracy and high confidence level of the results [42]. However, this lie detector has been criticized and its reliability is still unconfirmed [54]. In the federal evaluation of Farwell's method, Donchin declared that his lie detector "is not ready as a practical tool" [54]. His statement was based on two facts: first, the probe is chosen by investigator and not science and second, the P300 can be evoked because something is infrequent as well as meaningful; therefore an innocent person may generate P300 in response to a probe because it rarely happens and not because it's distinguished by brain [54]. Also Rosenfeld, a professor at the University of Utah, believes that Farwell looks at one P300 distribution for an individual subject while he should consider several P300s [54]. He also mentioned that Farwell recruited highly motivated subjects for his tests instead of ordinary people. Another issue here is the influence of the crime-related probe on the innocent people. Farwell most likely did not consider the fact that the crime oriented probes could produce an unwanted P300 if it surprises an innocent subject or if the subject recognizes the picture through the media leakage [47].

Our results confirm that either the P300-based lie detector is not practical or it's not as simple as it sounds and needs more investigation to be accurately developed.

2.2. Data Analysis

2.2.1. Removing Artifact

Artifacts are those types of waves in EEG data which are not due to the brain activity and must be removed (Fig. 2.10). Sweat artifact is a long-duration high-amplitude slow activity artifact which happens when the salt and lactic acid from sweating react with metals of the electrodes [50]. A high-pass filter can remove this type of artifact. However, because the P300 has a low frequency (almost 3Hz [48], [49]) the lowest possible frequency should be used for this filter [51]. We used 0.1Hz as low cutoff frequency in our applications [45]. A low-pass filter of 30 Hz could also remove high frequency artifacts such as muscle noise and 60 Hz line noise. Fig. 2.9 shows the raw and filtered EEG signal in the small period of time.

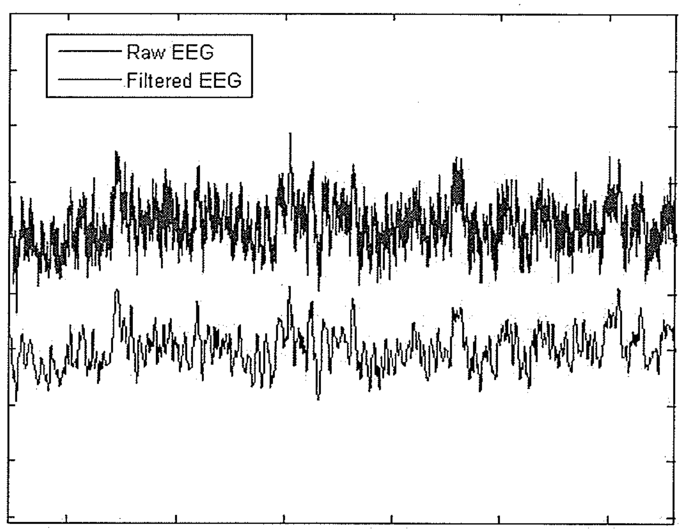


Fig. 2.9. Raw (Top) and filtered (Bottom) EEG signal

Eye artifacts such as eye blinks and eye movements may distort the signal as well. The easiest way is to reject those portions of data contaminated by eye artifacts. In this case, we may lose some valuable information. Therefore, some techniques such as Independent Component Analysis are used to remove eye artifacts without removing any segment of EEG signal. In the following section we discuss this method which was applied to our data.

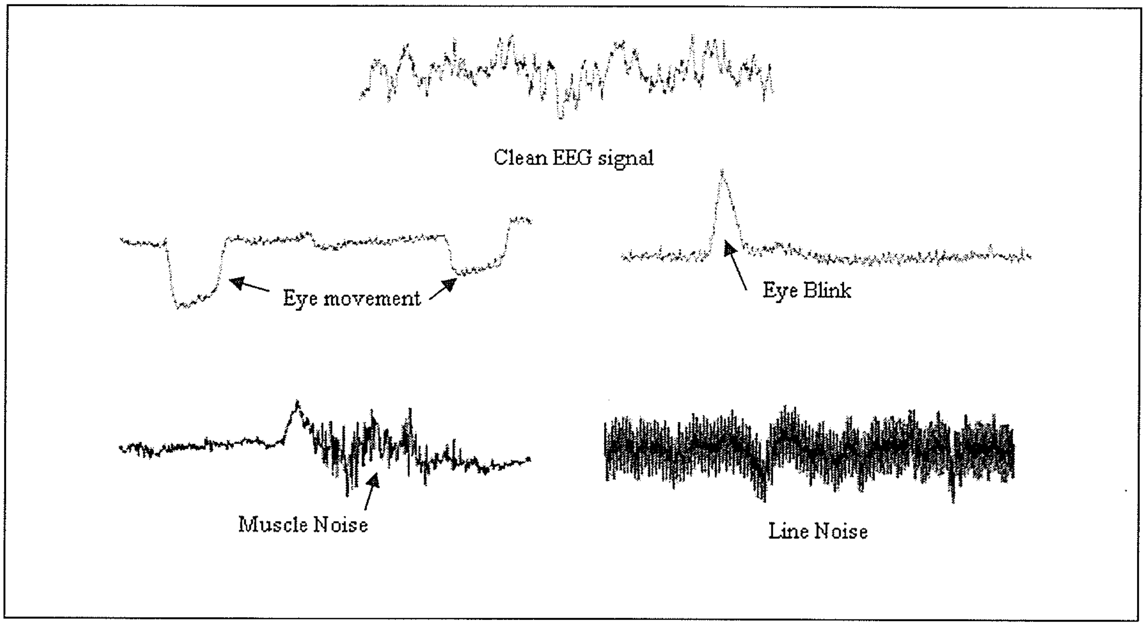


Fig. 2.10. Different types of artifacts

2.2.1.1. ICA

The main objective of Source Separation in signal processing is to find the original sources of the mixed signal. 'Cocktail party problem' is a well known example of Source Separation; trying to follow one of the discussions in a cocktail party where a number of people are talking simultaneously. Independent Component Analysis (ICA) is a successful approach that has been proposed for signal source separation. The independent sources of a signal could be found and separated by this method. The assumption is that EEG signal and artifacts are completely independent. Hence, applying ICA on raw EEG signal will extract the artifacts from the data and make the elimination possible. Mixing the components left after artifact removal gives us a clean EEG signal (Fig 2.11).

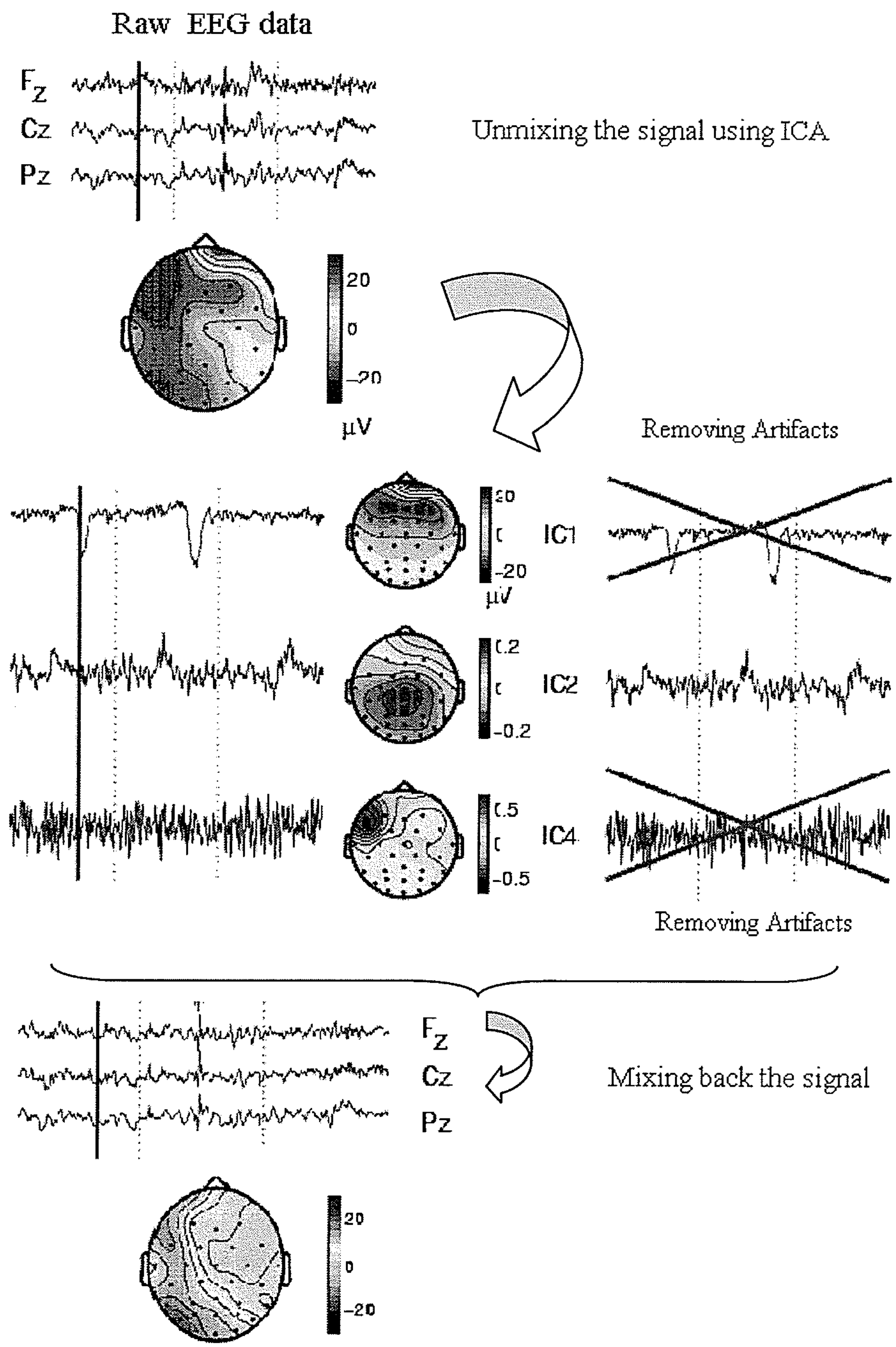


Fig. 2.11. Artifact removal using ICA (scaled color bars show the amplitudes of scalp maps for each component) [52]

As it was mentioned in the previous section, in our applications we have used ICA to remove eye artifacts. For this purpose, we need to distinguish the components that represent eye activities. We used a Matlab toolbox called EEGLab to generate the brain topography of each component and plot its activity power spectrum. In terms of brain voltage distribution, eye artifacts mainly should project to the frontal sites on the brain which will be clear on the brain map. In addition, the smoothly decreasing EEG spectrum is typical of an eye artifact (Fig. 2.12).

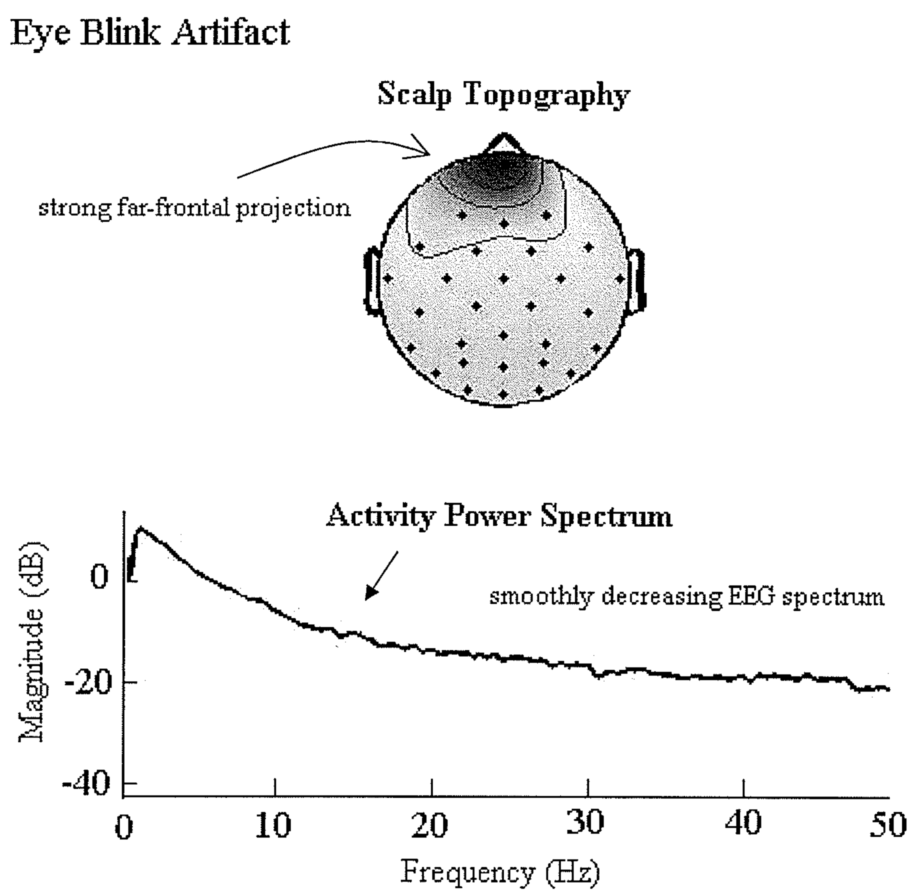


Fig. 2.12. Eye Artifact component [a] Brain Map [b] Activity Power Spectrum

In our applications, the following steps were followed to remove all of the artifacts including eye activities:

1) Filtering data using band-pass filter of 0.1Hz-30Hz,

2) Running ICA on the filtered data; the outcome should be different components that represent different sources of the signal,
3) Distinguishing and removing eye activities between components, and
4) Reconstructing the signal by mixing the remained components to have a clean EEG.

2.2.2. P300 Detection and Classification

Because EEG is a combination of all ongoing brain activity [44], a P300 wave is too small in size of amplitude (~ 5-15μV) to be visible within regular EEG signal. However, the brain response to a particular stimulus (e.g. P300) is similar from trial to trial; therefore taking the average on a known event (e.g. stimulus presentation) cancels out the random variations within the EEG signal and as a result the P300 wave will be visible in the final plot. Averaging is the simplest yet powerful technique to detect the P300. For this method, it is required to have at least 20 single correct target stimuli to generate stable P300 [45]. As an example, in Fig. 2.13, it's clear how the visibility of P300 changes by increasing the number of targets. Note that, boosting up this number from 25 to 50 and 75 doesn't make a big difference.

EEG data were marked as a presentation of each stimulus in a paradigm. These markers could be exported to an ASCII file and used to find the initial point of EEG data required for taking the average.

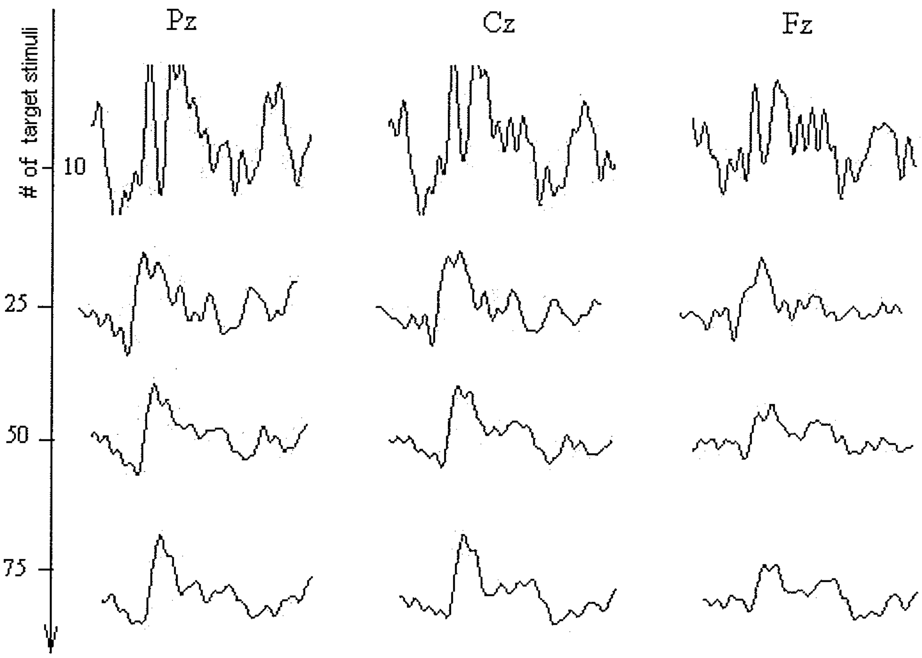


Fig. 2.13. Result of averaging with 10, 25, 50 and 75 target stimuli

Let's assume each stimulus is represented by a marker *'x'* and occurs at the time *'T(x)'*; therefore the EEG signal for all of the stimuli will be marked as

$$EEG(T(1)), EEG(T(2)), ..., EEG(T(n)) \qquad n: \text{number of markers}$$

If our target stimulus happens at *T(i)*, *T(j)*, ... , the average signal for finding the P300 will be:

$$if\ (\text{stimulus}\ @\,[T(i)\,\&T(j)\,\&...]) \Rightarrow Average\,(\text{stimulus}) = \frac{1}{m}\sum_{x=i,j,...}(EEG(T(x):T(x)+600ms))$$

Initial points are the markers which represent the time that stimuli occurred and the end points are 600ms after the initial points. This is because of the fact that P300 latency is between 250 and 500 ms (Section 1.3). After finding the average of the signals on each channel, *Grand Average* must be found for the classification which is the average of the averaged signal across all of the available channels.

Even though we tried to preprocess data and reject artifacts, they might not be fully removed. Thus, they may affect the results by producing a non-P300 peak in the averaged signal. Therefore, peak detection would not be enough for P300 recognition. However, in contrary of eye blinks and muscle noise, the P300 has a low frequency (~3Hz [48], [49]) and a non-sharp peak. We could consider this feature of P300 for better detection. One possible technique is to consider an interval around the peak for all of the averaged signals and calculate the summation of the signal values within the interval. The interval was 20ms in our program (10ms after and 10ms before the peak) and it was found by trial-and-error. Consider $Pk(Sg_1)$, $Pk(Sg_2),\cdots$ are the maximum peak values between 200ms and 500ms of the signals Sg_1, Sg_2, ... respectively. Subsequently, for the signal q, the summation of the signal values or η in 20ms interval around the peak is (Fig. 2.14):

$$\eta = Sum(Sg_q) = \sum_{Pk(Sg_q)-10ms}^{Pk(Sg_q)+10ms} Sg_q \qquad q = \text{signal's number}$$

The signal with the highest value is considered as P300. After taking the average, each signal represents one specific stimulus in our paradigms which is specific group of characters in 7-region paradigm, Probe/Target/Irrelevant stimuli in lie detector paradigm and one row or one column in DF paradigm. In 7-region paradigm, finding the highest value is equivalent to finding the target group while in DF paradigm. The highest value between rows and columns will be the row and column of the target.

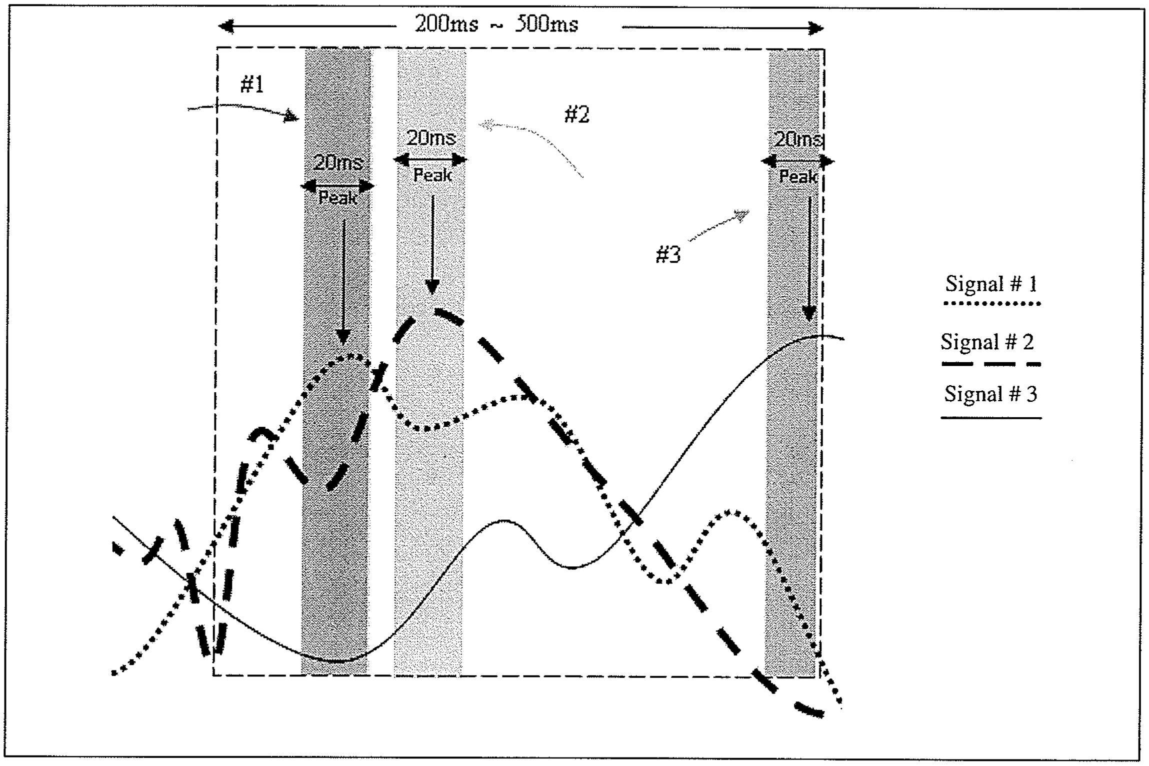


Fig. 2.14. Finding the value of the signals around the peak for P300 detection

Nomenclature of Chapter 3

TS: Target stimulus	Page 49
β: Index of accuracy based on the probability of target detection	53
KS: Kolmogorov-Smirnov test	67

Chapter 3 Results & Discussion

In this chapter, experimental results[†] are presented and discussed.

3.1. Minimum Number of Targets

Averaging is a simple and reliable method to uncover the P300 [45]. In this method, EEG signal is chunked into small portions and then averaged over. An averaged signal, whether it includes the P300 response or not, consists of numerous random variables that make the P300 detection complicated. The amount of these variations is inversely proportional to the number of the chunked signals which represents the number of target stimulus or *TS*. Thus, increasing the number of *TS* decreases the random variations in the averaged signal and as the result the P300 will be more visible in the final plot (if there is any). In fact, having more targets gives us more uncontaminated signal and makes P300 detection easier. On the other hand, increasing the number of targets certainly makes the time of experiment longer. Therefore, to optimize the system, we must be aware of minim required number of *TS* before designing the paradigms.

[†] All of the values for the EEG amplitude in this chapter are 1/10 of the real values because the recorder scaled down the signal by 0.1 factor.

3.1.1. Determining the Number of Target Stimulus

We conducted an experiment with a typical oddball paradigm to find the minimum number of targets. The paradigm contained two types of stimuli: standard and target. The user was asked to count the number of targets. Meanwhile the signal was recorded at five different channels of Fz, Cz, Pz, C3 and C4 referred to the left mastoid and averaged over 5, 10, 15, 20, 25, 30, 50 and 70 *TS*. The results are shown in Fig. 3.1. Random variations are clearly visible when the average is taken over 5 to 20 stimuli, especially at channels C3 and C4 (Fig. 3.1) and barely noticeable after increasing the number from 25 to 70 (Fig. 3.2).

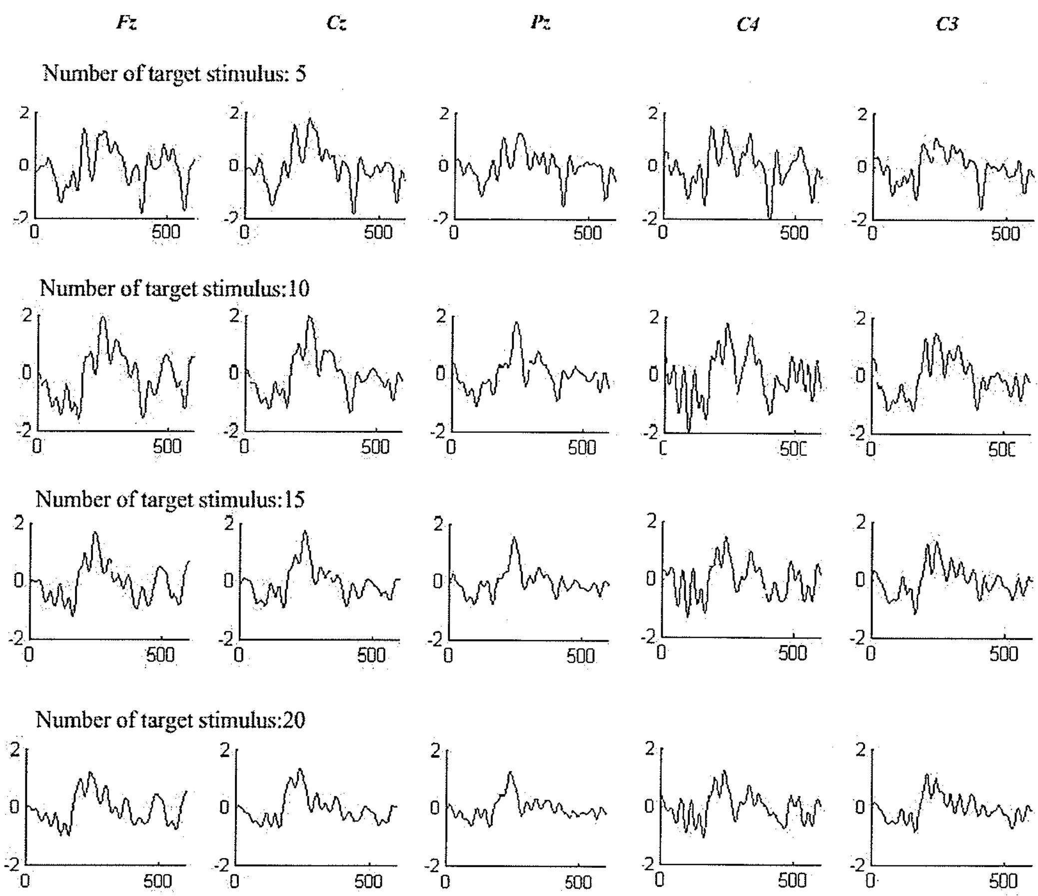


Fig. 3.1. Averaged signal over 5, 10, 15 and 20 target stimuli

The influence of targets' number is quite negligible when it turned into 30 and more.

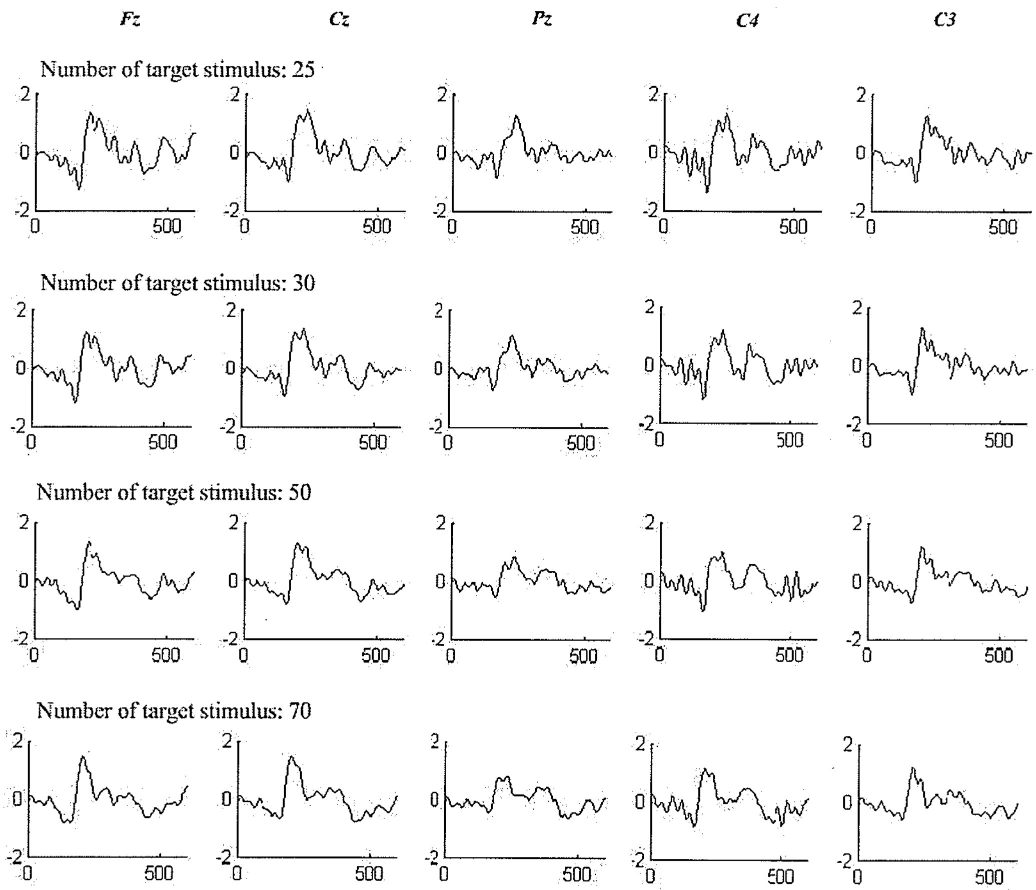


Fig. 3.2. Averaged signal over 25, 30, 50 and 70 target stimuli

The detected P300s' value (highest peak value between 250ms and 500ms [45]) and their average across available channels for different number of *TS* are extracted in Table 3.1.

# of target	***5***	***10***	***15***	***20***	***25***	***30***	***50***	***70***	***75***
Peak at Fz	1.38	1.92	1.52	1.19	1.36	1.25	1.30	1.46	1.51
Peak at Cz	1.75	1.96	1.58	1.34	1.40	1.31	1.29	1.49	1.52
Peak at Pz	1.24	1.78	1.46	1.22	1.25	1.12	0.85	0.80	0.80
Peak at C4	1.48	1.78	1.34	1.23	1.31	1.17	0.96	1.11	1.12
Peak at C3	1.07	1.47	1.25	1.13	1.27	1.28	1.18	1.18	1.23
Average	1.38	1.78	1.43	1.22	1.32	1.23	1.12	1.21	1.23

Table 3.1. Detected peak value for different number of *TS*

Consider the peak value at 75 as a baseline (75 targets are more than enough to detect the P300 [53]). The objective here is to find the minimum number of *TS* where the error (i.e. difference between the peak value and the baseline) can be ignored. Fig. 3.3 shows the peaks' average versus the number of *TS* and Fig. 3.4 illustrates the error.

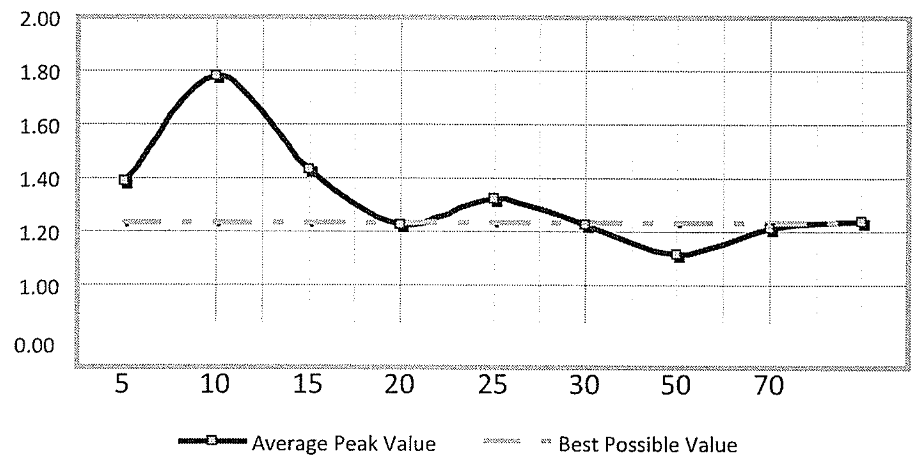


Fig. 3.3. Peaks' average vs. number of *TS*

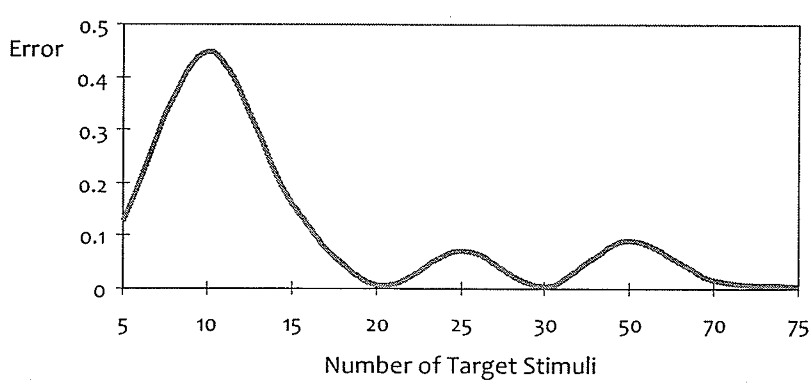


Fig. 3.4. Error vs. number of *TS*

It can be concluded that at least 20 *TS* are required in this paradigm to have fairly clear P300 responses in the averaged signals. More than 20 targets may deliver more visible P300 but at the same time it's very time-consuming and unnecessary. However, 25 *TS* were used in our paradigms in case if subjects somehow miss some *TS*s (up to 5) for some reasons such *AB* or *RB*.

3.2. DF versus 7-region Paradigm

The main goal of the study was to design, implement and evaluate P300-based applications for BCI. At the first step, the sources of errors in the DF paradigm speller were identified and removed and turned into designing a new speller named 7-region paradigm. We believe this proposed paradigm delivers higher accuracy than DF's and so it's relatively more functional and practical. The results for both DF and 7-region paradigms are discussed in the following sections.

3.2.1. Defining a New index

In this section, a new index which enables us to compare the speller paradigms is defined. There are seven different regions in 7-region paradigm that may or may not include the target. Therefore, the probability of detecting the target between them is $P = 1/7$ and so the probability of detecting a wrong region as a target will be $1 - P = 6/7$. On the other hand, *2K* levels are required if the target includes *K* characters (each character needs two levels). Therefore, the probability of detecting *R* and only *R* correct region between *2K* levels is $\left(1/7\right)^{R} \times \left(6/7\right)^{2K-R}$. However, because the order of elements is not important, this value must be multiplied by a combination of $C_R^{2K} = \binom{2K}{R}$, i.e. the probability of correctly detecting R regions after $2K$ levels is

$$P(R) = \left(\tfrac{1}{7}\right)^R \times \left(\tfrac{6}{7}\right)^{6-R} \times C_R^6.$$

For instance, let's say the target word includes three characters and the system detects all of them, i.e. $R=6$. Thus the probability will be:

$$P(6) = \left(\tfrac{1}{7}\right)^6 \times \left(\tfrac{6}{7}\right)^{6-6} \times C_6^6 = \left(\tfrac{1}{7}\right)^6.$$

Now, we are defining new index, β_{7R}, to normalize the results:

$$\beta_{7R} = \frac{\left(\tfrac{1}{7}\right)^6}{P(R)}$$

This index could be a value between 0 and 1. The higher value demonstrates the higher accuracy. As an example, if the system detects all of the target regions, then

$$\beta_{7R} = \frac{\left(\tfrac{1}{7}\right)^6}{\left(\tfrac{1}{7}\right)^6} = 1$$

and if it doesn't find any of them

$$\beta_{7R} = \frac{\left(\tfrac{1}{7}\right)^6}{\left(\tfrac{6}{7}\right)^6} = 2.14 \times 10^{-5} \approx 0$$

In DF paradigm, if the target includes K character the systems' output will be $2K$ values including the rows and columns of each character. This simply let us to use the same index for DF as the one in 7-region. However, in this paradigm we have 6 rows/columns, i.e. the probability of detecting right row or column is $P' = \tfrac{1}{6}$ which was $\tfrac{1}{7}$ in 7-region. Therefore this paradigm's index is defined as

$$\beta_{DF} = \frac{\left(\frac{1}{6}\right)^{2K}}{P'(R)}$$

$$\text{where } P'(R) = \left(\frac{1}{6}\right)^{R} \times \left(\frac{5}{6}\right)^{2K-R} \times C_{R}^{2K}$$

$P'(R)$ is the probability of correctly detecting R characters. For instance, if the speller finds all of the 6 characters of the target, then $\beta_{DF} = \frac{\left(\frac{1}{6}\right)^{6}}{\left(\frac{1}{6}\right)^{6}} = 1$.

3.2.2. Results and Discussion

In these series of experiments, EEG signals were recorded from 10 subjects (2 F, 8 M) at three electrode sites of Fz, Cz and Pz referenced to the left mastoid. These three recording sites are enough for detecting the P300 [45]. Subjects are asked to spell the word *P3A* by focusing their attention on desired characters one at a time. For every subject, the experiments conducted once with DF and another time with 7-region paradigm. In both cases, same techniques were used for removing artifacts and P300 detection.

In Figs. 3.5.A and 3.5.B, *detected peak value* means the P300 amplitude of detected regions or rows/columns while *expected peak value* indicates the highest amplitude of the signal when the average is taken over correct regions in 7-region or correct rows/column in DF paradigm (Appendix B). The differences between *detected* and *expected* peak values (*error*) in DF paradigm are generally more than the same value in 7-region paradigm. For every subject, Fig. 3.6 shows the errors in both paradigms while Fig. 3.7 illustrates their average over the levels. Both graphs present the less error and so the better performance for 7-region paradigm.

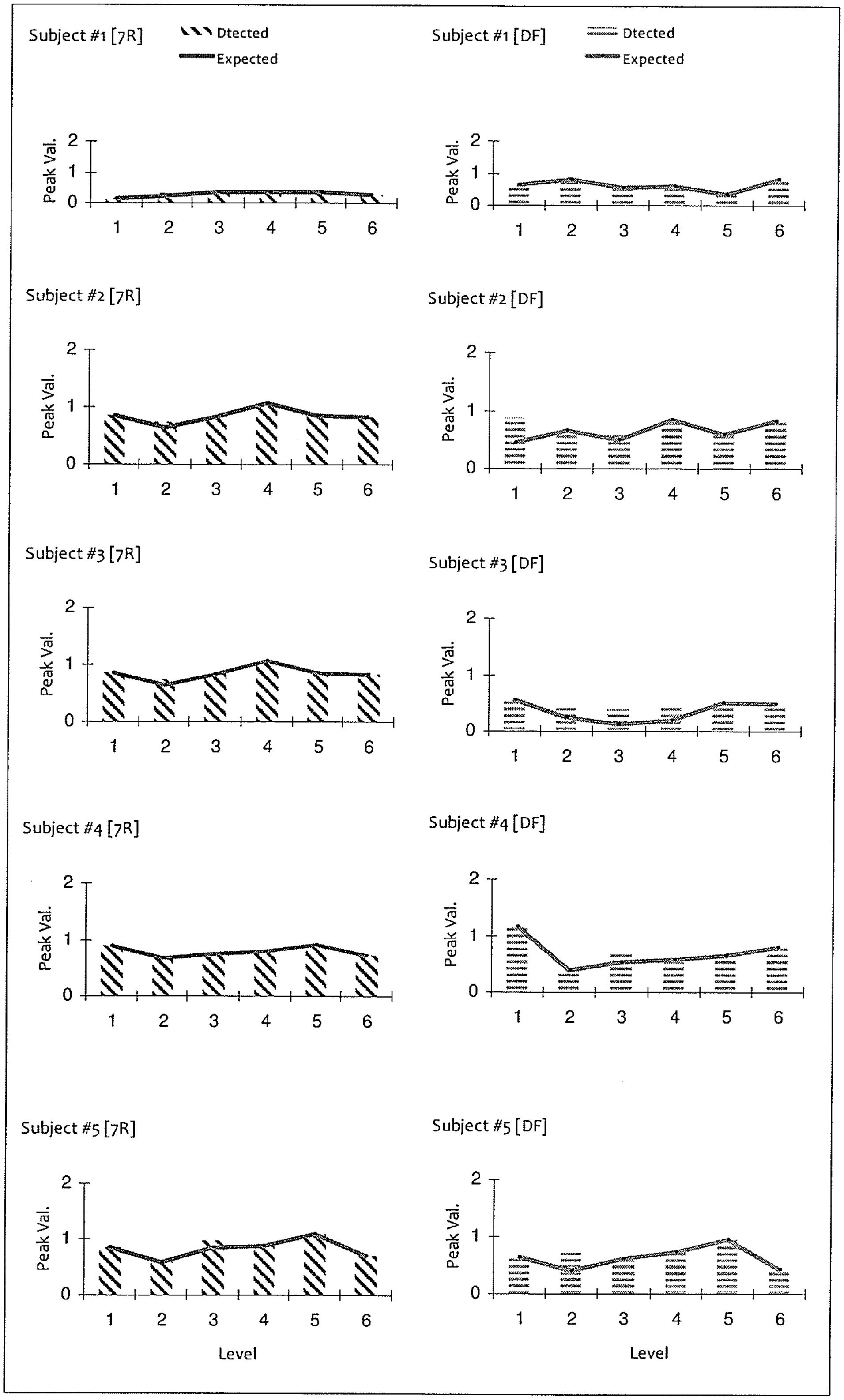


Fig. 3.5. A Peak Value vs. level's number (Subject 1-5)

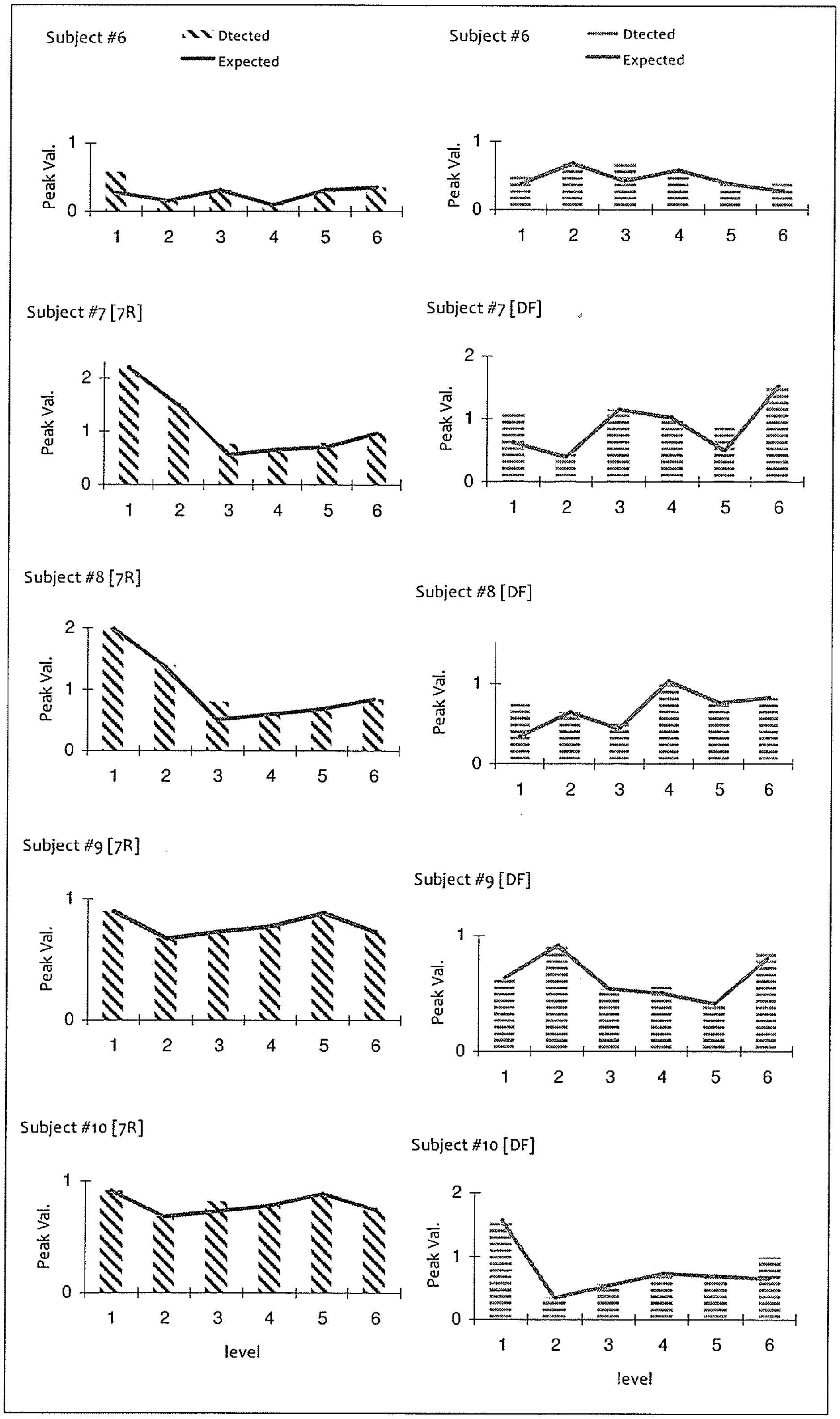


Fig. 3.5.B Peak Value vs. level's number (Subject 6-10)

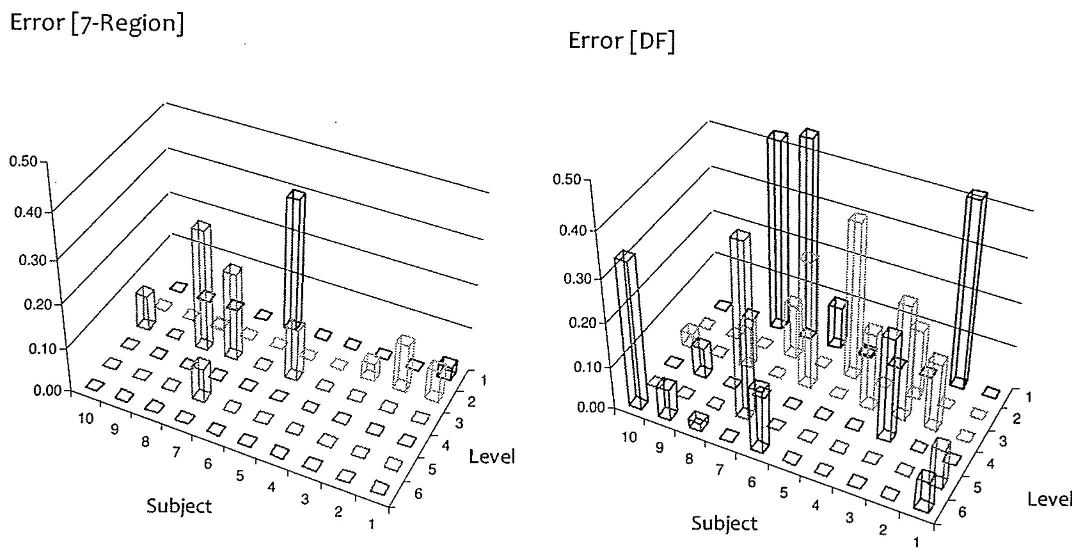
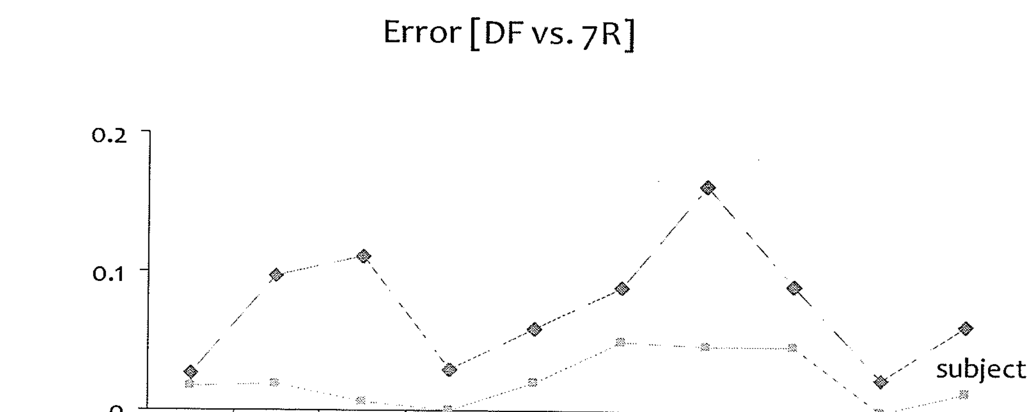


Fig. 3.6. Error vs. level's number for every subject



	1	2	3	4	5	6	7	8	9	10
DF	0.0271	0.0969	0.1105	0.0294	0.06	0.0892	0.1631	0.0913	0.0236	0.0619
7R	0.0173	0.0181	0.0066	0	0.0201	0.0508	0.0465	0.0468	0	0.0136

Fig. 3.7. Average of error vs. subject number

Fig. 3.8 compares the P300 amplitude in both paradigms for every subject (Appendix B). The 7-region paradigm evokes P300 with higher peak in general (for 8 subjects out of 10, the P300 amplitude was higher in the 7-region paradigm). The mean of P300 amplitude was $\text{Mean}_{\text{P3}}(7R) \cong 7.7\mu v$ and $\text{Mean}_{\text{P3}}(\text{DF}) \cong 7\mu v$ in 7-region and DF paradigm, respectively.

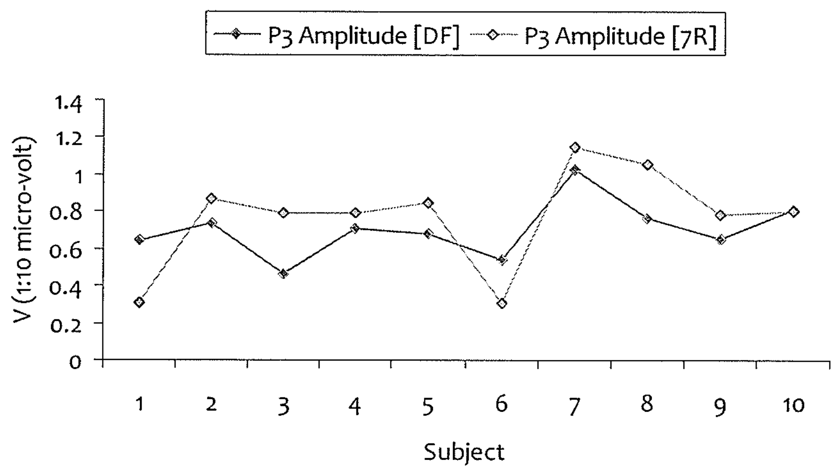
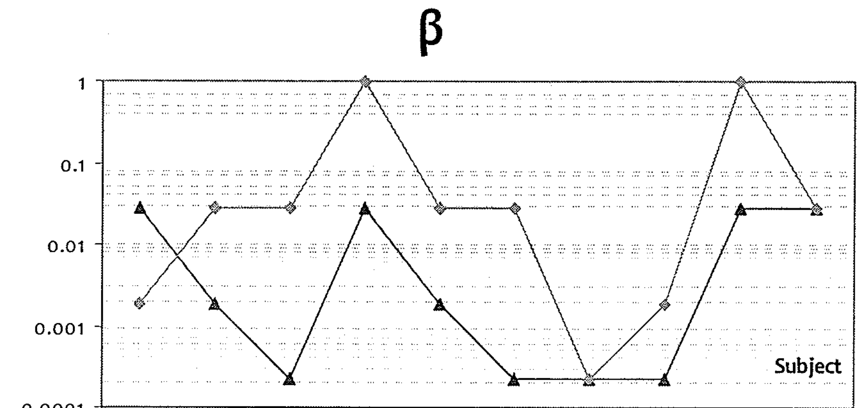


Fig. 3.8. P300 amplitude vs. subject number in DF and 7R paradigm

To compare the accuracy, β_{DF} and β_{7R} (Section 3.2.1) are calculated for both paradigms and depicted in Fig. 3.9. 7-region paradigm was more accurate and showed the better performance for all of the subjects except for the first one.

The outputs of the systems are shown in Tables 3.2.1-2 and 3.3.1-2. In these tables, those regions or rows/columns or characters that detected by mistake are highlighted. Note that, regions are numbered based on their order on the screen as seen in Fig. 3.10.

In two cases (subjects 4 and 9) 7-region system correctly found all of the regions and only in one case (subject 1) DF speller performs better. 11 regions out of 60 (=10 characters out of 30) and 22 rows/columns out of 60 (=17 characters out of 30) were wrongly detected (error) in 7-region and DF paradigm, respectively.



	1	2	3	4	5	6	7	8	9	10
DF	0.0278	0.0019	0.0002	0.0278	0.0019	0.0002	0.0002	0.0002	0.0278	0.0278
7R	0.0019	0.0278	0.0278	1	0.0278	0.0278	0.0002	0.0019	1	0.0278

Fig. 3.9. Beta value in DF and 7-Region paradigms. Note that beta axis is in logarithmic view.

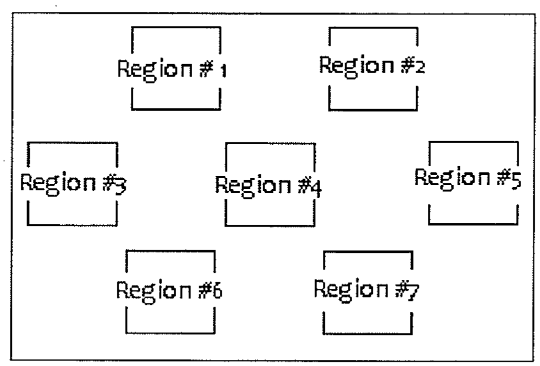


Fig. 3.10. Regions' number in 7-region Paradigm

Target Regions →	3	2	5	1	1	1	*Total Error*	*β*
Subject	*Detected Regions*							
1	4	5	5	1	1	1	2	0.001851852
2	3	3	5	1	1	1	1	0.027777778
3	3	6	5	1	1	1	1	0.027777778
4	3	2	5	1	1	1	0	1
5	3	2	1	1	1	1	1	0.027777778
6	1	2	5	1	1	1	1	0.027777778
7	3	2	4	1	2	1	2	0.001851852
8	3	4	4	1	1	1	2	0.001851852
9	3	2	5	1	1	1	0	1
10	3	2	1	1	1	1	1	0.027777778
Total Error	2	4	4	0	1	0	**11**	

Table 3.2. 1 The 7-region paradigm results: number of subjects=10, target=*P3A*

<table>
<tr><th>Target →</th><th colspan="2">P</th><th colspan="2">3</th><th colspan="2">A</th></tr>
<tr><th>Subject</th><th colspan="6">Detected</th></tr>
<tr><td>1</td><td>R #4</td><td>R #5</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>2</td><td>P</td><td>R #3</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>3</td><td>P</td><td>R #6</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>4</td><td colspan="2">P</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>5</td><td colspan="2">P</td><td>R #1</td><td>3</td><td colspan="2">A</td></tr>
<tr><td>6</td><td>R #1</td><td>P</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>7</td><td colspan="2">P</td><td>R #4</td><td>3</td><td>R #2</td><td>A</td></tr>
<tr><td>8</td><td>P</td><td>R #4</td><td>R #4</td><td>3</td><td colspan="2">A</td></tr>
<tr><td>9</td><td colspan="2">P</td><td colspan="2">3</td><td colspan="2">A</td></tr>
<tr><td>10</td><td colspan="2">P</td><td>R #1</td><td>3</td><td colspan="2">A</td></tr>
</table>

Table 3.2.2: The 7-region paradigm results: No. of subjects=10, target=*P3A* (R stands for region's number)

Target row/col →	**4**	**3**	**5**	**5**	**1**	**1**	*Total Error*	β
Subject	***Detected row/column***							
1	4	3	5	5	5	4	2	0.033333333
2	1	3	6	5	1	1	2	0.002666667
3	4	5	1	1	1	1	3	0.0004
4	4	3	1	5	1	1	1	0.033333333
5	3	4	5	5	1	1	2	0.002666667
6	6	3	2	5	1	2	3	0.0004
7	5	2	5	5	6	1	3	0.0004
8	1	3	6	5	1	4	3	0.0004
9	4	3	5	5	4	4	2	0.033333333
10	4	3	4	5	1	1	1	0.033333333
Total Error	5	3	6	1	3	4	**22**	

Table 3.3. 1: The DF paradigm results: number of subjects=10, target=*P3A*

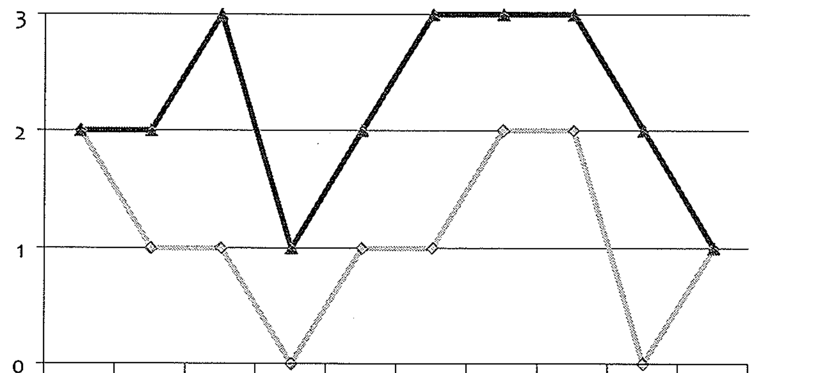
Target →	**P**	**3**	**A**
Subject	***Detected ↓***		
1	P	3	X
2	M	4	A
3	2	A	A
4	P	Z	A
5	U	3	A
6	R	0	G
7	K	3	F
8	M	4	D
9	P	3	V
10	P	2	A

Table 3.3.2: The DF paradigm results: number of subjects=10, target=*P3A*

Table 3.4 and Fig. 3.11 show the number of errors (detection of wrong region or row/column) for each subject. In all of the cases the error values are either the same (Subjects 1 and 10) or lower in the 7-region compare to the DF paradigm.

Subject>	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	Total
7R Error	2	1	1	0	1	1	2	2	0	1	11 (out of 60)
DF Error	2	2	3	1	2	3	3	3	2	1	22 (out of 60)
Total	4	3	4	1	3	4	5	5	2	2	33

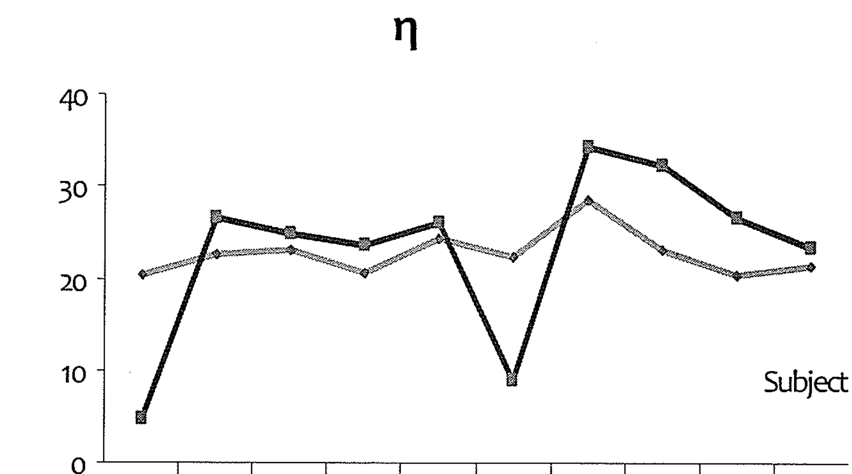
Table 3.4. The Error value for each subject in DF and 7-region paradigms



	1	2	3	4	5	6	7	8	9	10
DF_Error	2	1	1	0	1	1	2	2	0	1
7-Region_Error	2	2	3	1	2	3	3	3	2	1

Fig. 3.11. The Error value for each subject in DF and 7-region paradigms

In Section 2.2.2, η was the total value of the averaged signals in the specific interval around the P300 peak (Appendix B). Fig. 3.12 represents the average of η values for every subject. Once again, this index was higher in 7-region ($\mu_{7R} \cong 23.2, \mu_{DF} \cong 22.7$). It shows that the P300 responses to the 7-region paradigm generally have the higher amplitudes. As a result, this paradigm offers a trouble-free detection by better separating the P300 from artifacts compare to DF.



	1	2	3	4	5	6	7	8	9	10
DF	20.314	22.587	23.077	20.69	24.357	22.331	28.567	23.089	20.314	21.286
7R	4.747	26.462	24.904	23.537	26.197	9.0478	34.362	32.321	26.625	23.406

Fig. 3.12. DF vs. 7R, η value calculated for every subject

Average β value, average η value, total error and average of P300 amplitude are shown in the Table 3.5 for both spellers. Higher values demonstrate the better functionality of the paradigm (except the total error). Hence, the 7-region paradigm performs better than the DF paradigm overall.

	Average β	*Average η*	*Total Error*	*Average P300 Amplitude*
DF	0.011	22.661	36%	0.7048
7-Region	0.214	23.160	18%	0.7706

Table 3.5. DF paradigm vs. 7-region paradigm

3.2.3. Data Evaluation

The *Kolmogorov-Smirnov* or KS is a statistical test to ensure two samples of data are statistically different from each other. The output is *p* or level of significance. The lower the *p*, the more reliable the results. This test has the advantage of making no assumption about the distribution of data and so it is ideal for our case.

KS-test could be used to verify our results which were mainly obtained from the P300s' amplitude values. It can compare the distribution of P300s' amplitude values for DF and 7-region paradigm. In this case, the level of significance was low enough ($p = 0.0387 <= 5\%$) to reject the hypothesis that the distributions are the same. The value of *p*, however, is believed to be reasonably accurate for sample sizes n_1 and n_2 if $\frac{n_1 \times n_2}{n_1 + n_2} \geq 4$. In our case, the sample sizes were 60 for both DF and 7-region paradigm, hence *p* is accurate since $\frac{60 \times 60}{60 + 60} = 30 \geq 4$.

3.2.4. Influence of neighbors in the DF paradigm

It's believed that the major source of error in DF paradigm is *AB* by attracting user's attention to a non-target row/column adjacent to the target [38]. In this section, we study AB's influence on our data. However, low accuracy is expected because no training was arranged for P300 detection.

Overall, neighbor rows or columns were detected at least once during the analysis of 6 subjects (out of 10) that might be because of AB (Figs. 3.13.A-B). Table 3.6 shows how close the detected character was to the target character [38]. The number at the center of the table demonstrates the number of times that the target correctly detected. Other cells represent number of errors depends on the distance between the right row/column and detected row/column. From the center, each cell to the right and left shows the distance between detected row and target's row. Same thing is defined for columns as moving to the top and bottom. It could be inferred from this table that the error value increases in general by getting closer to the target's row and column. To evaluate this claim, we use the Chebyshev distance [37] formula as follow:

$$D = \lim_{k \to \infty} \left(\sum_{i=1}^{2} \left| e_i - c_i \right| \right)^{1/k} = \max_i \left(\left| e_i - c_i \right| \right)$$

where e_i and c_i are the locations of the target in the table and the wrongly detected characters respectively [38]. The results are illustrated in Fig. 3.14 where each sector represents the percentage of the error for different values of D.

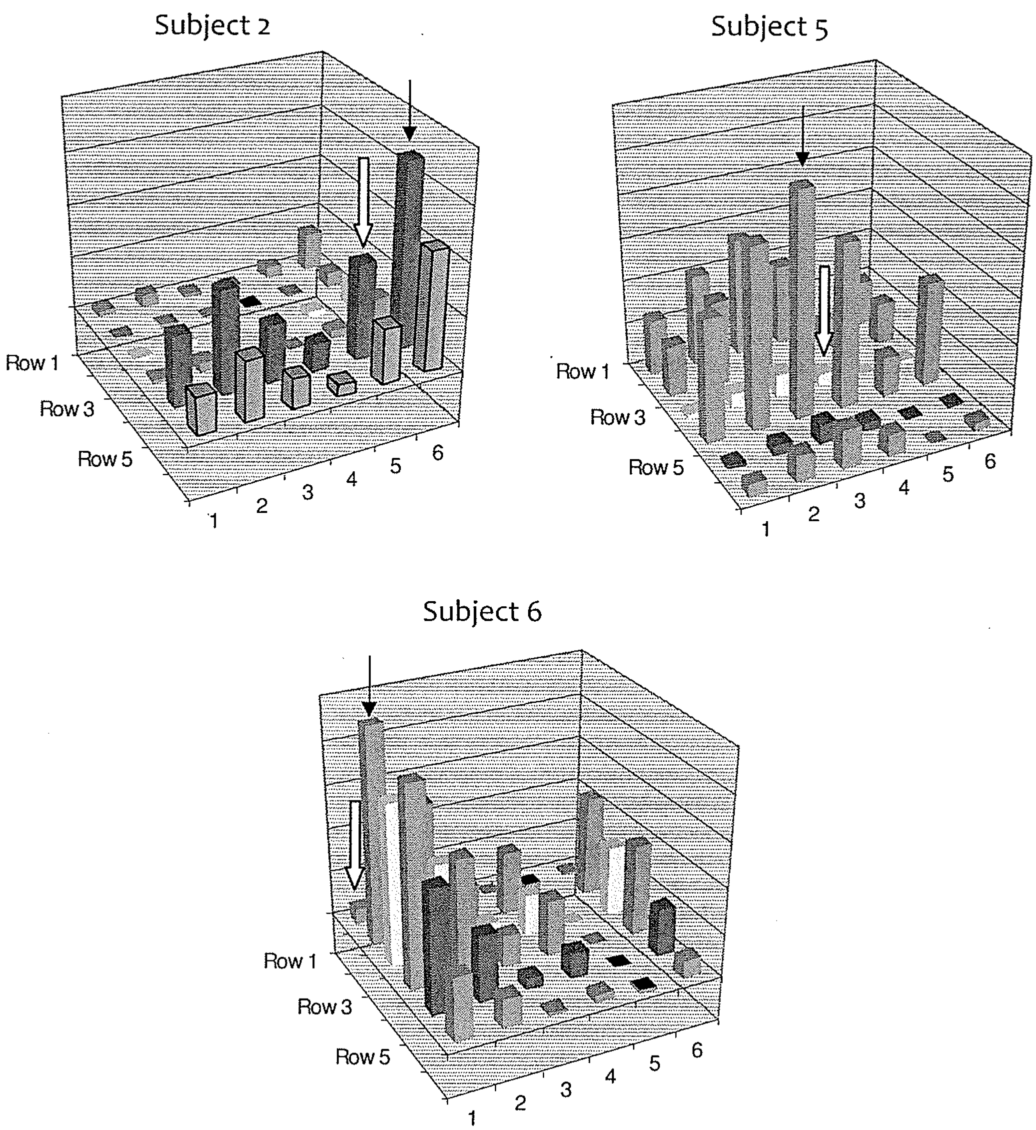


Fig. 3.13. A Neighbor character is detected instead of the target (Subjects 2, 5 and 6)

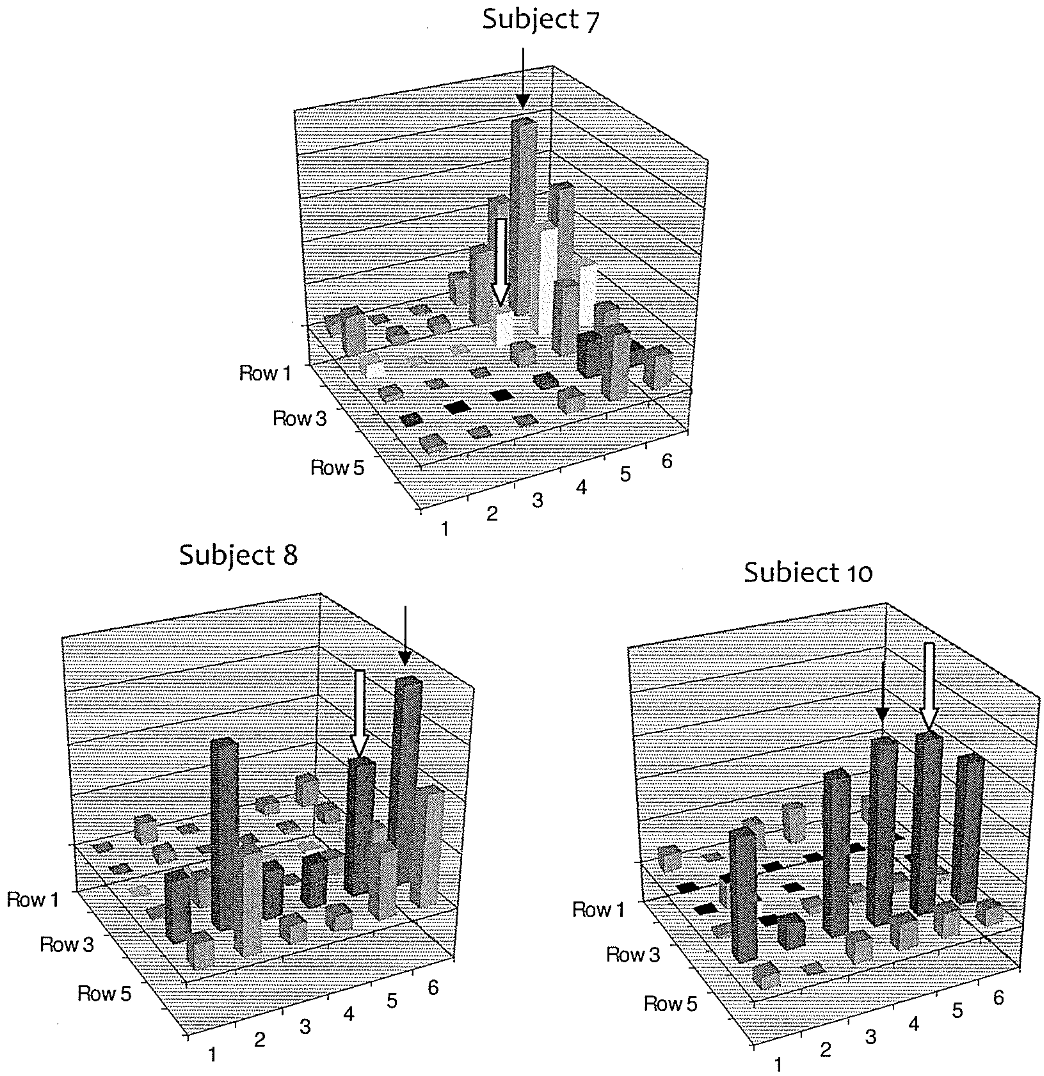


Fig. 3.13.B Neighbor character is detected instead of the target (Subjects 7, 8 and 10)

Row Difference \ Column Difference	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5	0	0	0	0	0	0	0	0	0	0	0
-4	0	1	0	0	0	0	0	0	0	0	0
-3	0	0	0	0	0	0	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	1	0	0	0	0
0	0	1	3	0	1	13	2	1	0	0	1
1	0	0	0	0	1	1	0	0	0	0	0
2	0	0	0	0	0	1	0	0	0	0	0
3	0	0	0	0	0	1	0	0	1	1	0
4	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0

Table 3.6. Error in target's row/column detection, the numbers show how far the row/column is detected from the actual row/column

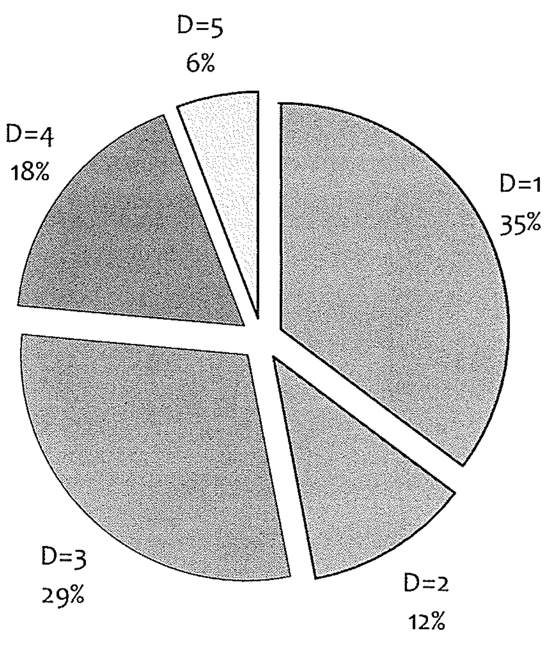


Fig. 3.14. Percentage error of Chebyshev distance in DF paradigm, the distance is defined between target's row/column and detected character's row/column

The adjacent row/column was detected in 35% of the time (D=1) more than any other rows/columns and confirms the influence of the neighbors in DF paradigm.

3.3. P300 Lie Detector

3.3.1. Experiment

The lie detector paradigm includes *P, T,* and *I* stimuli shown randomly to the subject. The *P* stimuli should evoke the P300 if it's meaningful to the subject. For this reason, to simulate the situation for the first series of the experiments, pictures of the subjects' own face were chosen as the *P* and specific group of images were selected as *T* and *I* stimuli (e.g. pictures of different flowers and different vehicles) (Fig. 3.15).

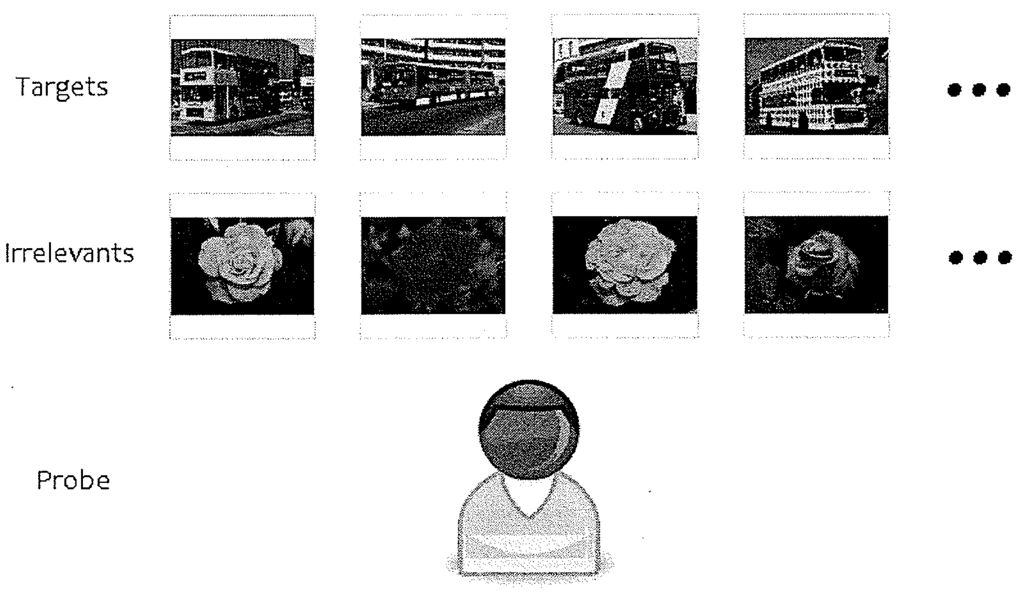


Fig. 3.15. PTI, first series of the experiments

After several experiments, we noticed that this design does not create the P300 as expected. Reasons can be summarized as follows:

1) In this design, the user will be quickly habituated to the picture of him/herself (*P*) because of using only one image in paradigm. As a result, he/she won't be able to generate the P300 in response to the *P* stimuli after a short period of time. As a reminder, the objective here is to study the influence of *P* stimuli on different subjects.
2) We expected the *I* stimuli to be neutral with no capability of P300 elicitation. However, they were too distractive. Hence, they can evoke an unnecessary P300 response (P3a).
3) A task is defined for the subjects to avoid habituation and attracting his/her attention and also to generate P300 (to compare the P300 which might be generated by *P* stimulus/stimuli). For this goal, the users must follow the *T* stimuli which are too difficult to track in this paradigm.

With considering these facts, we designed a new paradigm. For each of the subjects, we picked his/her friends' name as the *P* (without letting him/her know in advance) and random letters and numbers as the *T* and *I* stimuli, respectively (Fig. 3.16). In this design, *P* stimuli are dissimilar and so prevent the habituation. *I* stimuli are not supposed to generate P300 because they are not distractive anymore and *T* stimuli are easy to follow.

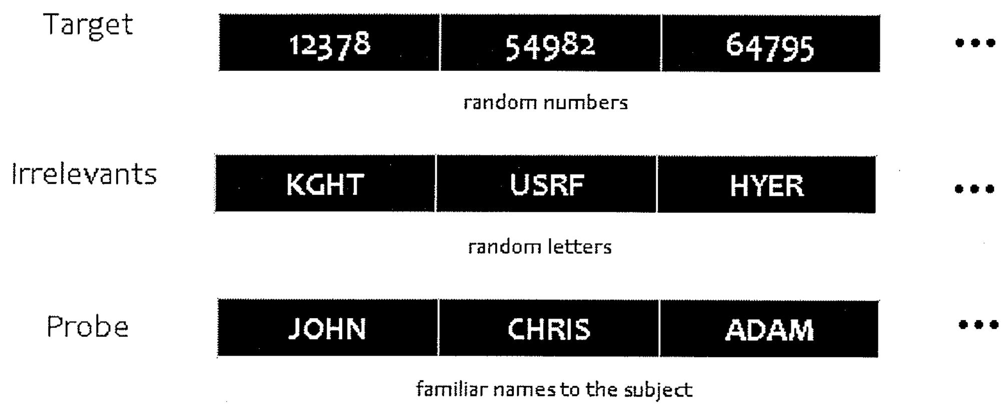


Fig. 3.16. PTI, second series of the experiments

3.3.2. Results and Discussion

In this section, the results of the second series of the experiments are discussed. In these experiments EEG signal was recorded at Fz, Cz and Pz using the left mastoid as the reference and forehead as the ground. 25 *T*, 25 *P* and 75 *I* stimuli randomly appeared on the screen for 1000 ms followed by 1000 ms blank screen (ISI:1 sec) while the subjects were asked to count the number of times that the *T* stimuli occur in the paradigm.

Fig. 3.17 and 3.18 show the result of two different experiments. As we expected, subjects generate P300 in response to *T* and *P* stimuli. Unexpectedly, they also respond to the *I* stimuli in the same way by generating the P300 response. It means despite the fact that random numbers are meaningless they could evoke P300. The reason might be because they were not as infrequent as they must have been [55]. It could be concluded that meaningless stimuli are able to elicit the P300 if they rarely happen. Therefore, a P300 might be observed in an innocent subject EEG signal in response to the infrequent meaningless *P* stimuli. This is absolutely against the first assumption of P300-based lie detector which is based on the difference between the influence of *P* stimuli on guilty and innocent subjects. To ensure about the validity of this statement, we designed four new paradigms discussed in Section 2.1.5.2.1 with infrequent meaningless *P* stimuli (black and white checkerboard). In these paradigms, 75 *P*, 75 *T* and 350 *I* (500 stimuli in total) were shown to the subjects. In addition, two of the experiments include a full-screen checkerboard as a *P* stimulus. This stimulus may distract the subjects in such a way that crime-related pictures are able to. The results are shown in Figs. 3.19-3.22.

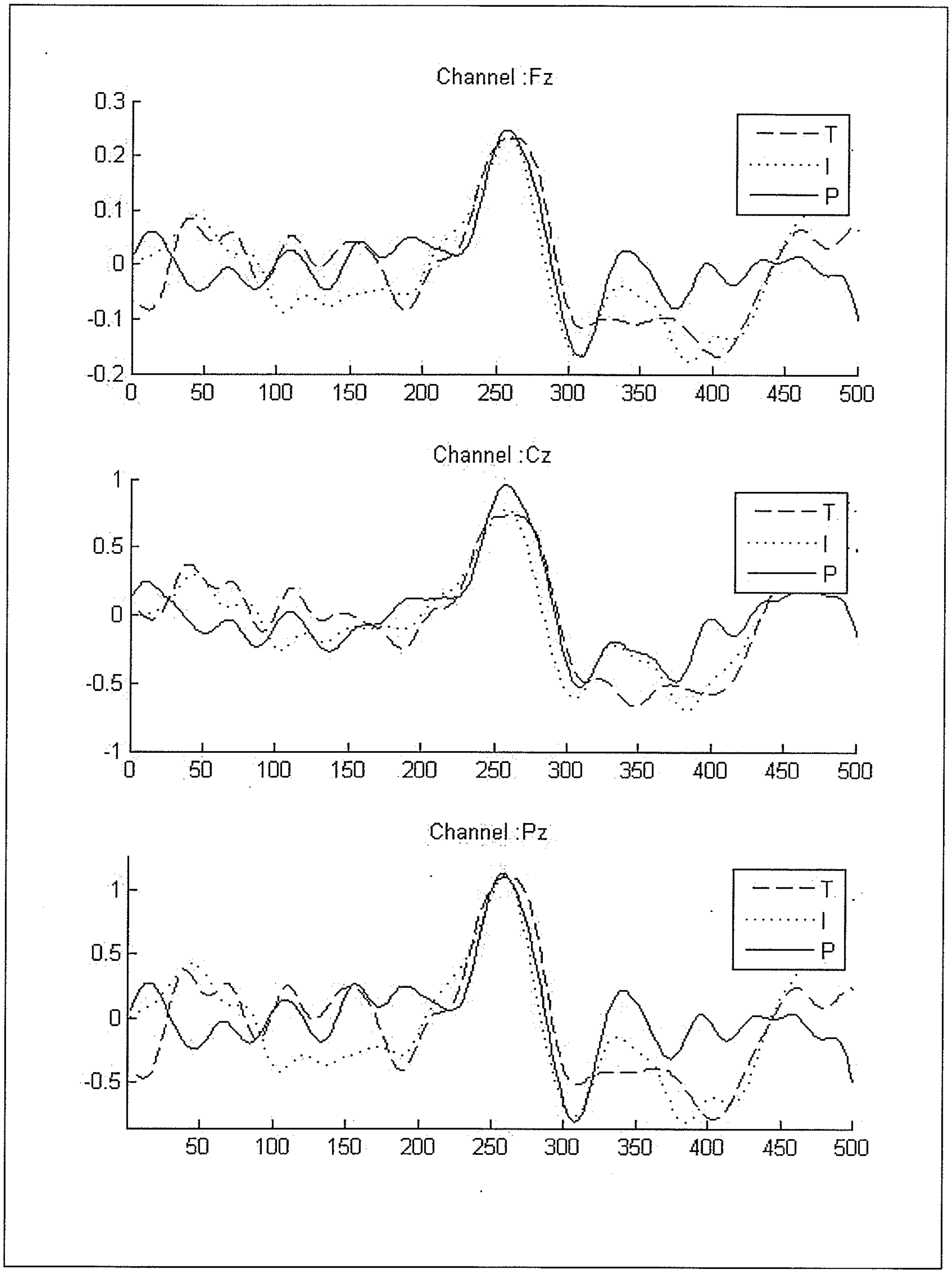


Fig. 3.17. ERP response to *P* (familiar names), *T* (random letters), *I* (random numbers) at Fz, Cz and Pz

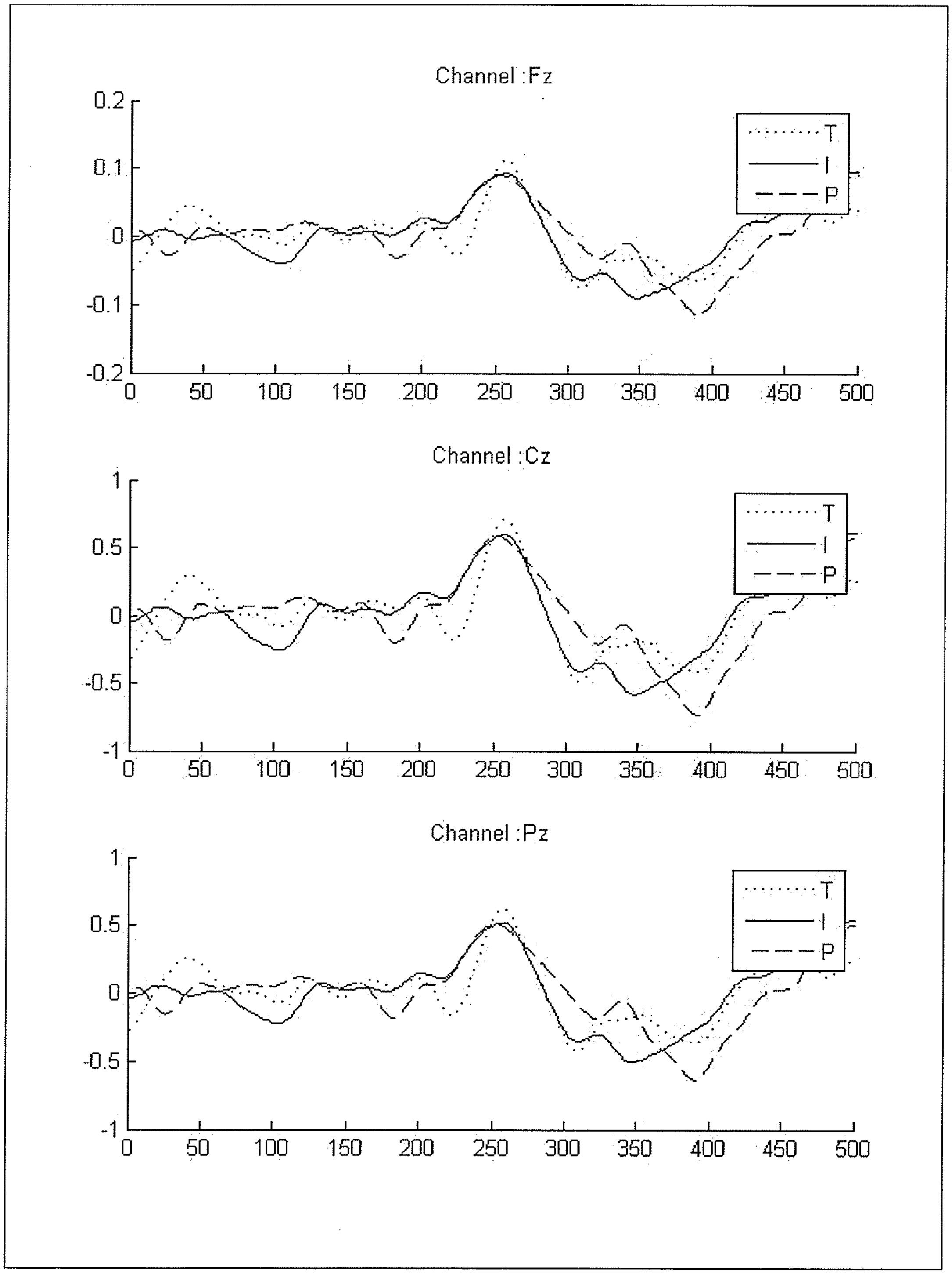


Fig. 3.18. ERP response to *P* (familiar names), *T* (random letters), *I* (random numbers) at Fz, Cz and Pz

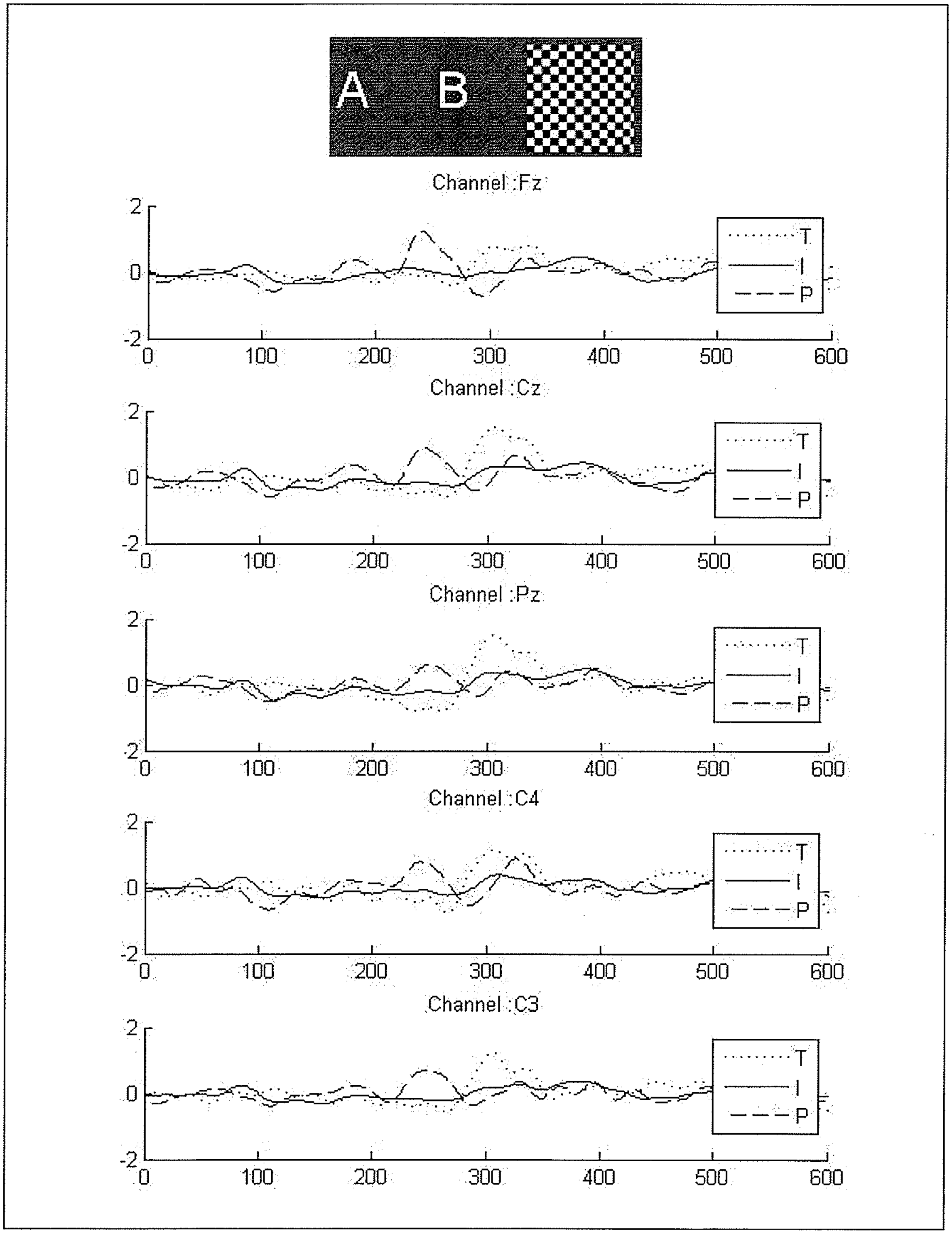


Fig. 3.19. ERP response to *P* (checkerboard), *T* ('B'), *I* ('A') at Fz, Cz, C3, C4 and Pz

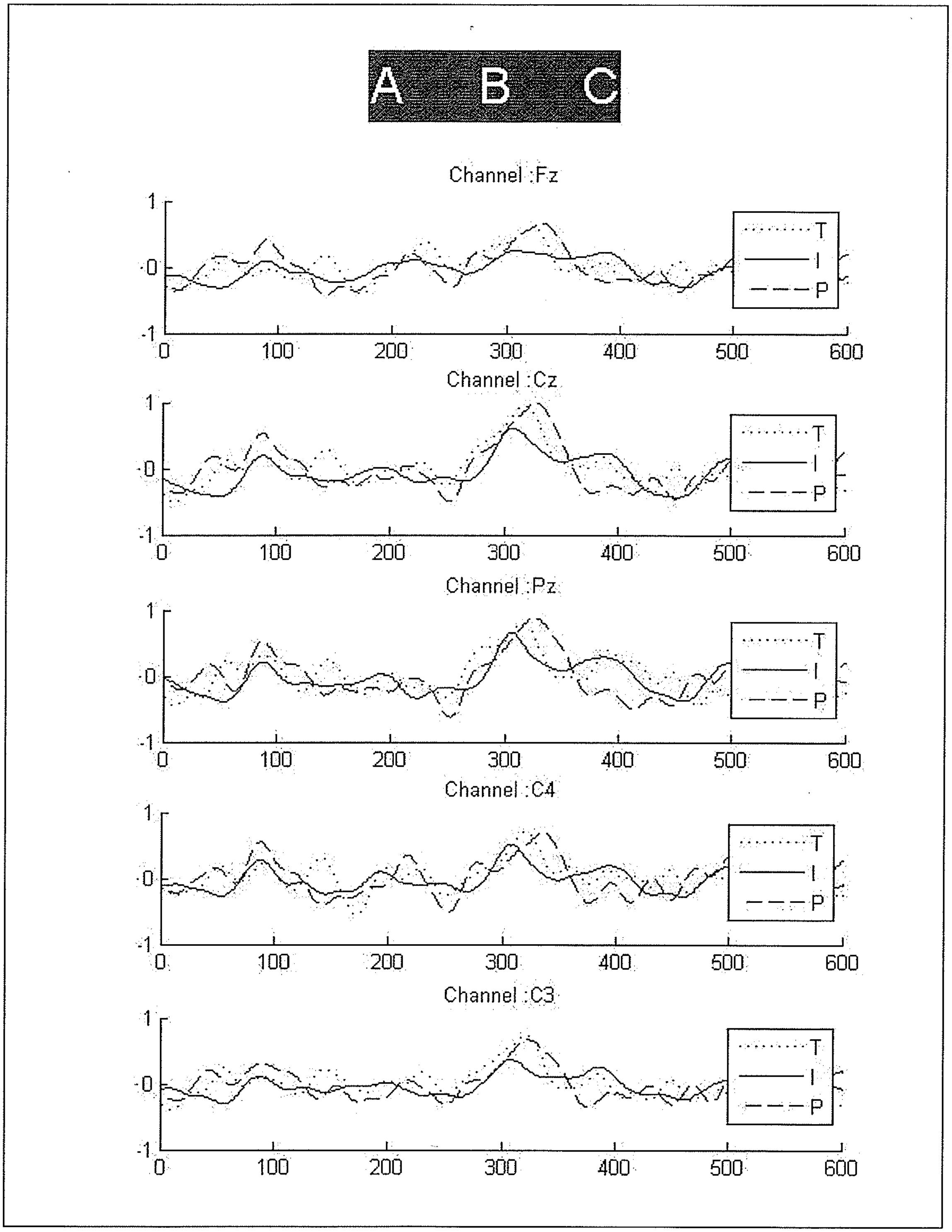


Fig. 3.20. ERP response to *P* ('C'), *T* ('B'), *I* ('A') at Fz, Cz, C3, C4 and Pz

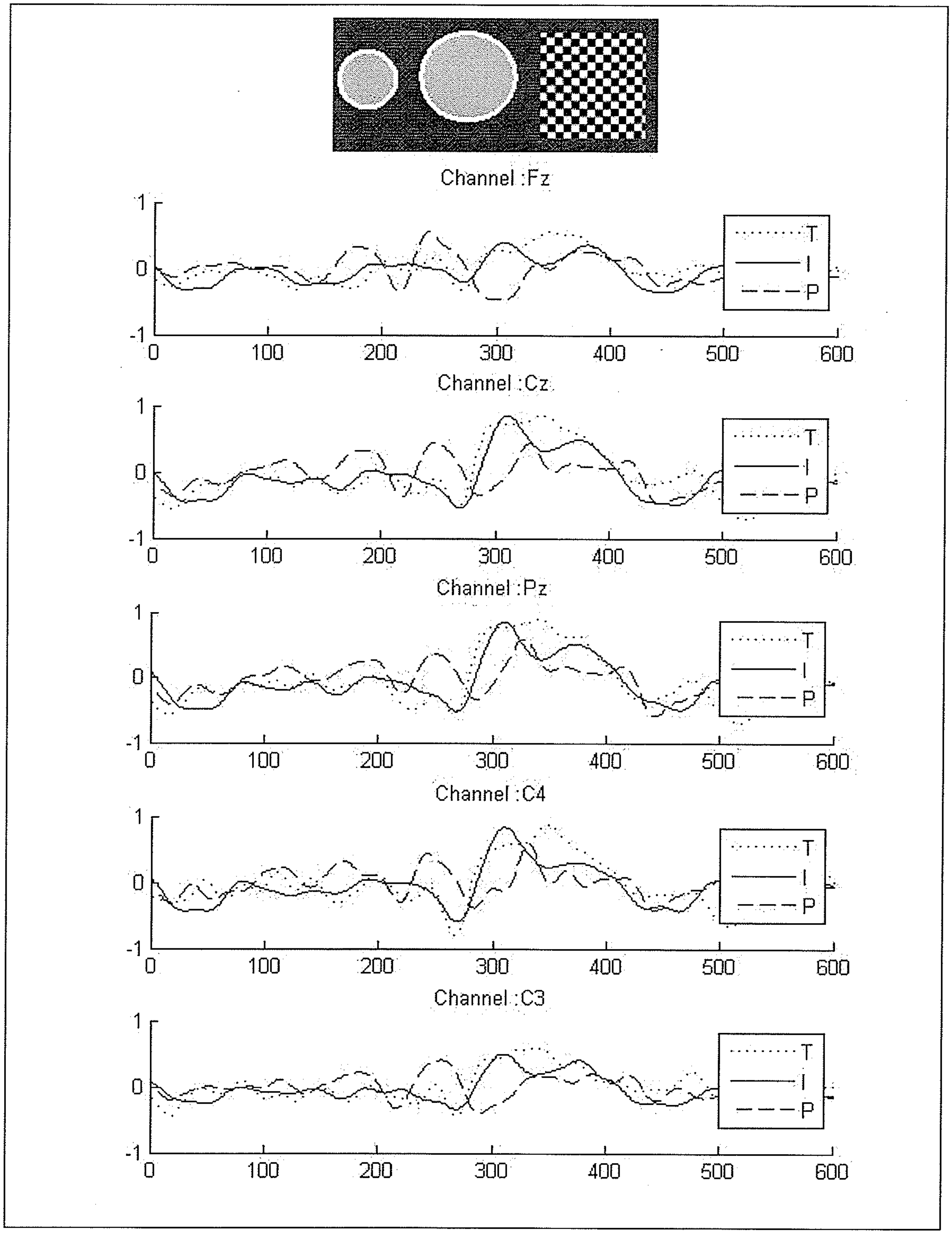


Fig. 3.21. ERP response to *P* (checkerboard), *T* (big circle), *I* (small circle) at Fz, Cz, C3, C4 and Pz

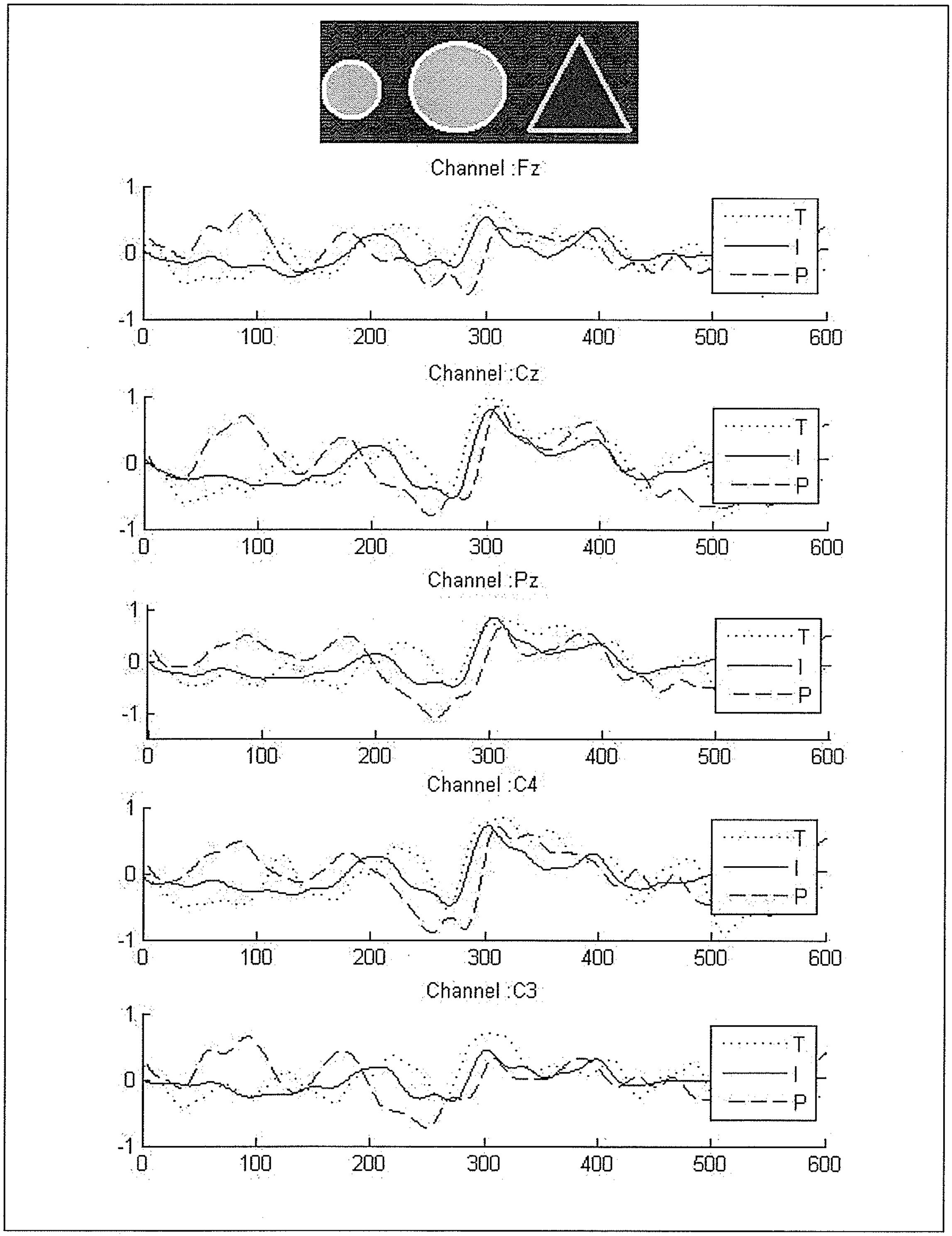


Fig. 3.22. ERP response to *P* (Triangle), *T* (big circle), *I* (small circle) at Fz, Cz, C3, C4 and Pz

Using the results of the third series of the experiments (Figs. 3.17-3.20) it can be deduced that:

1) Although *P* stimuli are meaningless to the subjects they could elicit the P300. It implies that 'response to the probe [may] ensure nothing' [[54]. However, in two cases where the checkerboard (distracter) was selected as the *P* stimulus the P3a was generated instead of regular P300 (P3b) response which was absolutely predictable (see Section 1.5). As a conclusion, whether the *P* stimulus is distracter or not it could generate the P300. The only difference might be between the type of this response.
2) By comparing the results, it can be noticed that *I* stimuli had more neutral effect when the task is *Easy* (distinguishing between the letter 'A' and 'B'). It could be helpful for designing a better paradigm as a future work.

Chapter 4 Conclusion

4.1. Conclusion

The main focus of this study was to design, implement and evaluate two applications of P300-based BCI: P300-based speller and P300-based lie detector. Designing these applications was not from the scratch and was based on the former studies. The first application, P300-based speller, was improved in terms of accuracy by designing a new paradigm. To confirm this improvement, several experiments were conducted. The results were promising enough to be a significant step towards developing the speller paradigm as a tool for disabled people for better communication. P300-based lie detector was the second application which was studied in this thesis. At the first step, due to the lack of criminals and crime-related situation, we tried to simulate this application and evaluate it using normal subjects. Results of the simulated lie detector confirmed the complexity of this application and the fact that it requires experts to select stimuli with comprehensive knowledge of the crime and the role of stimuli. However, we could not prove that probe stimuli have the same effect as the irrelevant stimuli if they mean nothing to the subjects. We can conclude that the P300 is not necessary due to the stored information in the subject's brain and may be happen because of the infrequency of the stimuli.

Therefore, P300-based lie detector could be criticized in two ways:

1) If the subject is innocent, we may observe the P300 in response to the probes because they infrequently take place in paradigm or they are distractive. This cannot confirm that the subject has some information in his memory about the stimulus.

2) Depending on the level of task difficulty, the irrelevant stimuli can generate the P300. Hence, in some cases they cannot create a baseline to compare the probe's responses.

Note that, due to several reasons such as the small sample of participants, non crime-related situation and replicated stimuli we neither verify nor refute the P300-based lie detector. We only believe that the P300-based lie detector is a complicated application that extremely depends on the choice of the stimuli and perhaps requires specific conditions to be practical.

4.2. Contribution

The contributions of this study are as follow:

- Implementing the Donchin-Farwell paradigm as a standard P300-based speller paradigm for comparison purposes.
- Designing and implementing a proposed speller paradigm (7-region paradigm) by considering the perceptual sources of errors in the DF paradigm.
- Conducting experiments to evaluate 7-region paradigm. The results proved that this paradigm performs with higher accuracy compare to the standard DF paradigm.
- Designing and implementing simulated P300-based lie detector.
- Evaluating the P300-based lie detector by conducting several experiments.

4.3. Future works

Since the P300-based speller doesn't require any complicated training, it's very effective method to help people who have lost the ability of communication. Our results signified that in the near future, paralyzed people will be able to quickly express their wishes with the external world with no difficulty. Even though our comparison proved that 7-region paradigm may offer the better result than standard DF paradigm, it requires to be tested on more number of subjects and especially on real patients. Moreover, to make it practical an error detection mechanism must be added to the system based on the user's feedback. Besides, as a future work, we can study the effect of characters' arrangement on the screen based on the probability of letters in English words and characters' background color during intensifications on the system's accuracy and speed. For this purpose, the 7-region paradigm was designed in such a way that let examiners select the location of each character and pick the desired color for their background (see Appendix A). Moreover, using other methods of P300 detection and classification such as wavelets would increase the accuracy of this application. In addition, P300-based lie detector may be our future polygraph to save innocent people which was simulated and tested in our laboratory. Although we couldn't prove its reliability but real situation might be required as well as more research and study to be fully developed and become practical.

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Appendix A Technical Aspects

A.1. Hardware

Our EEG instruments consist of an amplifier, an electrode-box with 32 channels, a PCI card which was installed on a PCI slot, several connector cables and ring electrodes (Fig. A1). All of the above items are made by *BrainProducts GmbH.*

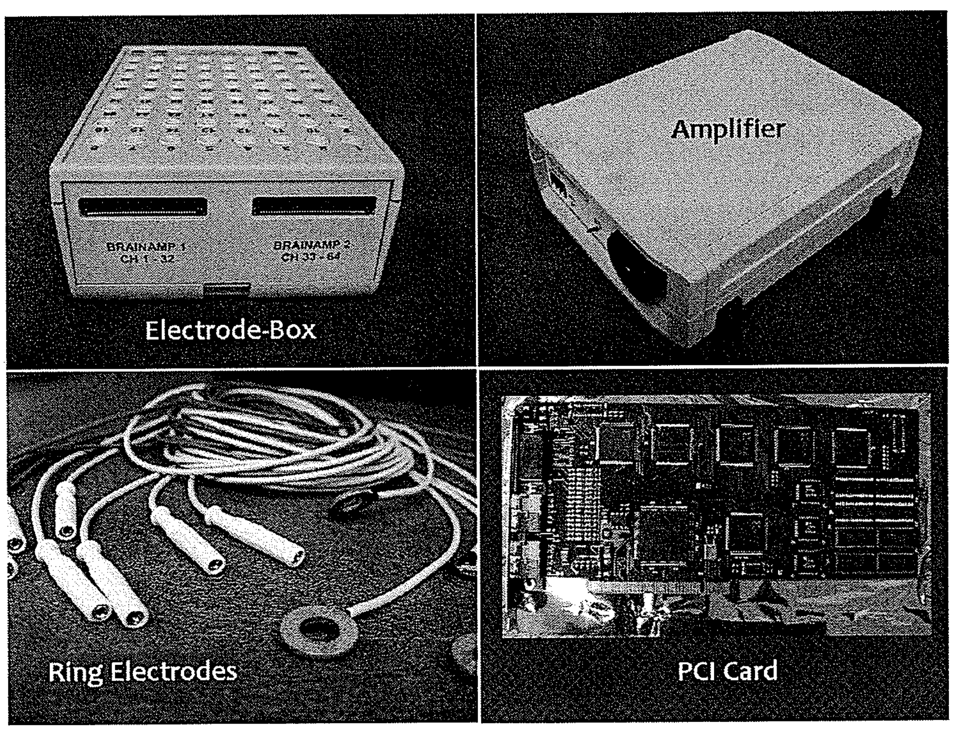

Fig. A.1. Experiments' hardware including an electrode-box, an amplifier, a PCI card and several ring electrodes

Recording the EEG needs some preparation which includes cleaning the skin with a skin prepping gel and reducing the impedance by placing an EEG paste on the electrode's area. We used '*Nuprep*' (Ingredients: water, Aluminum Oxide, 1,2 Propanediol, Sodium Polyacrylate, Methylparaben, Propylparaben, FD&C Blue 1, FD&C Red 40, FD&C Yellow 5) and '*Elefix*' (Ingredients: water, Polyoxyellylene Oleyiether Phosphate, Glycerin, Calcium Carbonate, Liquid Patrolatum, Propylene Glycol, Lanolin Alcohol, Sodium Chloride, Sodium Hydroxide, Polyoxyethylene Hydrogenated Lanolin, Coconut Fatty Acid Diethanolamide, Polyoxyethylene Stearylether, Polyoxyethylrne Oleylether, Egg Yolk Oil, Dibutylhydroxytoluene, Methl Parahydroxybenzoate, Propyl Parahydroxybenzoate) as the prepping gel and EEG paste respectively (Fig. A2). Both of them are CE approved. After preparation, the electrodes should be placed on the subject's head at the required recording sites based on 10-20 system.

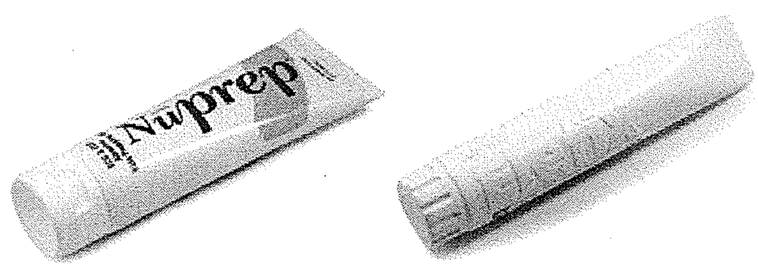

Fig. A.2. Nuprep (prepping gel) and Elefix (EEG paste)

A.2. Software

BrainVision Recorder (Fig. A3) was the software that we used to observe and record the EEG signal. In its environment, it is possible to

- See the markers within the EEG signal

- Create any number of display montages
- Configure acquisition parameters such as sample rate
- Change the scaling and polarity options.

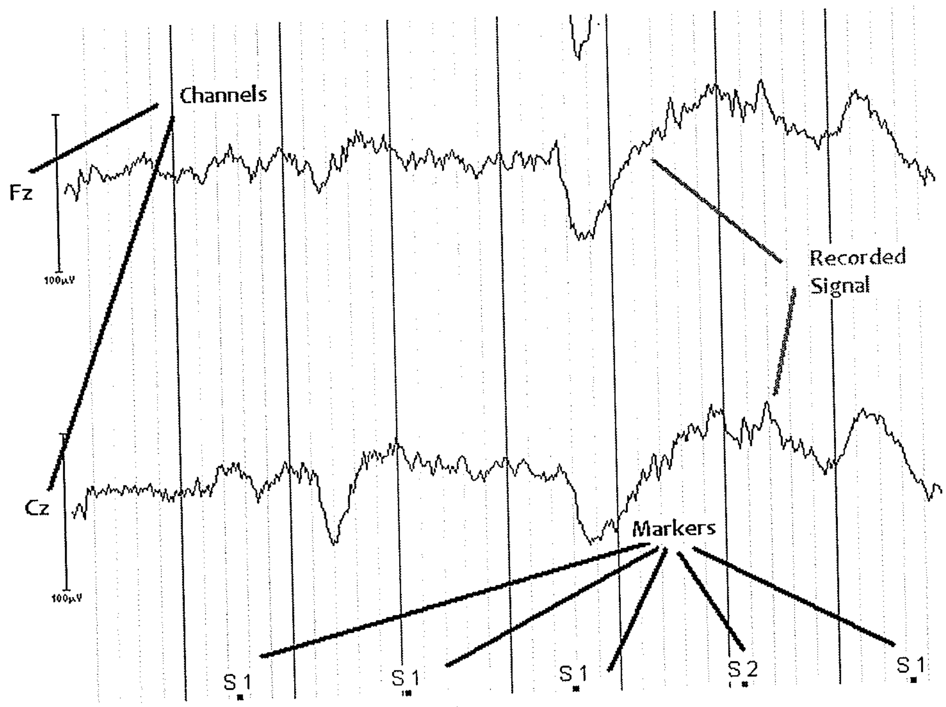

Fig. A.3. Screenshot of the EEG *Recorder* software

As mentioned in Section 4.3, the location of characters (region number) and their background color during flashing could be chosen in 7-region paradigm. These features are considered for further improvement. However, Fig. A.4 shows a screenshot of this paradigm's setup form where examiners are allowed to pick what regions include what characters and select the color in addition of setting up the time values and number of flashings.

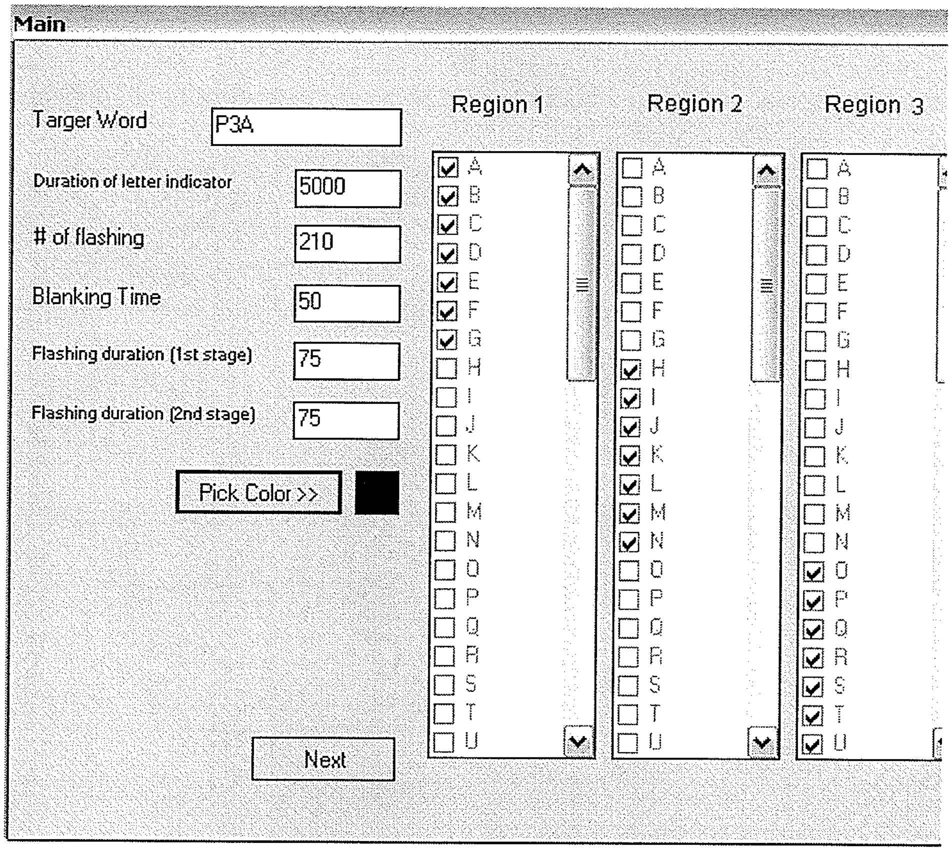

Fig. A.4. Screenshot of the 7-region paradigm's setup form

Fig. A.5 shows the setup form of the lie detector paradigm where so many features are considered for future developments.

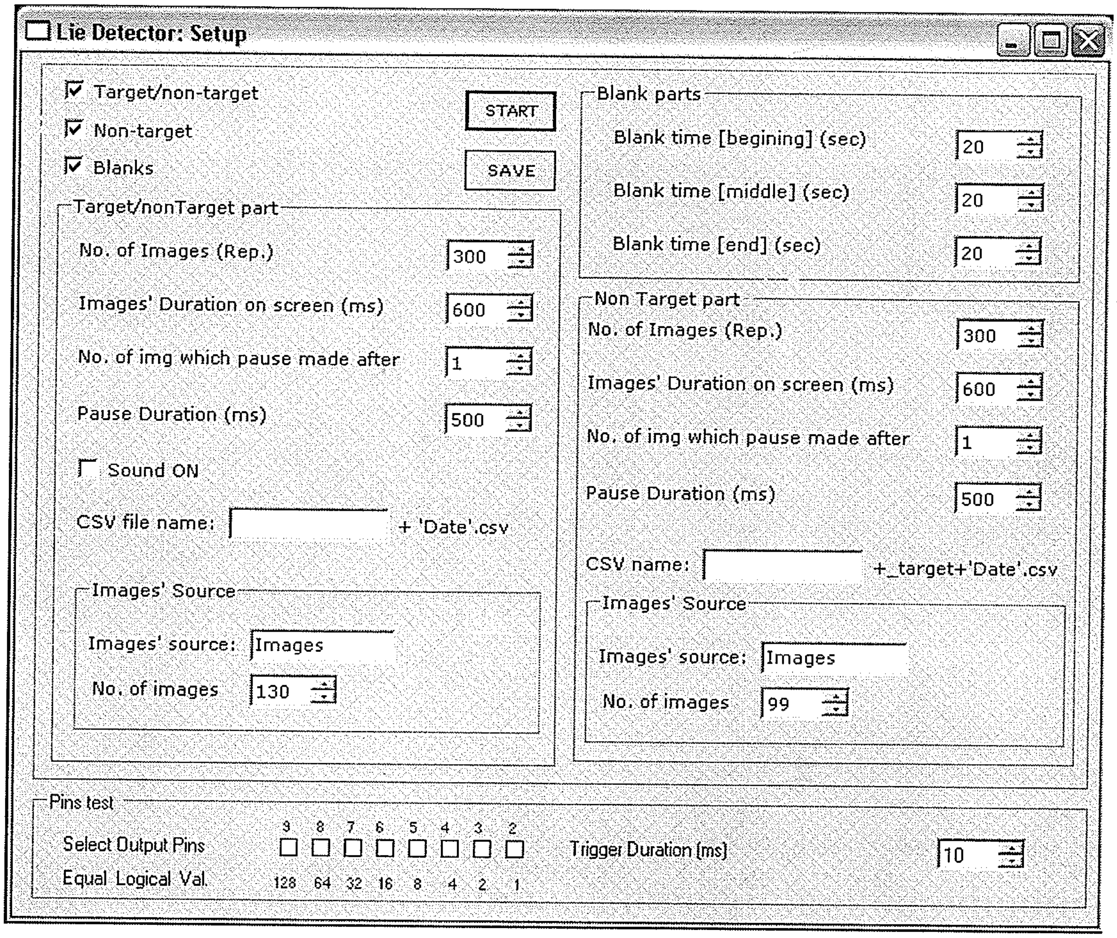

Fig. A.5. Screenshot of the lie detector's setup form

A.3. Synchronization

In an online mode, EEG signals are recorded and analyzed simultaneously. In contrary, in this study the data analysis was performed after the recording procedures. Thus, it's quite crucial to be able to locate the P300 wave within the recorded signal. One method is to mark the EEG signal instantly after the subject is confronted with the target stimulus. For this purpose, we connected the digital port of the amplifier's PC adapter card with LPT port. Additionally, the paradigms were programmed to trigger these ports immediately after the target stimulus comes to the view. Afterward, the EEG signals automatically were marked by the PCI card. In fact, marking the signal means storing the sample number of the signal in an ASCII file. Thereafter these markers could be used for taking the average.

To ensure that the EEG signal is perfectly synchronized with our computer interfaces, we decide to run a test. In this test we used the pin of the LPT port that is already connected to the digital port on the PCI card and fed it to one of the EEG input channels via a voltage divider with a 1:1000 ratio ($R_1 = 100\,\Omega$, $R_2 = 100\,k\Omega$, both 1% types) [†], i.e. V_{out} was 1:1000 of V_{in}. Afterwards, we trigger the LPT ports' pin and observe the recorded signal. The EEG signal was exactly marked at the same time as the voltage of the input channel gets high to 1.4 to 5 mV (1:1000 of TTL voltage). This technique simply proved the synchronization between markers and applications' interfaces.

[†] The whole test was done by consulting the company's scientific support manager and so it would not damage the equipments.

Appendix B Data Values

subject	η for each detected region in the 7-region paradigm						Ave(η)
1	2.3305	4.8467	5.7133	5.6981	5.642	4.2513	4.746983
2	25.5744	22.0533	26.7582	33.7861	25.8619	24.7397	26.46227
3	14.8129	22.009	20.4791	18.4162	36.3802	37.3265	24.90398
4	27.9192	20.737	22.3591	22.4365	27.2411	20.5282	23.53685
5	27.24674	18.8043	30.24951	26.09355	32.7633	22.02586	26.19721
6	17.9702	4.4955	9.7203	1.9661	9.8561	10.2786	9.0478
7	66.19192	46.13587	22.97329	19.46512	21.12884	30.27735	34.36206
8	61.03947	43.74142	23.7086	17.70764	20.81809	26.91307	32.32138
9	32.33814	24.03149	25.30544	24.55467	30.34966	23.16936	26.62479
10	28.13763	21.00367	22.34799	21.8046	26.44471	20.69699	23.40593

Table B.1.η for each detected region in the 7-region paradigm and the total average

subject	η for each detected row/column in the DF paradigm						Ave(η)
1	23.9316	34.043	8.9404	17.562	11.6994	25.7073	20.31395
2	22.8838	13.0936	24.0175	33.7861	20.3363	21.4064	22.58728
3	21.9034	16.7005	15.2833	21.5644	32.3265	30.683	23.07685
4	33.4879	10.2693	14.916	16.9899	27.2411	21.238	20.69037
5	16.39934	30.48069	14.81264	34.18126	35.10009	15.17066	24.35745
6	21.54004	31.29686	24.65086	27.69859	19.32425	9.474355	22.33083
7	24.86661	19.93039	28.32108	28.39392	25.34428	44.54302	28.56655
8	13.94644	25.26151	21.5028	35.75685	23.65342	18.41593	23.08949
9	23.93163	34.04299	8.940355	17.562	11.69945	25.7073	20.31396
10	34.50707	9.591585	11.76886	22.46851	19.5201	29.85971	21.28597

Table B.2.η for each detected row/column in the DF paradigm and the total average

DF paradigm						
Subject	Detected Peak Value in the DF paradigm (1:10 μv)					
1	0.637457	0.810789	0.538378	0.583319	0.410059	0.870386
2	0.882258	0.650881	0.646694	0.846622	0.588174	0.834185
3	0.564366	0.403155	0.388736	0.429314	0.517648	0.479913
4	1.145926	0.383617	0.696235	0.566523	0.653673	0.80005
5	0.639707	0.749908	0.617717	0.737849	0.943804	0.426504
6	0.475803	0.683312	0.712083	0.582001	0.385098	0.433163
7	1.077216	0.507407	1.142568	1.018001	0.89937	1.529462
8	0.763038	0.634881	0.530076	1.035652	0.763038	0.849104
9	0.637457	0.917061	0.538378	0.572441	0.407705	0.870386
10	1.560818	0.347917	0.56913	0.720478	0.697689	0.984634
Subject	Expected Peak Value in the DF paradigm (1:10 μv)					
1	0.637457	0.810789	0.538378	0.583319	0.319452	0.798385
2	0.458143	0.650881	0.489629	0.846622	0.588174	0.834185
3	0.564366	0.243789	0.124447	0.190137	0.517648	0.479913
4	1.145926	0.383617	0.519956	0.566523	0.653673	0.80005
5	0.635338	0.394177	0.617717	0.737849	0.943804	0.426504
6	0.378498	0.683312	0.419626	0.582001	0.385098	0.287537
7	0.623796	0.383381	1.142568	1.018001	0.498016	1.529462
8	0.330904	0.634881	0.431526	1.035652	0.763038	0.831912
9	0.637457	0.917061	0.538378	0.502589	0.407705	0.798385
10	1.560818	0.347917	0.535283	0.720478	0.697689	0.647267

Table B.3. Detected and Expected Peak Value in the DF paradigm

7-region paradigm						
Subject	Detected Peak Value in the 7-region paradigm (1:10 μv)					
1	0.155326	0.314156	0.364627	0.364543	0.364624	0.283448
2	0.86889	0.745849	0.843085	1.070355	0.855861	0.836476
3	0.485932	0.714496	0.652989	0.600416	1.137421	1.160127
4	0.901792	0.672234	0.739448	0.80043	0.912527	0.732492
5	0.863004	0.588884	0.972388	0.867089	1.101585	0.706135
6	0.587783	0.153464	0.313677	0.100849	0.327685	0.357795
7	2.200497	1.489402	0.767378	0.668452	0.787879	0.960119
8	2.006971	1.38939	0.789887	0.604908	0.694174	0.85481
9	0.901792	0.672234	0.726039	0.775831	0.885736	0.732492
10	0.908974	0.680761	0.811507	0.782167	0.893421	0.738704
Subject	Detected Peak Value in the 7-region paradigm (1:10 μv)					
1	0.12444	0.24148	0.364627	0.364543	0.364624	0.283448
2	0.86889	0.637538	0.843085	1.070355	0.855861	0.836476
3	0.485932	0.674747	0.652989	0.600416	1.137421	1.160127
4	0.901792	0.672234	0.739448	0.80043	0.912527	0.732492
5	0.863004	0.588884	0.851577	0.867089	1.101585	0.706135
6	0.283184	0.153464	0.313677	0.100849	0.327685	0.357795
7	2.200497	1.489402	0.56614	0.668452	0.710265	0.960119
8	2.006971	1.385779	0.512808	0.604908	0.694174	0.85481
9	0.901792	0.672234	0.726039	0.775831	0.885736	0.732492
10	0.908974	0.680761	0.729825	0.782167	0.893421	0.738704

Table B.4. Detected and Expected Peak Value in the 7-Region paradigm

Subject	The DF paradigm P300 peak value (1:10 μv)					
1	0.637457	0.810789	0.538378	0.583319	0.410059	0.870386
2	0.882258	0.650881	0.646694	0.846622	0.588174	0.834185
3	0.564366	0.403155	0.388736	0.429314	0.517648	0.479913
4	1.145926	0.383617	0.696235	0.566523	0.653673	0.80005
5	0.639707	0.749908	0.617717	0.737849	0.943804	0.426504
6	0.475803	0.683312	0.712083	0.582001	0.385098	0.433163
7	1.077216	0.507407	1.142568	1.018001	0.89937	1.529462
8	0.763038	0.634881	0.530076	1.035652	0.763038	0.849104
9	0.637457	0.917061	0.538378	0.572441	0.407705	0.870386
10	1.560818	0.347917	0.56913	0.720478	0.697689	0.984634

Table B.5. P300 peak value for each detected row/column in the DF paradigm

Subject	The 7-region paradigm P300 peak value (1:10 μv)					
1	0.155326	0.314156	0.364627	0.364543	0.364624	0.283448
2	0.86889	0.745849	0.843085	1.070355	0.855861	0.836476
3	0.485932	0.714496	0.652989	0.600416	1.137421	1.160127
4	0.901792	0.672234	0.739448	0.80043	0.912527	0.732492
5	0.863004	0.588884	0.972388	0.867089	1.101585	0.706135
6	0.587783	0.153464	0.313677	0.100849	0.327685	0.357795
7	2.200497	1.489402	0.767378	0.668452	0.787879	0.960119
8	2.006971	1.38939	0.789887	0.604908	0.694174	0.85481
9	0.901792	0.672234	0.726039	0.775831	0.885736	0.732492
10	0.908974	0.680761	0.811507	0.782167	0.893421	0.738704

Table B.6. P300 peak value for each detected region in the 7-region paradigm