TIME-FREQUENCY ANALYSIS OF EVENT RELATED BRAIN POTENTIALS ELICITED WITH FOUR DIFFERENT COGNITIVE PARADIGMS

139088

by

H. Yasemin Keskin

B. S. in Medical Biological Sciences Department,
Cerrahpaşa Medical Faculty, İstanbul University, 2000

Submitted to the Institute of Biomedical Engineering
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Biomedical Science

Boğaziçi University
August, 2003

139088

TIME-FREQUENCY ANALYSIS OF EVENT RELATED BRAIN POTENTIALS ELICITED WITH FOUR DIFFERENT COGNITIVE PARADIGMS

APPROVED BY:

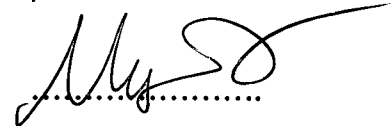Assoc. Prof. Dr. Ahmet Ademoğlu
(Thesis Supervisor)

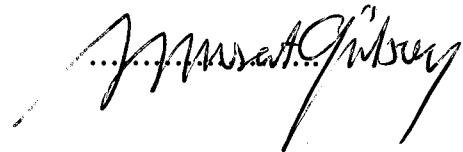Prof. Dr. Tamer Demiralp
(Thesis co-supervisor)

Assistant Prof. Dr. Ata Akın

Assoc. Prof. Dr. Mehmed Özkan

Assistant Prof. Dr. Murat Gülsoy

DATE OF APPROVAL:

ACKNOWLEDGMENTS

Firstly, I would like to thank to my supervisor Assoc. Prof. Dr. Ahmet Ademoğlu for his helps and interest not only during this study, but during my graduate education in Institute of Biomedical Engineering.

I am deeply grateful to Prof. Dr. Tamer Demiralp, who motivated me to study in this field, for his support and suggestions throughout this study and in my academic progress.

I would like to express my special thanks to Assoc. Prof. Dr. Müge Devrim, for our long, helpful, pleasant, and motivating scientific conversations and reading sessions.

I also thank to the all members of the Department of Physiology of the İstanbul Medical Faculty for providing me with the opportunity of carrying out this study in their electro-neurophysiology laboratory. Also, thank to the co-workers of this laboratory for their helps and friendship.

Lastly, I would like to thank my family, who supported me with great patience.

ABSTRACT

TIME-FREQUENCY ANALYSIS OF EVENT RELATED BRAIN POTENTIALS ELICITED WITH FOUR DIFFERENT COGNITIVE PARADIGMS

Event related potentials (ERPs), which reflect fundamental cognitive operations, are generated by the parallel and/or the sequential processing of different neural groups in the brain. In time domain representation of ERPs, temporally overlapping processes are hidden and they cannot be distinguished. However, the surface ERPs can be decomposed into functional neuronal components using time-frequency analysis. The aim of this study is to differentiate the time-frequency components that are related with specific cognitive operations (i.e. signal discrimination, motor response task, motor response inhibition, and context updating) in the auditory ERPs. For this purpose, by making systematic modification in cognitive content of the paradigms, experimental set that consists of four auditory paradigms was designed. ERP reflections of these modifications both in the time domain and in the time-frequency plane were explored in order to assign specific ERP sub-components to specific cognitive processes. Data obtained from 16 healthy volunteers were decomposed by discrete wavelet transform into six sets of wavelet coefficients. Alpha, theta, and delta band coefficients and P200 and P300 measurements of the midline electrodes (Fz, Cz, Pz) that were obtained from individual average ERPs for each stimulus condition were analyzed with five-factor analysis of variance (ANOVA) design. Compared to time domain analysis, results of the time-frequency analysis brought detailed information about the stimulus processing steps in different conditions. However, some components showed varying topographic distributions across the paradigm set. Namely, the wavelet transform could partially decompose these spatially overlapping events into functionally distinct sub-components. Therefore, in order to decompose ERPs more accurately into their functional sub-components, spatial decomposition methods should also be incorporated to the time-frequency analysis.

Keywords: Event Related Potential (ERP), P300, P200, Time-frequency Analysis, Wavelet Transform.

ÖZET

DÖRT FARKLI BİLİŞSEL PARADİGMA İLE ELDE EDİLEN OLAYA İLİŞKİN BEYİN POTANSİYELLERİNİN ZAMAN-FREKANS ANALİZİ

Temel bilişsel süreçleri yansıtan olaya ilişkin potansiyeller (OİP'ler), beyinde farklı nöral grupların paralel ve/veya birbirini takip eden etkinlikleri sonucu oluşurlar. Zamansal olarak üst üste gelen süreçler OİP'lerin zaman alanındaki gösterimlerinde gizlenmişlerdir ve ayrıştırılamazlar. Fakat zaman-frekans analizi kullanılarak yüzey OİP'leri fonksiyonel bileşenlerine çözümlenebilir. Bu çalışmanın amacı, işitsel OİP'lerdeki spesifik bilişsel süreçler (sinyal ayrımı, motor yanıt ödevi, motor yanıt inhibisyonu ve bağlamın yenilenmesi) ile ilişkili zaman-frekans bileşenlerini ayırt etmektir. Bu amaçla, paradigmaların bilişsel içeriklerinde sistematik değişiklikler yapılarak dört işitsel paradigmadan oluşan deney seti tasarlandı. Spesifik OİP alt bileşenlerini spesifik bilişsel süreçlere atamak için bu değişikliklerin OİP yansımaları zaman alanı ve zaman-frekans uzayında incelendi. 16 sağlıklı gönüllüden elde edilen veriler ayrık dalgacık dönüşümü ile 6 set dalgacık katsayısına çözümlendi. Her uyaran koşulu için, her bir deneğin ortalama OİP'lerinden elde edilen orta hat elektrotlarının (Fz, Cz, Pz) alfa, teta ve delta katsayıları ve P200 ve P300 ölçümleri beş-faktör varyans analizi (ANOVA) dizaynı ile incelendi. Zaman alanı analizine kıyasla zaman-frekans analizinin sonuçları farklı koşullarda uyaranın işlenme aşamaları ile ilgili daha detaylı bilgiler sağladı. Fakat, bazı bileşenler paradigma dizisi boyunca değişen topografik dağılımlar gösterdiler. Yani, dalgacık dönüşümü uzaysal olarak üst üste gelen bu olayları kısmen farklı işlevsel alt bileşenlerine çözümleyebildi. Bu nedenle, OİP'leri daha doğru bir şekilde fonksiyonel alt bileşenlerine çözümleyebilmek için uzaysal çözümleme metotları zaman-frekans analizi ile birleştirilmelidir.

Anahtar Sözcükler: Olaya İlişkin Potansiyel (OİP), P300, P200, Zaman-frekans Analizi, Dalgacık Dönüşümü.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

A1 - 10	Alpha coefficients
ANOVA	Analysis of variance
C, NC	Context updating, No-context updating
D, ND	Discrimination, Non-discrimination
D1 - 5	Delta coefficients
DWT	Discrete Wavelet Transform
EEG	Electroencephalography
EMG	Electromyogramphy
EOG	Electrooculogram
ERP, ERPs	Event Related Potential(s)
fMRI	Functional Magnetic Resonance Imaging
FT	Fourier Transform
I, NI	Inhibition, No-inhibition
ICA	Independent Component Analysis
PCA	Principal Component Analysis
PET	Positron Emission Tomography
STFT	Short Time Fourier Transform
T, NT	Motor response task, No-motor response task
T1 - 5	Theta coefficients
TW	Time Window
WC	Wavelet Coefficient
WT	Wavelet Transform

1. INTRODUCTION

1.1 Background

Event related potentials (ERPs) are promising tools in order to investigate physiological correlate of information processing because they can be recorded at the time the cognitive processes are supposedly occurring. However, ERPs do not reflect one type of cognitive operation; rather, they reflect more than one process, P300 potential for example is associated with not only working memory but also voluntary attention [1, 2]. In other words, ERPs are generated parallel and/or sequential processing of functionally different neural groups in the brain during stimulus processing.

Conventional ERP analyses, as amplitude and latency measurement in averaged potentials are limited because ERP peaks are assumed to be descriptors of the unique neural activities, but ERPs are not homogeneous phenomena. Rather, stimulus or response locked voltage fluctuations in the EEG that reflects the summated time courses of underlying neural events. In the usual time domain representation of ERPs, the sub-components that may occur at different frequency ranges cannot be always discriminated if they are overlapping partly or fully in time.

Different methods such as ERP subtraction, frequency analysis and statistical methods were used to differentiate sub-components of the ERPs. In ERP subtraction method, difference wave is obtained by subtracting one waveform from another. This method was used efficiently to identify many different ERP components such as mismatch negativity and processing negativity [2, 3]. Nevertheless, two conditions that are compared should differ only in a process of interest in order to apply this method. Further, if the waveforms differ in latency, subtraction yields a spurious component.

Other attempt for component extraction is to use pattern of covariation in the ERP data sets. Statistical methods, principal component analysis (PCA) and independent component analysis (ICA) are commonly used in previous studies [4-6]. These methods assume that topography is constant along time, and these techniques find out common

spatial patterns that co-exist under different conditions with different weights and time-courses. However, the same anatomical structure may show separate activations in relation with different aspects of information processing. In addition, activation in a single anatomical location does not necessarily imply that the function is located there, but it is usually a part of distributed activity, which in total corresponds to a unique function. Therefore, spatial or temporo-spatial decomposition techniques like PCA and ICA are of limited value for the functional decomposition of ERPs.

The frequency content of ERPs was suggested as a significant clue to differentiate the neural substrates and functional mechanisms generating them [7, 8]. Analysis of EEG and ERPs in the frequency domain already revealed that different spontaneous or evoked EEG rhythms are functionally related to information processing and behavior [9, 10]. In these studies, alpha response is suggested to be generated from the thalamo-cortical and the cortico-cortical feedback loops during retrieval of the information from long term memory [8, 9]. In addition suppression of the alpha response is associated with the cognitive performance and attention [8, 9]. Theta response is thought to be generated by hippocampal-cortical feedback loops during signal detection and encoding of new information [9, 10]. Delta response is also thought to be generated by hippocampal-cortical loops and associated with signal matching, decision making, and surprise [10].

Frequency domain analysis like Fourier transform (FT), which breaks signal down into a series of component frequencies that can be added together with correct proportions to reconstruct the original waveform, represents frequency content of the signals, but it cannot give any information about timing of the transient neuronal events. Therefore, an efficient means for studying the multi-component structure of the ERPs is to apply time-frequency analysis.

One alternative method is adaptive band pass filtering introduced by Basar [11], which is a combined time and frequency domain analysis. In that method, firstly, the major frequencies in the ERP signal are determined using FT and then the timing of stimulus related oscillations are obtained by using adaptive digital band pass filters [11]. Although this method allows the presentation of the time course of the frequency content of the signal, it cannot extract overlapping time-varying spectral features of it.

Another commonly used method for time-frequency analysis is the short time Fourier transform (STFT) [12]. The STFT divides the time domain into uniformly spaced windows and applies FT to the signal in each of these epochs. However, using fixed time windows causes loss of information; because the longer the window size the worse time resolution and the shorter the window, the worse the frequency resolution of the signal. Thus, the time-course of the transient high-frequency components in the ERPs cannot be detected by using STFT.

Wavelet transform (WT), unlike the STFT, allows flexible control over the resolution for different frequency range in the signal involving shorter time windows for higher frequencies and longer time windows for lower frequencies. Consequently, wavelet decomposition provides precise measurement of when and to what degree transient functional components occur in the ERP signal, and when and how the frequency content of a waveform changes over time.

The WT has been demonstrated to be an efficient approach with optimal time and frequency resolutions [13-23]. This method previously applied to ERPs elicited in an oddball task to examine multiple functional components within the auditory P300 [14, 18, 19, 20]. In these studies, three time-frequency components from the delta (0.1–4 Hz), theta (4–8 Hz), and alpha (8–16 Hz) bands within the P300 latency range were found different in processing of the infrequent targets from processing of the frequent non-targets [14, 18, 19, 20]. In the view of the results of the previous studies, Demiralp et al, [21] used WT to detect presence of P300 potential in the single trial ERPs.

In another study, Yordonova et al, [22], systematically varied paradigm properties (i.e., stimulus probability, discrimination, and mental counting properties), that are known to affect P300 amplitude, of the oddball paradigm and they investigated time-frequency reflections of these manipulations. Results of this study revealed that previously defined alpha, theta, and delta components significantly depend on the factors that affect P300 potential and these components showed distinct patterns [22].

Further, Demiralp et al., [23] applied WT in order to investigate target/standard discrimination difficulty and novelty effect on the responses to both target and non-target stimuli in the three-stimulus paradigm. Consequently, it was suggested that although target/standard discrimination difficulty, instead of the novelty, determines the generation of the visual P3a, yet additional theta effect was found for the novel stimuli in the time-frequency analysis.

Although the mathematical decomposition of the data by means of WT would not produce the precise neural sub-components of the ERPs, the decomposition gives logarithmically scaled frequency bands, which are also the basic frequency bands (gamma, beta, alpha, theta and delta) of the EEG. Further, defined alpha, theta and delta components in the previous studies and their physiological interpretations are in accordance with the P300 generating processes [18–23]. Hence, wavelet transform is a promising method to investigate dynamic time-frequency characteristics of the ERPs.

1.2   Objectives

A number of sensory and cognitive paradigms are designed and used to obtain P300 potential and other earlier potentials. Previous ERP studies revealed that the differences in the physical properties of stimuli such as modality, duration, and intensity [24, 25], in the relative properties of stimuli such as probability, task-relevance and context [26-28], and in the psychological variables and/or states of the subjects such as motivational value, attention, general and phasic arousal [29, 30] produce detectable changes in the parameters of the P300 potentials.

In addition, biological factors such as age, gender, diurnal cycles, etc., may substantially modulate ERPs [30]. Further, in some neuropsychological disorders such as schizophrenia and Alzheimer's disease, P300 parameters differ significantly from healthy controls frequently in correlation with cognitive impairment [31, 32].

In time domain representation of ERPs, these changes can be merely analyzed as the amplitude and/or the latency and/or the topographic differences, but the effects of these factors on different ERP components cannot be known. Because the time-frequency plane analysis by means of wavelet transform divides ERPs into several time-frequency components, which corresponds approximately to the common frequency bands of EEG, this analysis might bring with more detailed information about electrogenesis of these effects.

In the present study, a special paradigm set was constructed to investigate possible differences in time-frequency components of ERPs, which might be produced by cognitive properties of the paradigms. For this purpose, the paradigms were designed and ranked with systematic modification in their cognitive content. In time domain analysis, late positive deflections, P200 and P300, which are mostly associated with fundamental cognitive processes and also affected by the cognitive manipulations in the paradigms, were analyzed. The results obtained using the time-frequency decomposition of ERPs were compared with the time-domain results to test the efficiency of the wavelet transform in obtaining more detailed description of the processing steps of the study.

This study, as a continuation of the previous studies, in which WT was used to investigate time-frequency characteristics of the ERPs, was aimed to expand current information about time-frequency components of the ERPs in relation with the different cognitive processes. Further, the time-frequency characteristics of different paradigms, such as single-stimulus and go/no-go paradigms, with different cognitive content that were not previously studied were investigated. The results of our prospectively designed study, which includes wide range of paradigm types, may also construct a time-frequency template for this paradigm set for further studies both in healthy population and different patient groups.

1.3   Outline of the Study

This study consists of seven chapters. The first chapter reviews background related to several analyses methods of ERPs and the objectives of our study. Chapter 2 introduces the basic concepts of the ERPs with the potentials that were investigated in this study and the used paradigm types. Chapter 3 covers the basic information about time-frequency analysis by means of wavelet transform. In the Chapter 4, experimental design and the application of analyze methods are introduced. The results of the analyses are given in the Chapter 5 and discussed in the Chapter 6. Conclusions are given in the seventh chapter of this study.

2. EVENT RELATED POTENTIALS AND FOUR AUDITORY PARADIGMS

2.1 Introduction

ERPs are the summation of the electrical activities that are generated synchronously by different neuronal groups in the brain, which might be reflecting specific cognitive operations. In other words, ERPs consist of multiple components that are most probably neural groups firing in different frequency range with different function.

Formerly, ERPs were divided into two types of components, "exogenous" and "endogenous" components. Exogenous components were thought as early ERPs like N100 and it was thought that their amplitudes and latencies are influenced by physical properties of sensory stimuli (e.g., intensity, modality, duration) but not by cognitive manipulations (e.g., attention, task relevance). The endogenous components on the other hand, were thought as late ERPs like P300 and it was regarded that they depend on the processing required by the stimulus and they are influenced by cognitive manipulations. However, almost all early potentials were shown as modifiable by cognitive manipulations like attention [33, 34] and many of the later components were shown to be influenced by the physical attributes of the eliciting condition like stimulus modality [25]. Hence, it is more plausible that these two types of components are rather coextensive with the time and early potentials tend to be more exogenous and late potentials tend to be more endogenous [35].

In order to minimize changes in exogenous component of the ERPs, modality, intensity, and duration of the stimuli was kept stable; stimulus types, probabilities and inter stimulus intervals were kept as similar as possible throughout our paradigm set. However, cognitive content of the paradigms was systematically manipulated to observe ERP reflections of these manipulations both in time domain and time-frequency plane.

In the present study, late positive deflections P200 and P300, which are regarded as more endogenous potentials, were analyzed in the time domain. Section 2.1.1 and 2.1.2 cover the basic information about these potentials.

2.1.1 P300 Potential

Sutton and his colleagues discovered P300 in 1965 [36] and after almost four decade, it still attracts special attention among other ERPs. Although a lot of information about its possible generators and psychological correlates was obtained, the precise neural origins and, therefore, neuropsychological meaning of this potential remains to be answered.

In general, P300 potential is obtained using the "oddball" paradigm, wherein two stimuli presented in random order with one occurring less frequently than the other one. The participant is required to discriminate the infrequent stimuli from the frequent one by responding covertly (mentally counting) or overtly (button press). The P300 elicited as a response to infrequent target stimuli is a positive deflection that is largest over the parietal electrode sites and occurs at about 300 ms after the stimulus onset in normal adults [31]. It is also known as P3b and is thought to reflect updating of working memory or, in Donchin's terminology, to 'context updating' [37]. Squire and his colleagues [38] described another positive wave that is occurred earlier than the P3b and distributed fronto-centrally. Later, Courcesne et al. [39] used a modification of the oddball paradigm in which a third, infrequent non-target (novel) stimuli inserted into stimulus sequence of oddball paradigm. Fronto-centrally distributed P300 response to novel stimuli was also labeled as P3a. Then it was revealed that this potential could also be obtained by the typical (not-novel) non-target stimuli [40]. The P3a and the P3b were distinguished by Näätänen [3] by considering that the P3a is a reflection of an attentional switch produced by the mismatch between a stimulus presented which deviates from the passively formed neuronal trace of another stimulus. The P3b, on the other hand, reflects the match between the stimulus and a voluntarily maintained attentional trace [3].

Huge number of evidence from depth and scalp electrode recordings, neuroimaging, source localization, and lesion studies support the suggestion that P300 has a multi-

component structure [41-47]. In these studies, generally the medial temporal lobe including hippocampus and parahippocampal gyrus [42, 43, 44, 47]; the superior temporal lobe, and temporo-parietal junction [41, 45] are associated with the generation of the P300 potential and additional frontal and cingulate gyrus activations are revealed as a response to the novel stimuli [41, 46].

In the light of these studies, it is quite clear that P300 potentials are generated by the simultaneous and/or sequential activity of both the cortical and the subcortical (limbic) brain structures.

2.1.2 P200 Potential

The P200 is a positive-going waveform whose peak varies in latency from 150–250 ms in post stimulus epoch and it is generated in the secondary auditory cortex [47, 48-50]. Although less is known about the P200 than the P300, the results of several studies revealed that the P200 is not merely an exogenous component but is related to endogenous or cognitive processing variables [33]. The P200 may index mechanisms of selective attention [51], feature detection processes [52], and other early sensory stages of item encoding.

In many studies, P200 potentials obtained with single-stimulus paradigm were found significantly larger than in the oddball paradigm, but the possible causes of this difference were not discussed [53-56].

2.2 Paradigms

In this section, cognitive content and stimulus properties of the paradigms used are explained. Cognitive properties of the paradigms are also summarized in Table 2.1 and physical properties of the stimuli are summarized in the Table 4.1.

In the present study, in order to differentiate the effects of the specific cognitive processes on ERP components, four cognitive constructs, signal discrimination, motor response, motor response inhibition and context updating, were defined, and corresponding experimental paradigms were designed accordingly.

Definitions of the cognitive operations are as follows:

Signal discrimination: Whether a task requires a discrimination of one type of stimuli among a set of stimuli or not. All paradigms in this study except the single-stimulus paradigms contained this process.

Motor response: Whether a paradigm requires a motor task (i.e. lifting right index finger in this case) as a response to the adequate stimuli or not.

Motor response inhibition: Inhibition of the motor response to the inadequate stimuli in the active paradigms.

Context updating: Shift of the context of the working memory generated by the frequent stimuli with less probable type of stimuli (that are infrequent). In other words, this process is engaged by the stimuli with low probability.

In this study, four basic auditory P300 paradigms were used: single-stimulus paradigm, oddball paradigm, go/no-go paradigm and three-stimulus paradigm. Single-stimulus and oddball paradigms were presented in both active (i.e. lifting the index finger of the right hand) and passive conditions (i.e. passive listening) whereas remaining

paradigms applied actively. Thus, there were six paradigms and eleven conditions or stimulus types in our experimental design.

2.2.1 Single-stimulus Paradigm (Passive and Active)

Polich et al. (1994) reported that P300 potentials could be obtained with a variant of the auditory oddball paradigm, which is called 'single-stimulus' paradigm [53]. In this situation, a target tone occurs randomly in time as in the oddball paradigm, but standard tone is replaced by silence. In active condition, subjects are required to react to the target. In passive condition, however, subjects are instructed to passively hear the tone.

The P300 from the single-stimulus paradigm yielded amplitude and latency topography effects similar to the P300 from the traditional two-stimulus oddball paradigm [53-56]. In passive condition, P300-like potentials were also reported and significantly larger P300 amplitude was found with respect to the passive oddball condition [54]. Furthermore, because P300 obtained with single-stimulus paradigm can be modulated similarly by the stimulus properties like modality, it was suggested that the underlying neural and cognitive generators of the oddball P300 and single-stimulus P300 are the same [55].

Almost all studies that were used single-stimulus paradigm reported that P200 potential was higher in single-stimulus condition than in the oddball paradigm, but none of them discussed these differences [53-56].

In the present study, a single type of stimulus, 2000 Hz tone was used with randomly varying inter stimulus interval (ISI) between 2 and 4 seconds with mean duration 3 s in order to avoid stimulus anticipation by the subject.

Both passive and active task conditions were applied. In the passive condition, this paradigm was required none of the defined cognitive operations. Because there was only one type stimulus, signal discrimination and context updating were not engaged; moreover, as there was no motor response task there was no inhibition. In the active condition, on the

other hand, a motor response is required to all stimuli in the paradigm. Thus, the active condition differs from the passive one with only the motor response requirement.

2.2.2 Oddball Paradigm (Passive and Active)

In this paradigm, two stimuli are presented in a random order, with one occurring more frequent than the other one. In the active condition, the participants are required to distinguish the infrequent target stimulus overtly or covertly [31].

A passive version of the paradigm was also used in few studies and P300-like potentials with similar scalp distributions and latencies were reported, though P300 amplitude from the passive procedure was smaller [57].

In this study, both active and passive oddball paradigms were applied. Two types of tones, 1500 Hz and 2000 Hz were used with 0.8 and 0.2 probability. In the active condition, the participants were required to distinguish the infrequent target stimulus by lifting index finger of their right hand. In this case, signal discrimination, motor response task, and context updating processes were thought to be engaged as a response to target stimuli. For standard stimulus with high probability, only signal discrimination and inhibition operations were engaged. Because this stimulus type created the general context of the paradigm, motor response should be inhibited. In the passive condition, however, there was no motor response requirement to frequent stimulus (deviants) and there was no inhibition process.

2.2.3 Go/No-Go Paradigm

Several paradigms such as visual and auditory go/no-go paradigms and the modifications of the continuous performance test (CPT) are used to obtain ERPs in relation to response inhibition [58-60].

In some studies, different stimulus probabilities were examined, and it was found that less probable go and no-go stimuli elicited larger P300s than more probable stimuli [58]. It is thought that, high probability of the target (go) stimuli produces a bias to button

press and subject has difficulty to inhibit finger movement for non-target (no-go) stimuli. This inhibition was associated with frontal cortex activity. Accordingly, the no-go P300 was found maximal at anterior sites, whereas P300 in the go condition was found maximal at the centro-parietal sites [60].

In this study, two different auditory stimuli, 1500 and 2000 Hz with equal (0.5) probability was used as go and no-go stimuli. The subjects were required to distinguish the target (go, 1500 Hz) stimulus by lifting their right index finger. In order to increase inhibition effect or motor response bias, go/no-go paradigm was presented after the oddball paradigm in which high frequency tones were target and the probability of the target tone was increased from 20 % to 50 %. Cognitive characteristics of the no-go stimulus and standard stimulus of the active oddball paradigm were the same (i.e. signal discrimination and inhibition processes are present). Cognitive properties of the go (target) stimulus of this paradigm and target stimulus of the oddball paradigm were the same, except the lack of context updating in go/no-go paradigm because of equal probability of the two type of stimuli.

2.2.4 Three-stimulus Paradigm

The three-stimulus paradigm is a modification of oddball task; an additional infrequent, distractor non-target stimulus is inserted into the sequence of infrequent target and frequent standard stimuli. When "novel" stimuli are presented as distractors within the oddball series, a large P300 occurs over the fronto-central areas [39]. This novelty P300, is also called as P3a, is thought to reflect frontal lobe function [41].

In another three-stimulus paradigm, 'typical' (i.e. not novel) infrequent non-target stimuli are inserted into the sequence of target and standard stimuli. These typical non-target stimuli have been found to elicit a P300 with maximum amplitude over the central-parietal area, [28, 40, 61]. In addition, Katayama and Polich showed that P3a could be obtained by using typical (i.e. not novel) stimuli when the perceptual discrimination between the target and standard stimulus is difficult [61].

In this study, typical non-target stimuli (500 Hz tones) were inserted into standard and target tones of the oddball paradigm. Probability of target, non-target, and standard stimuli were 0.2, 0.2, and 0.6, respectively. The cognitive characteristics of the standard and target stimuli in the three-stimulus and in the active oddball paradigm were the same. Non-target (infrequent, typical) stimulus types thought to be engaged signal discrimination, context updating and inhibition of the motor response process.

Table 2.1
The cognitive characteristics of the stimuli in the designed paradigm set.

Paradigm	Condition	Stimulus type	Signal discrimination	Motor response	Context updating	Inhibition
Single-stimulus	Passive	Standard	—	—	—	—
Single-stimulus	Active	Target	—	+	—	—
Oddball	Passive	Standard	+	—	—	—
Oddball	Passive	Deviant	+	—	+	—
Oddball	Active	Standard	+	—	—	+
Oddball	Active	Target	+	+	+	—
Go/No-go	Active	No-go	+	—	—	+
Go/No-go	Active	Go	+	+	—	—
Three-stimulus	Active	Standard	+	—	—	+
Three-stimulus	Active	Target	+	+	+	—
Three-stimulus	Active	Non-target	+	—	+	+

3. TIME-FREQUENCY ANALYSIS OF ERPS USING WAVELET TRANSFORM

In this study, WT was used to decompose ERP signals into time-frequency components. WT is an efficient method to investigate the time frequency characteristics of the ERPs, because in this transform, both the time and the frequency resolutions are optimized as WT uses shorter time windows for faster activity and longer time windows for slower ones.

3.1 Wavelet Transform

The single wavelet is typically an amplitude oscillating function that is well localized in both time and frequency (e.g., Figure 3.2). It is localized in the time because its energy is large during a restricted time period and is very low or zero outside of that time period. A wavelet is localized in frequency because it is composed of a limited range of several frequencies [16].

The continuous wavelet transform (CWT) decomposes a signal *x(t)* using families of functions $h_{a,b}$:

$$h_{a,b}(t) = \frac{1}{\sqrt{|a|}} h\left(\frac{t-b}{a}\right) \qquad a,b \varepsilon \ R, \ a \neq 0, \qquad (3.1)$$

that are generated from a single function *h(t)* called 'mother wavelet' by the operation of scaling and translations [62]. The scale parameter 'a' stretches the wavelet function and position parameter 'b' shifts it in time domain to localize the time that frequency content occurs. Theoretically, there are an infinite number of wavelets in a wavelet family because there are in principle an infinite number of scales and an infinite number of time translations for any wavelet.

The continuous wavelet transform (CWT$_X$) of a signal *x(t)* at scale **a** and position **b** can be defined as:

$$CWT_X(b,a) = \left\langle x(t), \frac{1}{\sqrt{|a|}} h * \left(\frac{t-b}{a} \right) \right\rangle \qquad (3.2)$$

$$= \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) h * \left(\frac{t-b}{a} \right) dt$$

where '*' represents complex conjugation and '⟨x, h⟩' represents the inner product which measures the similarity between the signal and wavelet.

At each scale and each time position, the wavelet is correlated with the shape of the signal at that position. This correlation, known as a wavelet coefficient, measures how much of the wavelet at that scale and at that position is included in the signal. This process produces a sequence of wavelet coefficients at each scale plotted as a function of translation time and generally reveals where in the waveform events at those scales occur [16].

Infinite number of wavelet coefficient can be obtained with the CWT. However, if the signals are discrete, coefficients can be obtained easily according to the sampling rate of the signals. In order to compute the discrete wavelet coefficients, the CWT is converted into multiresolution analysis. Obtained correlations with the different scale wavelet functions can be arranged in a hierarchical scheme called multiresolution decomposition [63]. The wavelet function, which is actually a band-pass filter, is converted into low-pass and high-pass discrete filter sequences (Figure 3.3). The wavelet coefficients that represent the activity in different frequency bands at different time locations can be determined by performing vector multiplication of the discrete signal with these discrete filter sequences.

Multiresolution analysis decomposes the signal into a set of frequency channels, which have the same bandwidth in a logarithmic scale. This property is known as constant-Q or constant relative bandwidth frequency analysis by octave band filters [15]. Multiresolution property is the major advantage of the WT, which allows us to observe

higher frequencies in shorter and lower frequencies in longer time windows that are optimal for both time and frequency.

In the present study, Quadratic B-spline wavelet was used to obtain six sets of coefficients in 64-128 Hz (upper gamma), 32-64 Hz (gamma), 16-32 Hz (beta), 8-16 Hz (alpha), 4-8 Hz (theta), and 0.1-4 Hz (delta) frequency bands.

The choice of the mother wavelet to be compared with the signal is critical for the analysis. In principle, the wavelet function should have a certain shape to be localized in the original signal [16]. Further, the choice of the specific wavelet function determines the orthogonality of the obtained time-frequency decomposition of the signal. Orthogonality means that the waveform information is partitioned into distinct scales (independent frequency bands) and time locations [16].

Although some other wavelet functions like cubic spline were tested on ERP data and the results looked similar, the quadratic B-spline proved better [13-23]. The quadratic B-spline function and its associated wavelet are shown in Figures 3.1 and 3.2. Quadratic B-spline wavelet appears approximately applicable to analysis of ERPs because its shape fits raw EEG waveforms, field potentials that are directly recorded from group of cells [64] and frequency components obtained with digital filtering technique evoked EEG activity [11]. However, B-spline wavelets have near optimal time-frequency localization and are semi-orthogonal [15, 65].

The "smooth" behavior of B-splines is also important in order to avoid border effects when making the correlation between the original signal and a wavelet function with abrupt patterns. Thus, a reliable input to statistical analyses is supplied for testing the functional distinctiveness of different frequency components falling into different time windows.
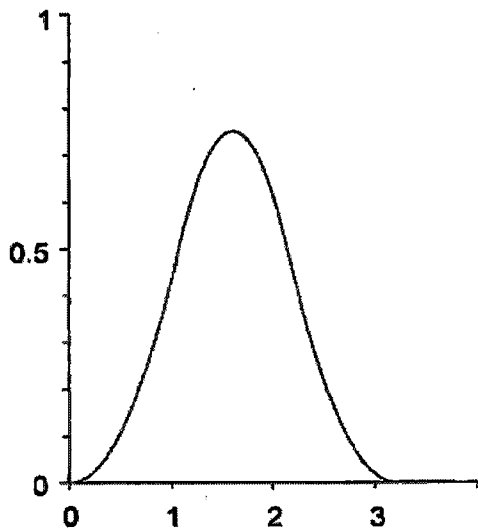
Figure 3.1 The quadratic B-spline function
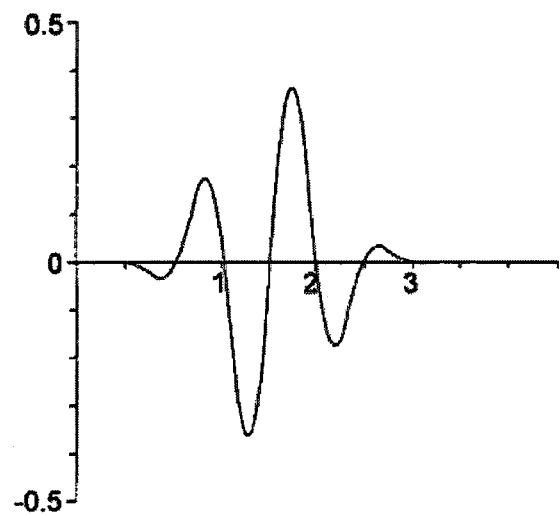
Figure 3.2 The quadratic B-spline wavelet

3.2 Fast Algorithm

In the fast algorithm, standard pyramidal filter scheme was used to decompose averaged ERPs using the quadratic B-spline wavelet (for detailed description of the method see [13]). The computational block diagram for the 5 octave wavelet decomposition is given in Figure 3.3. In this figure "↓2" indicates down sampling by 2, H(z) and G(z) represents the low bass and high pass filters (coefficients of these filters are given in the appendix). At the resolution level 0, the input to the block diagram is the original signal. In each resolution level, the output of the high-pass filtering yields the wavelet coefficients for that resolution and the output of the low-pass filtering yields the input to the next resolution level. For scaling, decimation by two (down sampling) is performed after each filtering application. Five octave wavelet decomposition of ERP sampled with 256 Hz gives 5 octaves coefficients and a residual coefficient.

19

H (Z) = Low-pass filter   G(Z) = High-pass filter
↓2 = Decimation by 2

ERP signal (256 Hz)

H(z)

H(z)

H(z)

H(z)

H(z)

Residual Coefficient delta (0.1 – 4 Hz)

G(z)   ↓2   5th Octave WC theta (4 – 8 Hz)

G(z)   ↓2   4th Octave WC alpha (8 – 16 Hz)

G(z)   ↓2   3rd Octave WC beta (16 – 32 Hz)

G(z)   ↓2   2nd Octave WC gamma (32 – 64 Hz)

G(z)   ↓2   1st Octave WC upper gamma (64 –128 Hz)
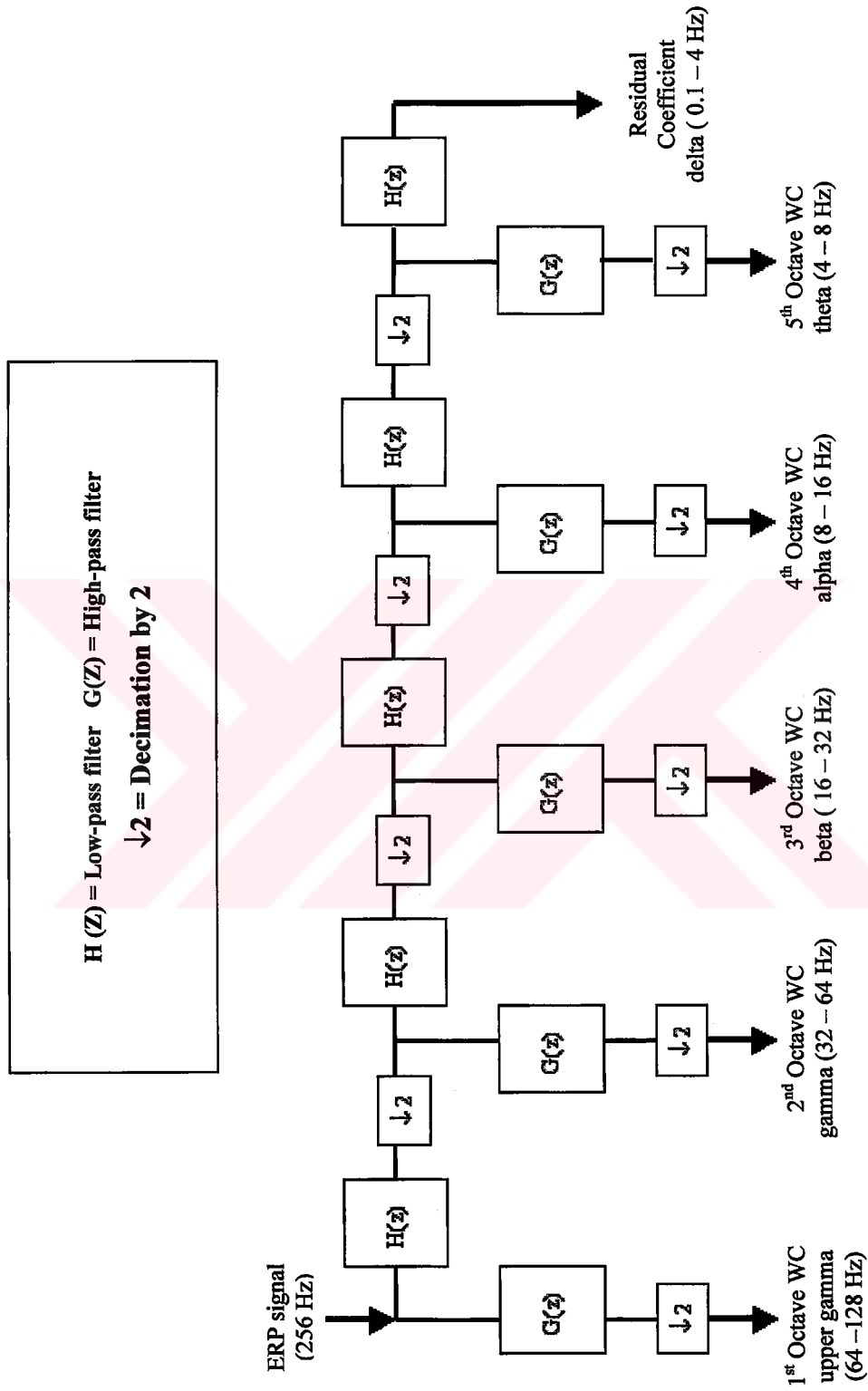
Figure 3.3 The schematic diagram of the 5 octave wavelet decomposition algorithm.

4. APPLICATION

4.1 ERP Recordings

Subjects were 16 healthy (eight female and eight male) volunteers aged between 21-35 (25.9 ± 3.5). The subjects reported no neurological or hearing problems in the past and were free of any medications known to affect the EEG.

The subjects sat in an electrically shielded, sound-diminished, and dimly illuminated room. The data were derived with 14 Ag-AgCl disc electrodes placed on the frontal (F3, Fz, F4,), central (C3, Cz, C4), parietal (P3, Pz, P4), temporal (T3, T4), and occipital (O1, Oz, O2) locations according to the international 10/20 system (Figure 4.1), referenced to linked earlobes (A1 and A2). EOG was recorded for both horizontal and vertical eye movements with two electrodes placed at the outer canthus of the right eye and the nasion. EMG activity was also recorded to detect subject's motor response by using two electrodes placed on the right hand. Impedance of the electrodes was kept below 20 kΩ. A Nihon-Kohden Neurofax EEG device was used for these recordings. 500 ms pre-stimulus and 1000 ms post-stimulus periods were amplified. The cut-off frequencies of the amplifier were 0.1 and 70 Hz. Amplified signals were digitized using a National Instruments AT-MIO 16 E analog/digital converter with a sampling rate of 256 Hz (12 bit), and stored on the hard disc of a PC.
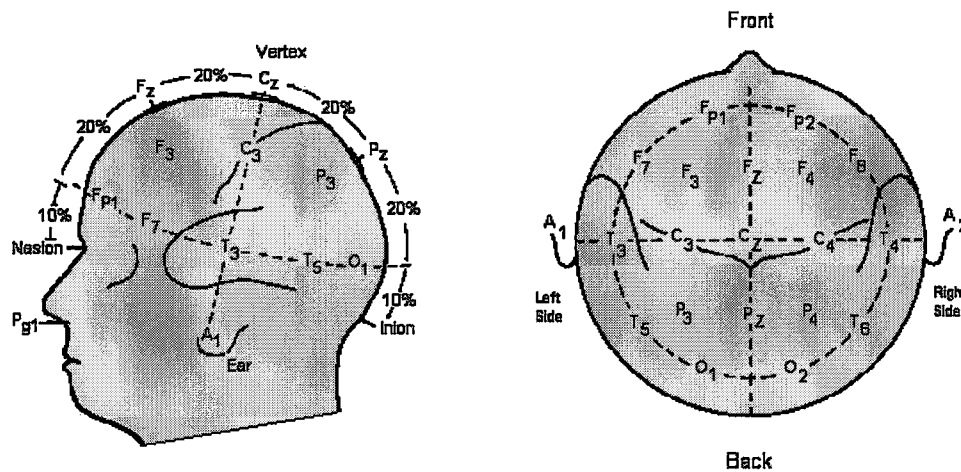
Figure 4.1 Electrode locations according to international 10/20 system.

4.2 Experimental Design

Auditory stimuli were produced by the sound card of a separate computer, which was triggered by the recording computer via parallel port, and presented by using a headphone. Sound pressure level (SPL) was 75dB and stimulus duration was 50 ms for all stimuli in the all experiments. The cognitive content of the paradigms were already described in Section 2.2 and summarized in Table 2.1. The physical properties of the stimuli in the all experiments were showed in Table 4.1. Paradigms were applied in constant order to all subjects as passive single-stimulus paradigm, active stimulus paradigm, passive oddball paradigm, active oddball paradigm, go/no-go paradigm, and three-stimulus paradigm.

Table 4.1
Experimental design with stimulus properties in the paradigms.

Paradigm	Stimulus type	Tone (Hz)	Sweep #	Probability (%)	ISI (s)
Single-stimulus	One type stimulus	2000	100	100	2 - 4 (mean 3)
Oddball	Standard	1500	240	80	2
Oddball	Deviant / target	2000	60	20	2
Go/No-go	No-go	2000	150	50	2
Go/No-go	Go	1500	150	50	2
Three-stimulus	Standard	1500	180	60	2
Three-stimulus	Target	2000	60	20	2
Three-stimulus	Non-target	500	60	20	2

4.3   Analysis of the Data

ERP data obtained from all conditions were analyzed both in the time domain and in the time-frequency plane. Before the analysis of the data, the manual artifact elimination based on the reviewing of single ERP trials was applied. After the artifact elimination, single ERP trials were averaged off-line to obtain the individual averaged ERPs.

4.3.1   ERP Analysis in the Time Domain

In time domain analysis of ERPs, after the artifact elimination, ERPs were digitally filtered, in which cut-off frequencies were 0.1–30 Hz for P200 potential and 0.1–15 Hz for P300 potential, and then individual amplitudes and the latencies of the P200 and P300 potentials were measured in each condition. P200 potential was identified as the most positive peak between 150–250 ms and P300 potential as the most positive peak between 250–450 ms after the stimulus onset. Amplitudes and latencies of the P200 and P300 potentials were measured to the all type of stimuli in the paradigm set with a baseline of 250 ms pre-stimulus.

4.3.2   ERP Analysis in the Time-Frequency Plane

In the present study, a fast wavelet transform algorithm in a standard pyramidal filter scheme that was previously developed and used in various studies was employed to decompose averaged ERPs [13, 14, 18-23]. The algorithm is based on DWT by the B-spline wavelet function, which is regarded as a band pass filter and performed by two equivalent, high pass and low pass filters in the form of multiresolution decomposition (Figure 3.3).

Application of the five-octave WT to the data sampled at 256 Hz produced 6 sets of coefficients including the residual scale: 64–128 Hz (upper gamma), 32–64 Hz (gamma), 16–32 Hz (beta), 8–16 Hz (alpha), 4–8 Hz (theta) and residual 0.1–4 Hz (delta) (Figure 3.3). Because our data were initially filtered with 0.1 - 70 Hz filter, the upper gamma coefficients with 64 - 128 Hz band range are almost "0".

In this study, only the differences in delta, the theta and the alpha band coefficients were investigated and 5 delta, 5 theta and 10 alpha coefficients of each stimulus condition within 0–625 ms time interval in the post stimulus epoch were subjected to statistical analysis.

The wavelet coefficients were designated with a letter corresponding to each frequency band (D for delta, T for theta, and A for alpha) and with a coefficient number (e.g. the first delta coefficient represented as D1). The time localization of each theta and delta coefficients was as follows: 1st coefficient (0–125 ms), 2nd coefficient (125–250 ms), 3rd coefficient (250–375 ms), 4th coefficient (375–500 ms), and 5th coefficient (500–625 ms). The time localization for each alpha coefficient was: A1 (0–62.5 ms), A2 (62.5–125 ms), A3 (125–187.5 ms), A4 (187.5–250 ms), A5 (250–312.5 ms), A6 (312.5–375 ms), A7 (375–437.5 ms), A8 (437.5–500 ms), A9 (500–562.5 ms), and A10 (562.5–625 ms).

4.3.3 Statistical Analysis

Wavelet coefficients of midline electrodes (Fz, Cz, Pz) obtained from the averaged potentials of each subject in each paradigm were analyzed by repeated measure analysis of variance (ANOVA). The ANOVA design consisted of 5 factors: signal discrimination (2 levels: discrimination = D versus non-discrimination ND), motor task (2 levels: motor response task = T versus no-motor response task = NT), motor response inhibition (2 levels: inhibition = I versus no-inhibition = NI), context updating (2 levels: context updating = C versus no-context updating = NC), topography (3 levels: Fz, Cz, and Pz, CH). The amplitude and the latency measures of P200 and P300 potentials were subjected to the same type of analysis. Degrees of freedom (d.f.) were adjusted with the Greenhouse-Geisser epsilon coefficient for possible violations of the sphericity assumption and corrected P-values were reported.

5. RESULTS

5.1   Preprocessing of the Recordings

Before analyzing the electrophysiological signals, the behavioral measures in active task conditions were controlled. The mean performance of the subjects in responding to target events under all conditions was 98.5 %. The trials, where the subjects missed target events or responded stimuli that are task irrelevant were excluded from the averaging procedure. To obtain a reasonable signal/noise ratio in the averaged potentials, at least 40 sweeps was aimed after the artifact elimination procedure. As all ERPs obtained in each condition of each subject satisfied this condition, no subject was rejected from the analyses.

Event-related potentials obtained under 11 different conditions in 4 different experimental paradigms were first analyzed in the time domain using the conventional ERP analysis parameters that are the peak amplitudes and latencies of the late significant deflections, P200 and P300. Although, only the measurements from the midline electrodes (Fz, Cz, Pz) were statistically analyzed, topographic distribution obtained from 14 electrodes of the ERP peaks were shown in Figures 5.1, 5.2, and 5.3; and the wavelet coefficients for each condition were shown in Figures 5.6–5.16.

5.2   Results of Time Domain Analysis of the ERPs

Time domain analysis of ERPs was restricted to the late positive potentials, P200 and P300. Amplitudes and latencies of the midline electrodes (Fz, Cz, Pz) of these potentials subjected to the statistical analysis. Grand-averaged midline waveforms obtained from each type of stimulus in the paradigms are shown in the Figure 5.1 and topographic distributions of these potentials that were obtained from 14 electrodes are shown in Figures 5.2 and 5.3. Summary of the statistical analysis for P200 and P300 potentials was reported in Tables 5.1.

5.2.1 P200 Potential

Amplitude of the P200 potential was significantly higher in the non-discrimination condition (D, ND: p < .01). Additional motor response x topography, context updating x topography and inhibition x topography interactions were found for P200 amplitude (T x CH: p < .001, C x CH: p < .05, and I x CH, p < .001). These topography effects showed that the presence of motor response, context updating and inhibition increased parietal amplitude of the P200, whereas they decreased its fronto-central amplitudes (parietal vs. fronto-central, T x CH: F (1/168) = 42.359, p < .001; C x CH: F (1/168) = 9.38, p < .05; I x CH: F (1/168) = 13.20, p < .001).

Latency of the P200 potential (188 ± 2.5 ms) was not affected by the presence of any cognitive operation.

5.2.2 P300 Potential

Amplitude of the P300 potential was influenced by the presence of task requirement, context updating and inhibition processes, and in the presence of these cognitive operations, the amplitude of the P300 potential increased significantly (T, NT; C, NC; I, NI; p < .001). In addition, signal discrimination, task and context updating enhanced mostly the parietal amplitudes of the P300 (parietal vs. fronto-central, D x CH: p < .05, T x CH: p < .001 and C x CH: p = .001). Inhibition, however, increased its amplitude on the vertex and in this way, P300 showed a centro-parietal distribution (vertex vs. frontal, I x CH: p < .05).

Latency of the P300 potential (335 ± 2 ms) was influenced by the signal discrimination (D, ND: p < .05). In the discrimination tasks, latency of the P300 was longer over the parietal locations (D x CH: F (1/168) = 3.94, p < .05). Furthermore, discrimination x task x topography interaction had a significant effect on P300 latency (D x T x CH: p < .01), wherein the presence of both discrimination and motor response increased the latency of the P300 potential prominently over the parietal region (parietal vs. fronto-central, F (1/168) = 6.86, p < .01).

Table 5.1
Summary of the analysis of variance performed on the P200 and P300 potentials
($* p < .05, ** p < .01, *** p < .001$)

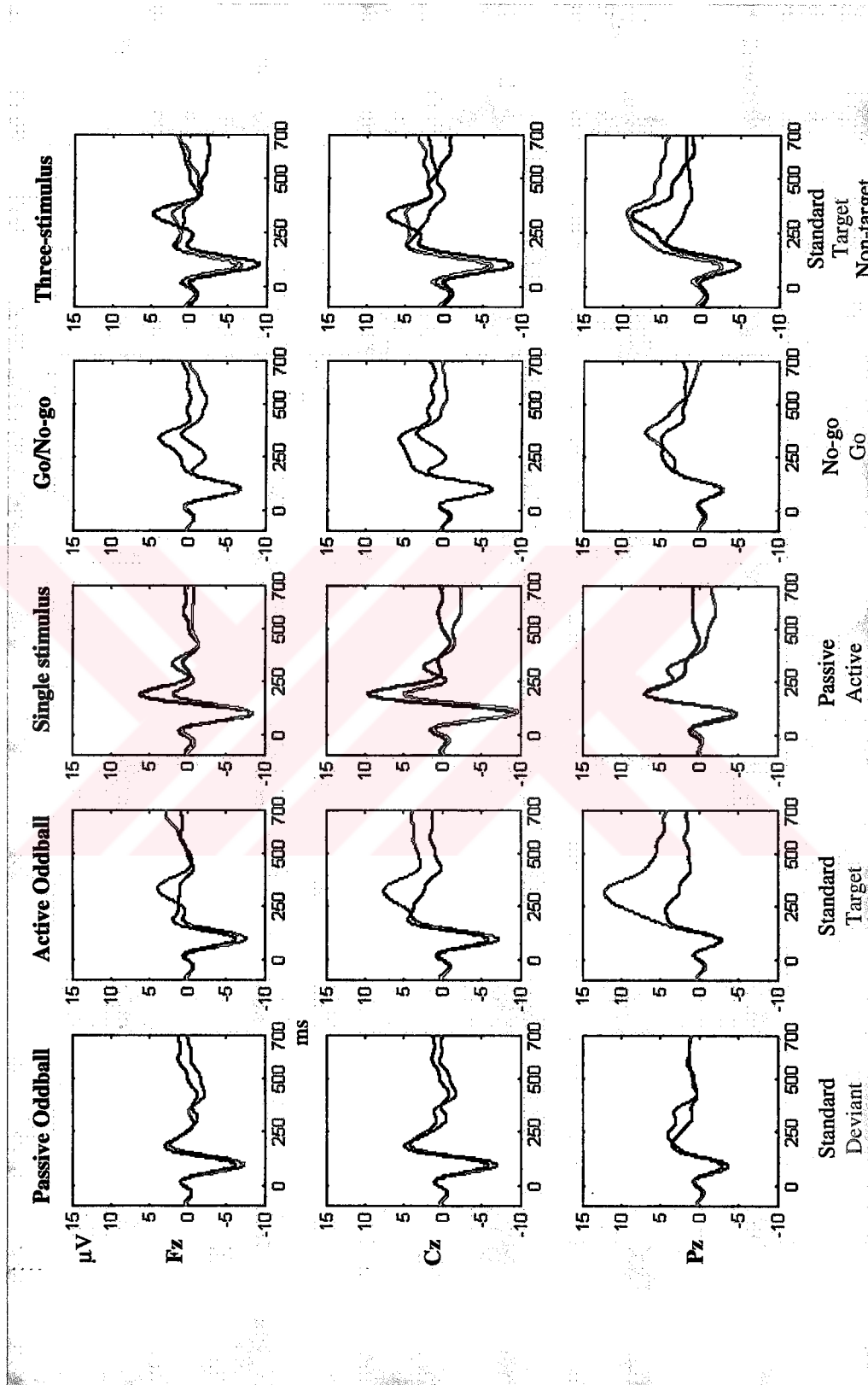| Sources	d.f.	P200 amplitude	P200 latency	P300 amplitude	P300 latency
Discrimination (D, ND)	1/84	8.71**	–	–	3.9*
Motor Response (T, NT)	1/84	–	–	19.79***	–
Context Updating (C, NC)	1/84	–	–	30.04***	–
Inhibition (I, NI)	1/84	–	–	23.3***	–
D x CH	2/168	–	–	4.07*	3.94*
T x CH	2/168	26.39***	–	10.65***	–
C x CH	2/168	3.44*	–	8.15**	–
I x CH	2/168	9.11***	–	–	–
D x T x CH	2/168	–	–	–	5.69**

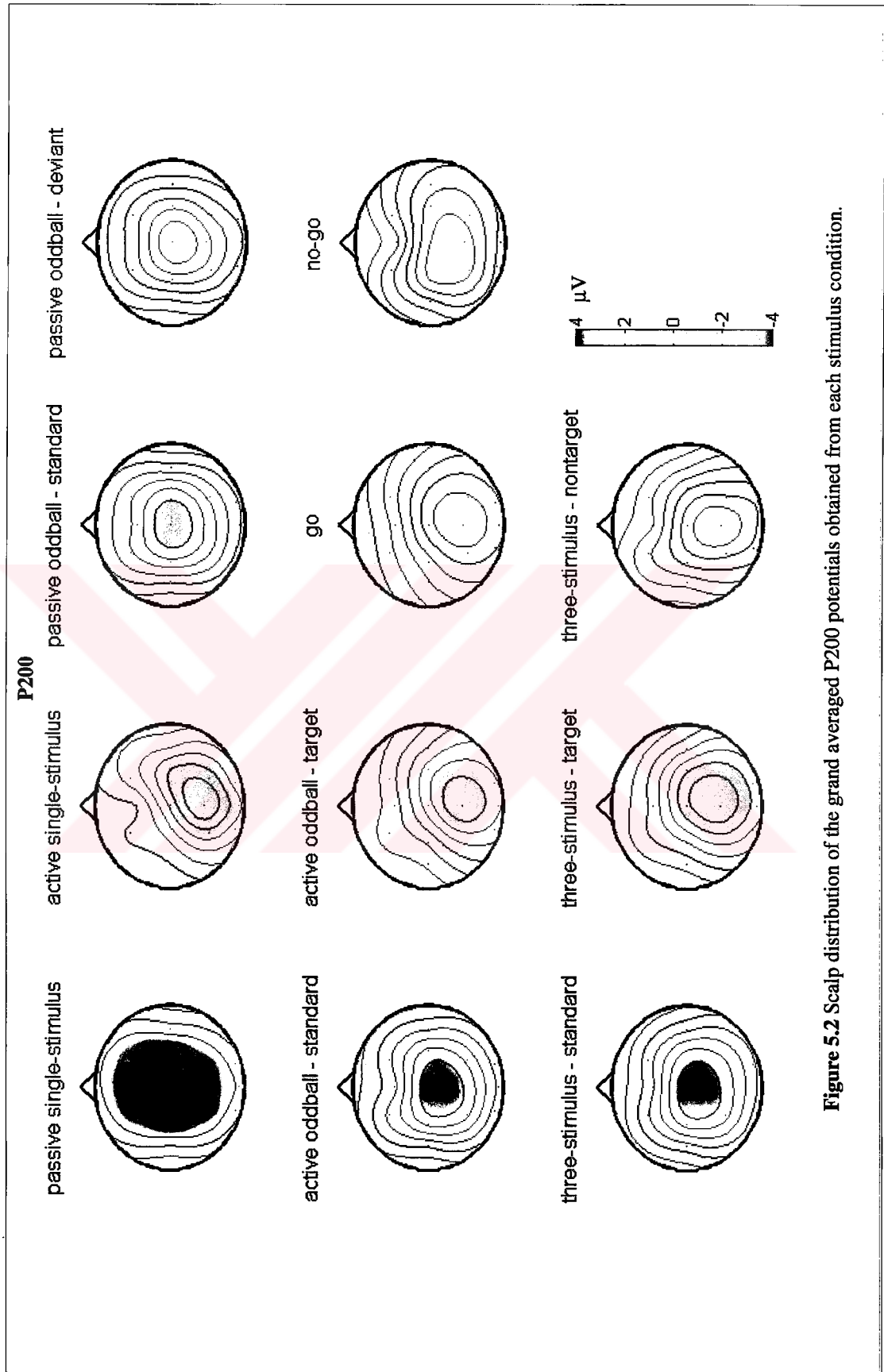Figure 5.1 Grand averaged ERPs obtained with four auditory paradigms.

Figure 5.2 Scalp distribution of the grand averaged P200 potentials obtained from each stimulus condition.
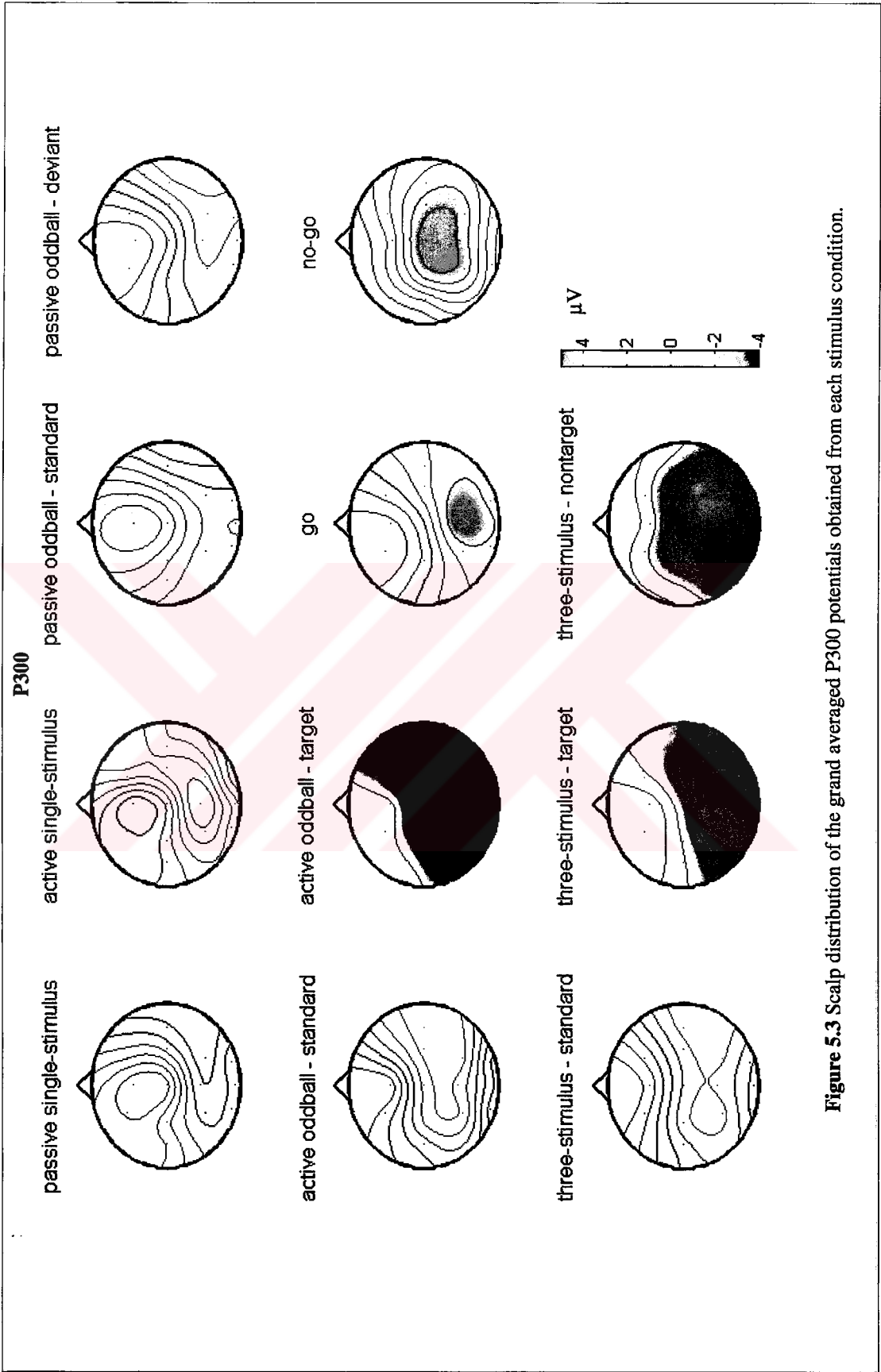
Figure 5.3 Scalp distribution of the grand averaged P300 potentials obtained from each stimulus condition.

5.3   The Results of Time-Frequency Analysis of the ERPs

In this section, the results of the time-frequency analysis of ERPs are reported firstly in the form of time windows and then these results are summed according to the cognitive correlates of the coefficients.

5.3.1   The Results Obtained for Each Time Window

Defined five time windows for the all coefficients in post stimulus epoch are as follows:

- 1st time window (0–125ms): D1, T1, A1, and A2 coefficients
- 2nd time window (125–250 ms): D2, T2, A3, and A4 coefficients
- 3rd time window (250–375ms): D3, T3, A5, and A6 coefficients
- 4th time window (375–500ms): D4, T4, A7, and A8 coefficients
- 5th time window (500–625ms): D5, T5, A9, and A10 coefficients

Multiresolution time-frequency representations of averaged wavelet coefficients of the midline electrodes (Fz, Cz, Pz) that are obtained from each type of stimulus are shown in Figure 5.5. In this figure, there are eleven boxes for multiresolution time-frequency representations of each type of stimulus. In these boxes, "x" axis represents the time interval that corresponds to 1000 ms post-stimulus epoch and "y" axis represents the logarithmically scaled frequencies. A sample for the replacement of the frequency bands in these time-frequency representations is shown in Figure 5.4. Topographic distributions of the coefficients in the each time window (TW) obtained from all type of stimulus are shown in Figures 5.6–5.16. Results of the 5 factor analysis of variance (D, ND x T, NT x C, NC x I, NI x CH) performed on the delta, theta and alpha coefficients are summarized in the Tables 5.2, 5.3 and 5.4.
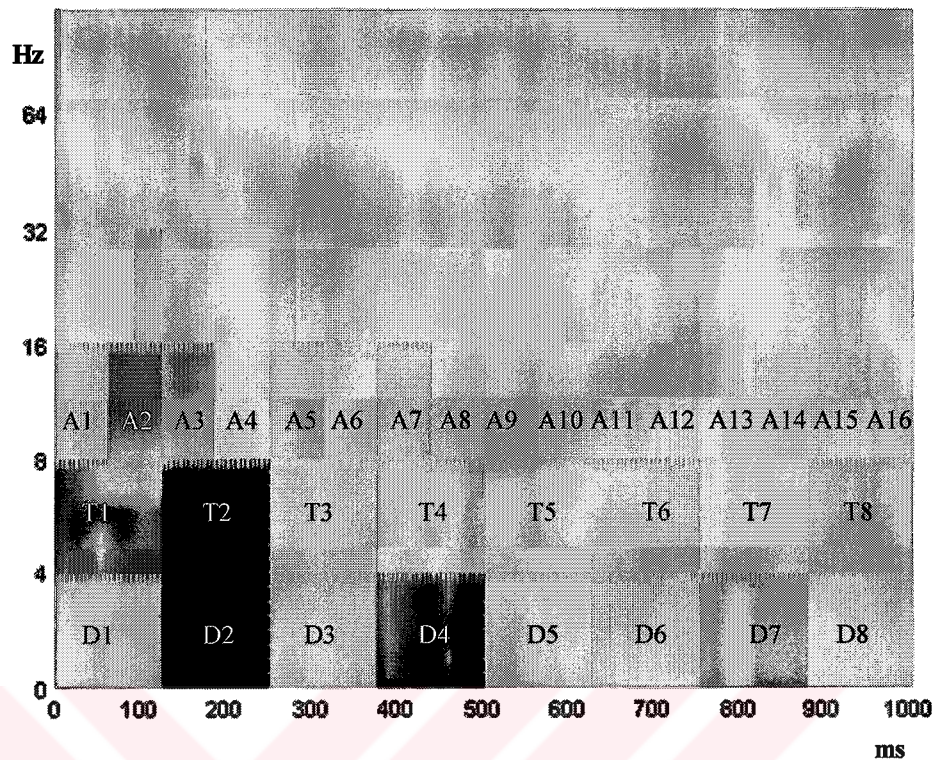
Figure 5.4 A sample of the multiresolution time-frequency representation obtained with WT

The first time window (0–125ms)

Delta 1 (D1): The first delta coefficient, D1 was affected significantly by the presence of signal discrimination, and it was smaller in the paradigms in which signal discrimination was present (D, ND: $p < .001$). The presence of the motor response produced the same but slight effect on D1 (T, NT: $p < .05$). Context updating also influenced D1, however in contrast to signal discrimination and motor response requirement, D1 was higher when context updating was present (C, NC: $p < .001$). Significant motor response x topography, context updating x topography, and inhibition x topography interactions were also found for D1 coefficient (T x CH: $p < .05$, C x CH: $p < .05$, I x CH: $p < .01$). The presence of task requirement decreased fronto-central, but not parietal magnitude of this coefficient (parietal vs. fronto-central, $F (1/168) = 6.83$), $p < .05$). The presence of context updating increased fronto-central amplitude difference by increasing the central magnitude of D1 (central vs. frontal, $F (1/168) = 8.59$, $p < .01$). Moreover, motor inhibition influenced not only fronto-central (central vs. frontal, $F (1/168) = 7.44$, $p < .01$) but also centro-parietal distribution of D1 (parietal vs. centro-parietal, $F (1/168) = 4.52$, $p < .05$) and caused a

decrease in the frontal location, but an increase in the central and the parietal scalp locations.

Theta 1 (T1): In the same time window, presence of signal discrimination, context updating and task processes also affected the theta coefficient (T1). T1 was higher in the paradigms, which do not require signal discrimination and motor response (D, ND: p < .001 and T, NT: p < .05). In the presence of context updating, T1 became more positive than in the absence. Additionally, inhibition x topography interaction was significant (I x CH: p < .05). The magnitude of the T1 decreased in the frontal region of the scalp (frontal vs. parietal, F (1/168) = 4.03, p < .05), but slightly increased in the parietal region (parietal vs. fronto-central, F (1/168) = 3.78, p = .05).

Alpha 1 (A1) and alpha 2 (A2): In the alpha band, this time window corresponds to two alpha coefficients, A1 and A2. In the discrimination paradigms, both alpha coefficients were smaller (A1 was less negative and A2 was less positive) than in the single-stimulus paradigms (D, ND: p < .001 for A1 and p < .01 for A2). For both coefficients, discrimination x topography interaction was significant (D x CH: p < .001 for A1 and p < .05 for A2). Suppression of A1 and A2 coefficients was more prominent over the vertex (central vs. frontal, F (1/168) = 20.25, p < .001 for A1 and F (1/168) = 6.28, p < .05 for A2). Additional motor response x topography interaction was found (T x CH: p < .01) for second alpha coefficient, in which presence of the motor response resulted in increase in the parietal and the central A2 magnitudes with respect to the frontal (central vs. frontal, F (1/168) = 9.21, p < .01).

The second time window (125–250 ms)

Delta 2 (D2): For second delta coefficient, the most prominent effect was caused from context updating (C, NC: p < .001). Presence of this cognitive operation increased the negativity of D2. Additional motor response x topography, context updating x topography, and inhibition x topography interactions were found (T x CH, C x CH, I x CH: p < .01). When the stimuli required a motor response, D2 became dominant over central-parietal scalp locations with increase in the parietal and decrease in fronto-central region (parietal vs. fronto-central, F (1/168) = 9.54, p < .01); otherwise, it was dominant over the vertex.

Presence of inhibition process increased the frontal central difference in favor of central D2 magnitude (central vs. frontal, F (1/168) = 13.09, p < .001). The amplitude of the D2 was prominently affected by the presence of the context updating process especially over the centro-parietal scalp region (frontal vs. central, F (1/168) = 14.75, p < .001; parietal vs. fronto-central, F (1/168) = 5.02, p < .05). Additionally, motor response x context updating interaction was also significant: the presence of the both motor response and context updating task increased the negativity of the D2 (C x T, p = .001).

Theta 2 (T2): Signal discrimination and motor task properties of the paradigms influenced T2 coefficient: when these cognitive processes were required, T2 coefficient became less negative (D, ND: p < .001 and T, NT: p = .016). Moreover, presence of signal discrimination produced homogenous frontal-central distribution instead of central maximum; in other words, this process mainly decreased the central amplitude of the T2 (central vs. frontal, D x CH, F (1/168) = 16.48, p < .001).

Alpha 3 (A3) and alpha 4 (A4): Presence of the signal discrimination process suppressed both negative A3 and positive A4 coefficients (D, ND: p < .001 for both). This alpha suppression was more prominent over the vertex for both coefficients (central vs. frontal, D x CH, F (1/168) = 47.14, p < .001 for A3 and F (1/168) = 49.56, p < .001 for A4). Furthermore, task requirement created a significant increase in the third alpha coefficient (p < .001), but it was not significant for the fourth alpha coefficient. This increase was most prominently expressed in the central region of the scalp for both coefficients (central vs. frontal, T x CH, F (1/168) = 24.16, p < .001 for A3 and F (1/168) = 13.79, p < .001 for A4). In addition, discrimination x motor response x topography interaction was significant for the third alpha coefficient (D x T x CH: p < .05). In non-discrimination and motor response condition, A3 became more negative especially over the vertex (central vs. frontal, F (1/168) = 7.96, p < .01). The inhibition process created an overall decrease in the negativity of the A3 (p = .01), but it had only the topography effect on A4 (parietal vs. fronto-central, I x CH: F (1/168) = 4.44, p < .05). Presence of inhibition decreased the central magnitude of the A4.

The third time window (250–375ms)

Delta 3 (D3): There were significant decreases in D3 coefficients in the presence of motor response and signal discrimination (T, NT: p < .01 and D, ND: p < .05) and a slight decrease in inhibition condition (I, NI: p = .05). Furthermore, decreases, which resulted from motor response and inhibition requirements, were more prominent in fronto-central but not parietal region of the scalp (parietal vs. fronto-central, T x CH: F (1/168) = 31.23, p < .001 and I x CH: F (1/168) = 8.08, p < .01).

Theta 3 (T3): Only the signal discrimination process significantly affected the third theta coefficient, T3. Presence of this condition decreased T3 (D, ND: p < .01) and this decrease was most prominent on the vertex (central vs. frontal, D x CH: F (1/168) = 11.77, p= .001).

Alpha 5 (A5) and alpha 6 (A6): In the single-stimulus paradigms both 5th and 6th alpha coefficients were higher (i.e. more negative for A5 and more positive for A6) than in the other paradigms (D, ND: p < .001 for both). Midline magnitudes of these coefficients were very small almost "0" in the discrimination tasks. These differences between two conditions were more prominent in the central region (central vs. frontal, D x CH: F (1/168) = 49.84, p < .001 for A5 and F (1/168) = 14.4, p < .001 for A6). Presence of motor response requirement created an overall increase in A6 coefficient and task requirement enhanced especially central magnitudes of both coefficients (central vs. frontal, T x CH: F (1/168) = 7.88, p < .01 for A5 and F (1/168) = 11.07, p < .01 for A6). Furthermore, discrimination x motor response task x topography interaction was found for both coefficients (D x T x CH: p < .01 for A5 and p < .05 for A6). In the absence of discrimination but in the presence of the motor response, alpha coefficients got bigger particularly over the vertex (central vs. frontal, D x T x CH: F (1/168) = 11.32, p = .001 for A5, F (1/168) = 8.61, p < .01 for A6). Additional context updating effect was found for A6 coefficient and presence of this process suppressed A6 coefficient (C, NC: p = .01).

The fourth time window (375–500ms)

Delta 4 (D4): Presence of task, inhibition and context updating processes enhanced D4 coefficient magnitude over entire of the scalp (T, NT; I, NI; C, NC: p < .001). Presence of inhibition has additional topography effect (I x CH: p < .01). This process increased

particularly fronto-central magnitudes of the fourth delta coefficient (parietal vs. fronto-central, F (1/168) = 10.76, p = .001).

Theta 4 (T4): Context updating and inhibition processes affected antero-posterior distribution of the fourth theta coefficient (C, NC: p = .01 and I, NI: p < .05). It seems that the presence of these operations mostly influenced T4 in vertex wherein the magnitude of this coefficient was decreased (central vs. frontal, C x CH: F (1/168) = 11.54, p = .001 and I x CH: F (1/168) = 10.72, p = .001 for I).

Alpha 7 (A7) and alpha 8 (A8): In this time window, signal discrimination requirement reduced the magnitude of the alpha coefficients (D, ND: p < .001 for both coefficients), whereas context updating process enhanced these coefficients and presence of the context updating made A7 more negative and A8 coefficient more positive. (C, NC: p < .01 for A7 and p < .05 for A8).

The fifth time window (500–675 ms)

Delta 5 (D5): This coefficient was slightly affected by the presence of signal discrimination and became less negative in the discrimination condition (D, ND: p= .05). Signal discrimination x topography and motor response task x topography interactions were significant (D x CH: p < .001 and T x CH: p = .001). The presence of discrimination increased the parietal magnitude of D5 coefficient (D x CH: parietal vs. fronto-central, F (1/168) = 20.31, p < .001). The presence of the motor response increased not only parietal but also central D5 (T x CH, parietal vs. fronto-central: F (1/168) = 8.75, p < .01; central vs. frontal: F (1/168) = 7.29, p < .01). Discrimination x motor response task x topography interaction was significant also D5 (D x T x CH: p < .001). In the presence of both signal discrimination and motor task enhanced particularly parietal D5 amplitude (parietal vs. fronto-central, F (1/168) = 14.22, p < .001).

Theta 5 (T5): The fifth theta coefficient was higher in the paradigms that require context updating and inhibition processes than in the others (C, NC: p= .001 and I, NI: p < .01) but smaller in the signal discrimination paradigm than in the discrimination paradigm (D, ND: p < .01). The presence of the motor task suppressed T5 coefficient especially in the frontal

region (T x CH: p = .01, central vs. frontal: F (1/168) = 9.94, p < .01). Discrimination x motor response interaction was also significant (D x T: p < .01). When there was no signal discrimination, but there was motor response task the fifth theta coefficient got bigger through the positive values. Context updating produced eminent increase in centro-parietal magnitude of this coefficient, but not frontal (C x CH: p < .001, central vs. frontal: F (1/168) = 13.31, p < .001). In addition inhibition enhanced particularly the central amplitude of the T5 (I x CH: p < .05, central vs. frontal: F (1/168) = 6.64, p < .05).

Alpha 9 (A9) and alpha 10 (A10): Only the context updating effect reduced the magnitude of the A10 coefficient during this time interval for alpha coefficients (C x CH: p < .05).

Table 5.2
Summary of the analysis of variance performed on the delta coefficients
(* p < .05, ** p < .01, *** p < .001)

Sources	d.f.	Delta Coefficients				
		D1	D2	D3	D4	D5
Discrimination (D, ND)	1/84	14.21***	3.64	5.05*	–	3.77
Motor Response (T, NT)	1/84	4.0*	–	9.34**	25.78***	–
Context Updating (C, NC)	1/84	16.0***	14.18***	–	31.21***	–
Inhibition (I, NI)	1/84	–	–	3.88	33.17***	–
D x CH	2/168	–	–	–	–	14.62***
T x CH	2/168	4.38*	7.24**	22.34***	–	8.27**
C x CH	2/168	4.0*	7.52**	–	–	–
I x CH	2/168	5.57**	5.75**	5.77**	5.77 **	–
T x C	2/168	–	6.03**	–	–	–
D x T x CH	2/168	–	–	–	–	10.89***

Table 5.3
Summary of the analysis of variance performed on the theta coefficients
(* p < .05, ** p < .01, *** p < .001)

Sources	d.f.	Theta Coefficients				
		T1	T2	T3	T4	T5
Discrimination (D, ND)	1/84	21.56***	32.43***	8.61***	–	9.27**
Motor Response (T, NT)	1/84	5.41*	5.92*	–	–	–
Context Updating (C, NC)	1/84	12.97***	–	–	–	10.73***
Inhibition (I, NI)	1/84	–	–	–	–	9.05**
D x CH	2/168	3.05	7.86***	6.78**	–	–
T x CH	2/168	–	–	–	–	4.39**
C x CH	2/168	–	–	–	4.87*	8.57***
I x CH	2/168	3.88*	–	–	3.78*	3.25*
D x T	2/168		–	–	–	6.94**

Table 5.4
Summary of the analysis of variance performed on the alpha coefficients
(* p < .05, ** p < .01, *** p < .001)

Sources	d.f.	Alpha Coefficients				
		A1	A2	A3	A4	A5
Discrimination (D, ND)	1/84	16.98***	10.35**	15.14***	14.94***	22.64***
Motor Response (T, NT)	1/84	–	–	5.34*	–	–
Context Updating (C, NC)	1/84	–	–	–	–	–
Inhibition (I, NI)	1/84	–	–	5.94**	–	3.63*
D x CH	2/168	8.77***	4.08*	19.96***	12.55***	15.69***
T x CH	2/168	–	5.63*	12.37***	6.06**	5.08**
C x CH	2/168	–	–	–		–
I x CH	2/168	–	–	–	3.74*	–
D X T X CH	2/168	–	–	3.88*	–	6.87**

Sources	d.f.	A6	A7	A8	A9	A10
Discrimination (D, ND)	1/84	15.88***	15.2***	13.22***	–	–
Motor Response (T, NT)	1/84	4.09*	–	–	–	–
Context Updating (C, NC)	1/84	3.74*	7.48**	3.93*	–	4.32*
Inhibition (I, NI)	1/84	5.83*	3.61	–	–	–
D x CH	2/168	4.07*	–	–	–	–
T x CH	2/168	4.7*	–	–	–	–
C x CH	2/168	–	–	–	–	–
I x CH	2/168	–	–	–	–	–
D X T X CH	2/168	3.64*	–	–	–	–

5.3.2 Summary of the Results for Each Cognitive Construct

The results are summarized in this subsection according to previously defined four cognitive constructs, signal discrimination, motor response, motor response inhibition and context updating in order to assign specific coefficients to these cognitive processes.

Signal Discrimination

D1, D3, T1, T2, T3, T5, and A1–8 coefficients were influenced by the signal discrimination. These coefficients were suppressed by the presence of the signal discrimination process. In addition, antero-posterior distribution of the D5, T2, T3, and A1–6 coefficients were influenced by the presence of signal discrimination operation. The presence of the signal discrimination suppressed T2, T3, and A1-6 coefficients most prominently on vertex, but D5 more on parietal region.

Motor Response Requirement

Presence of the task requirement suppressed D1, D3, T1, and T2, but enhanced D4, A3 and A6 coefficients. Moreover, the presence of the motor response changed antero-posterior magnitude distribution of the D1, D2, D3, D5, T5, and A3-6 coefficients. Motor response task decreased D1, D2, and D3 coefficients prominently over the fronto-central but not parietal region. Task related decrease in the T5 was also prominent over the frontal region. D5 and A3-6 coefficients, however, increased especially over the centro-parietal region by the presence of the motor task.

Context updating

D1, D2, D4, T1, T5, A7, and A8 coefficients were enhanced, but A6 and A10 coefficients were suppressed by the presence of the context updating process. Furthermore, this cognitive operation modified the topography of D1, D2, and T5 coefficients by especially increasing their magnitudes over the centro-parietal scalp locations. Context updating decreased T4 over the vertex but slightly increased it in the frontal region.

Inhibition

Inhibition process enhanced the D4, T5, and A6 coefficients but suppressed A3 and D3 coefficients. Scalp distribution of the D1–4, T1, T5, and A4 coefficients were influenced

by inhibition of inadequate motor response. D1 and D2 showed a centro-parietal increase but a slight frontal decrease, D3 showed a fronto-central decrease, D4 showed a fronto-central increase, T1 showed slight frontal decrease and parietal increase, T5 showed a central increase and A4 coefficient showed a prominent central decrease with the presence of inhibition.
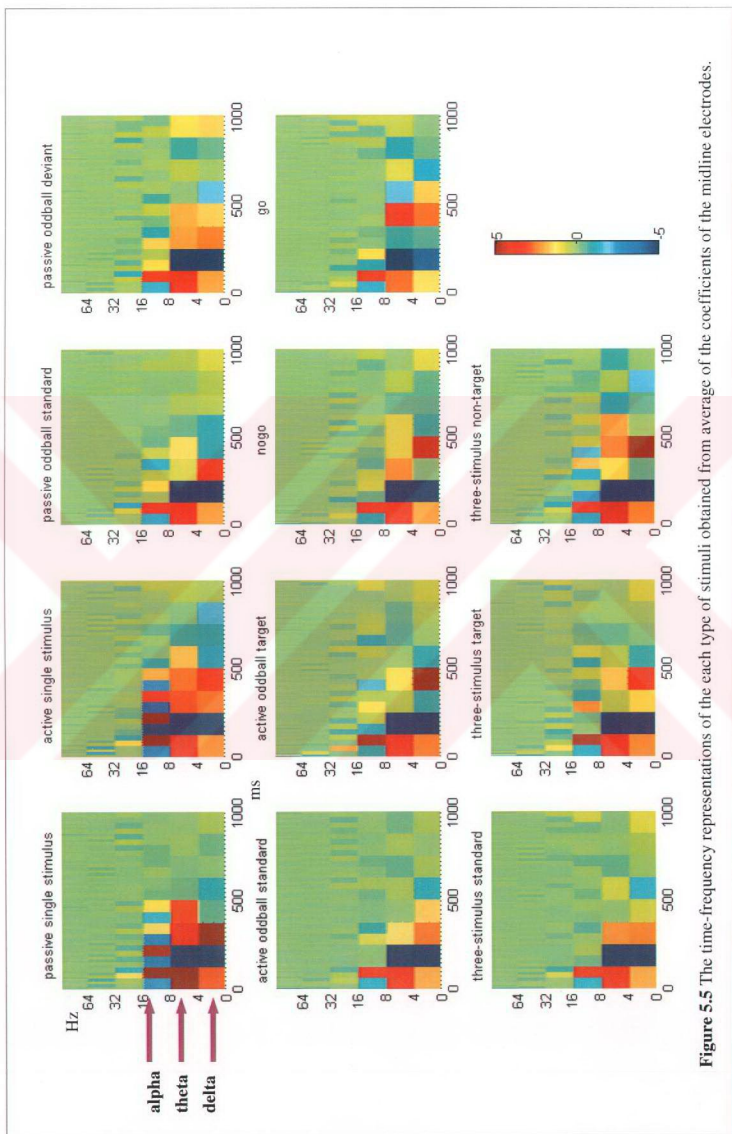
Figure 5.5 The time-frequency representations of the each type of stimuli obtained from average of the coefficients of the midline electrodes.
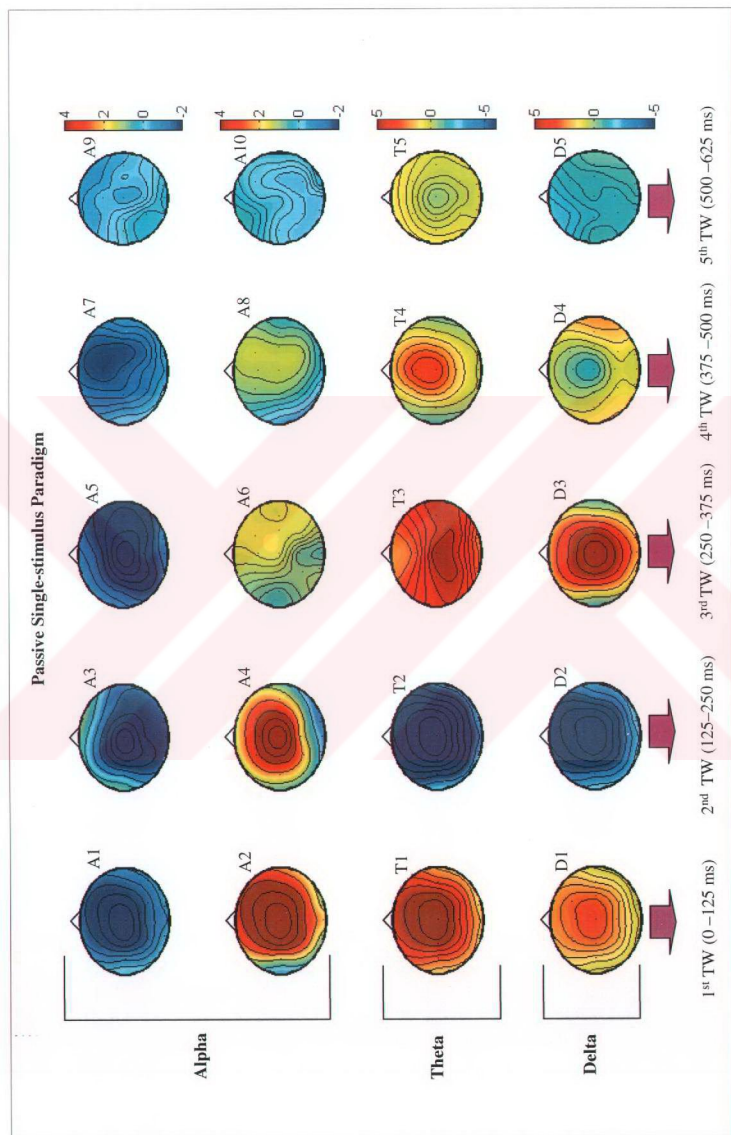
Figure 5.6 Scalp distribution of alpha, theta and delta coefficients in the passive single-stimulus paradigm for each time window.
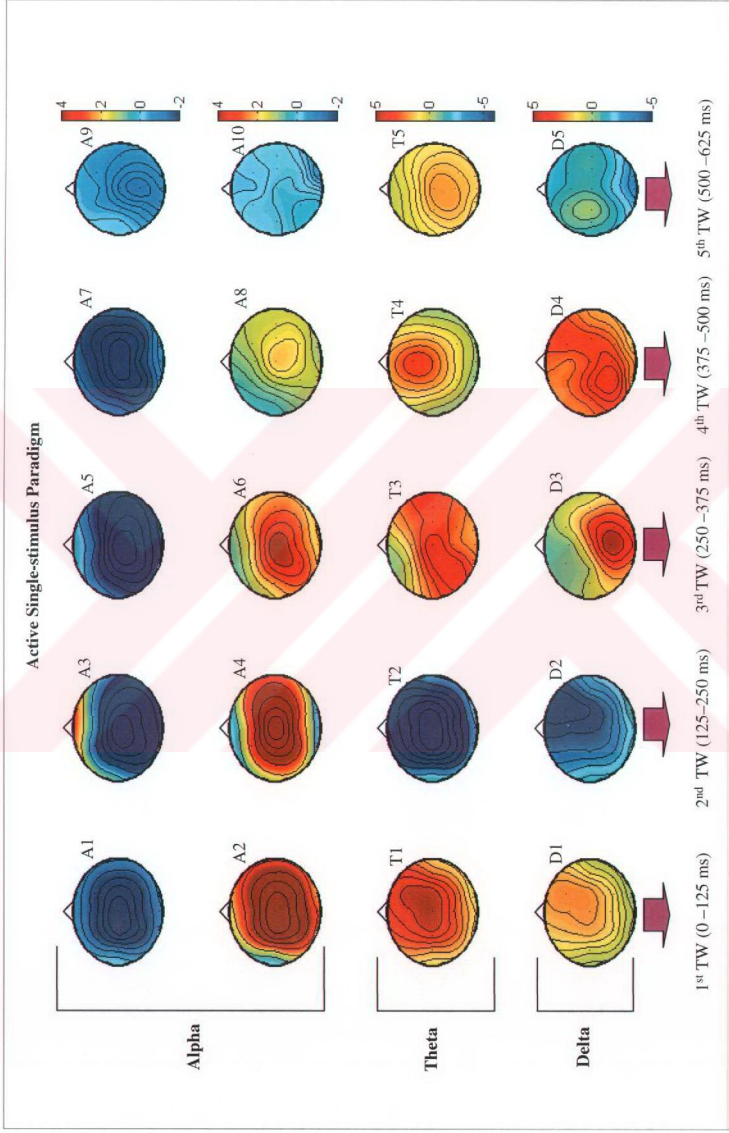
Figure 5.7 Scalp distribution of alpha, theta and delta coefficients in the active single-stimulus paradigm for each time window.

Figure 5.8 Scalp distribution of alpha, theta and delta coefficients in the standards of the passive oddball paradigm for each time window.

44

Figure 5.9 Scalp distribution of alpha, theta and delta coefficients in the deviants of the passive oddball paradigm for each time window.
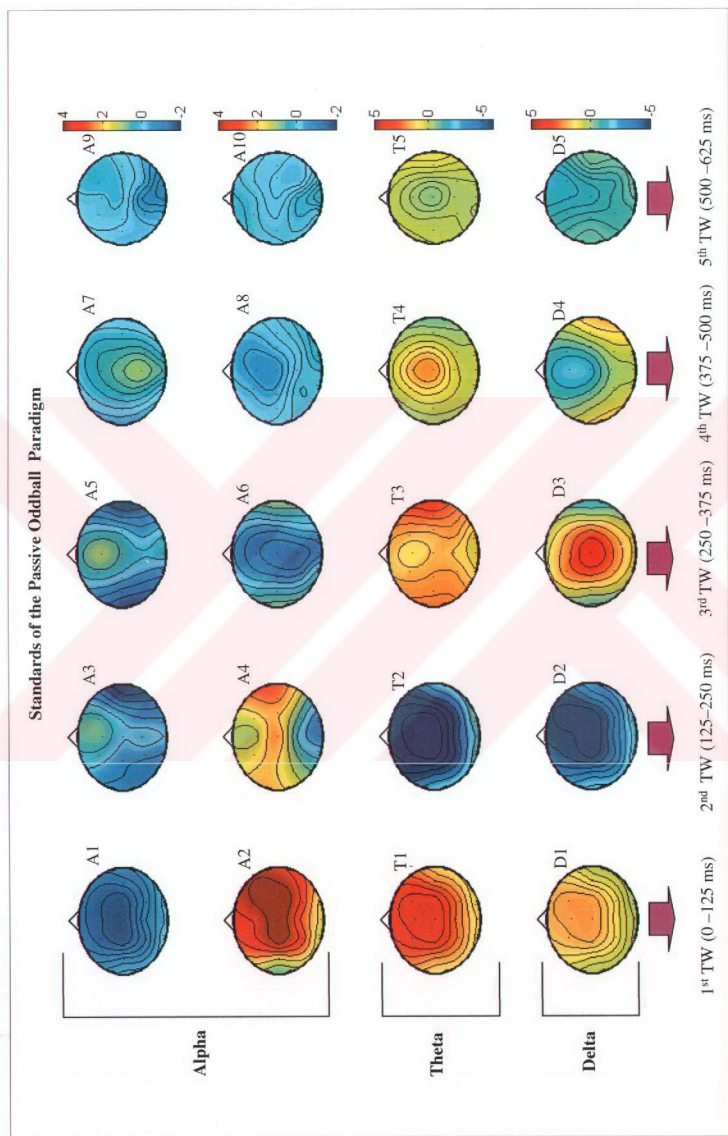
45
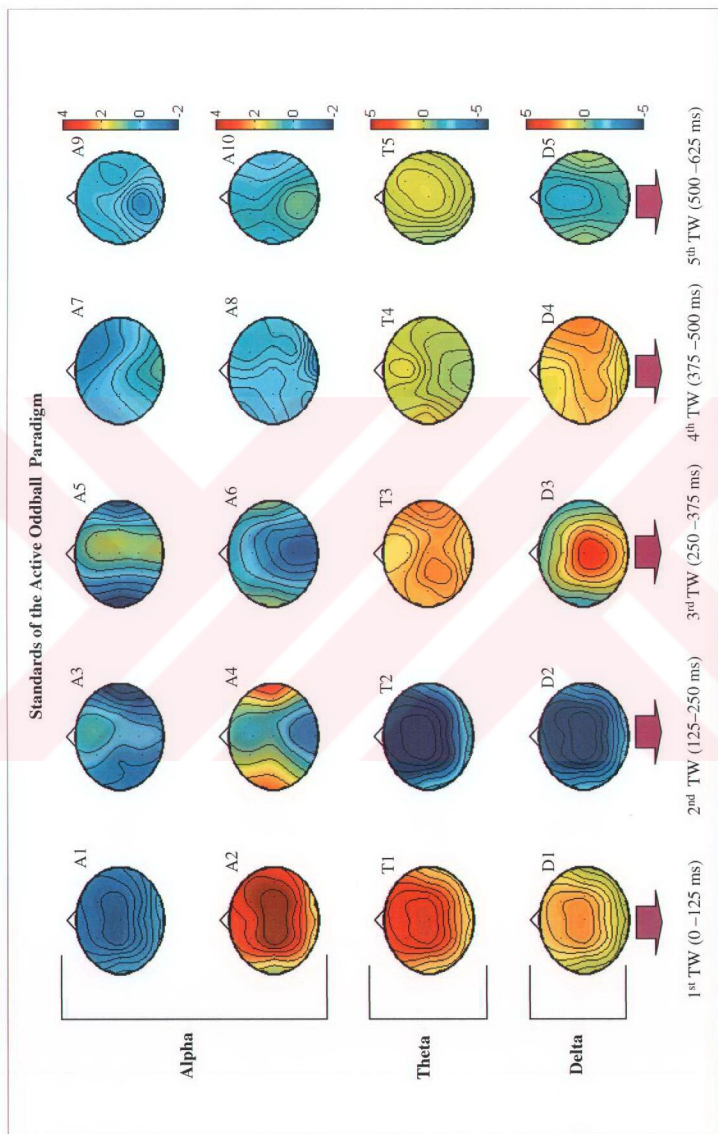
Figure 5.10 Scalp distribution of alpha, theta and delta coefficients in the standards of the active oddball paradigm for each time window.
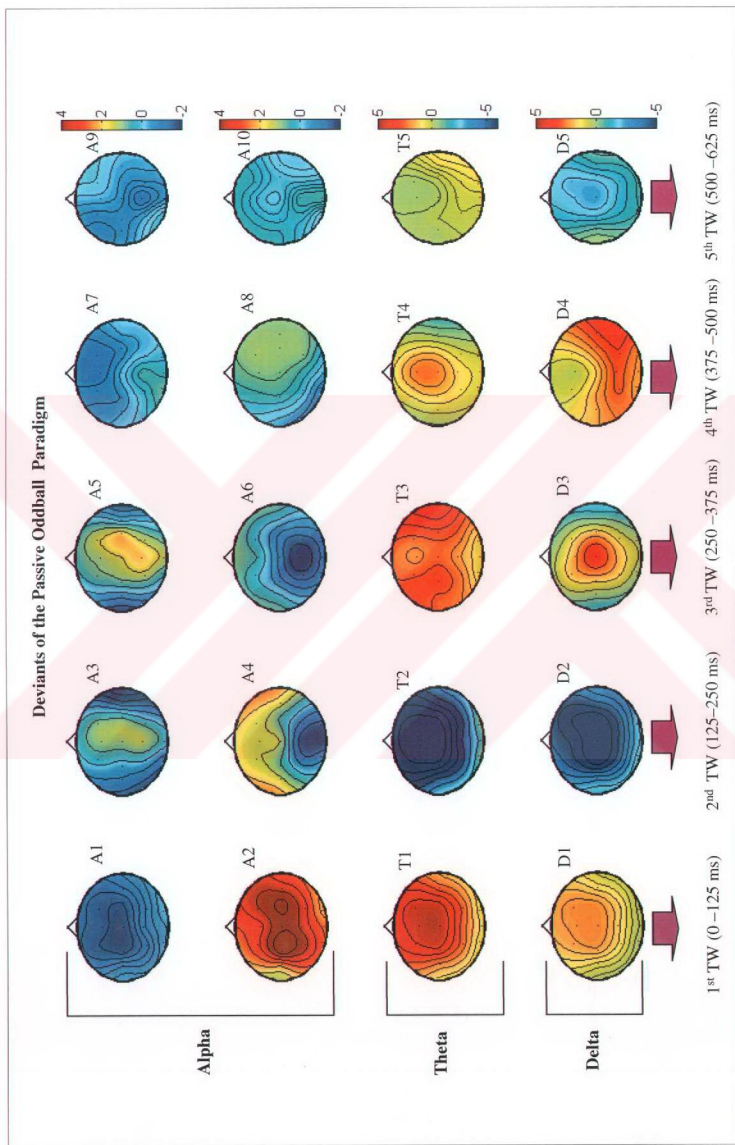
Figure 5.11 Scalp distribution of alpha, theta and delta coefficients in the deviants of the active oddball paradigm for each time window.
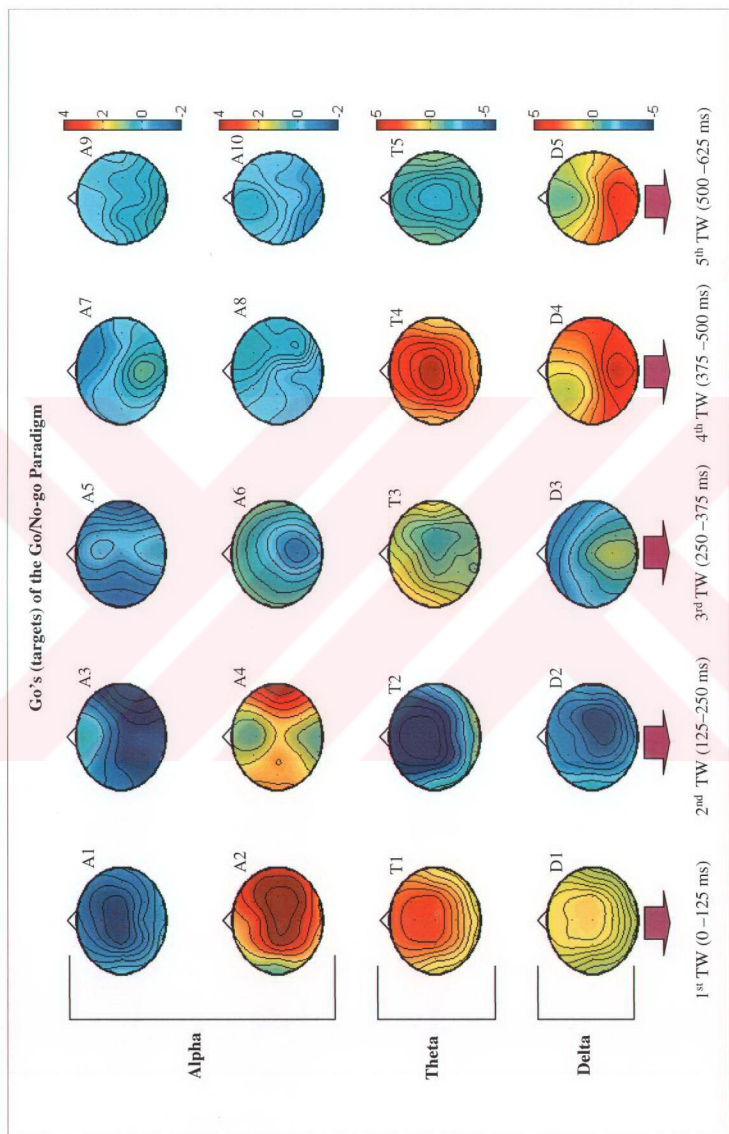
Figure 5.12 Scalp distribution of alpha, theta and delta coefficients in the go stimulus of the go / no-go paradigm for each time window.

Nogo's (Non-targets) of the Go/No-go Paradigm

Figure 5.13 Scalp distribution of alpha, theta and delta coefficients in the no-go stimulus of the go/no-go paradigm for each time window.

Standards of the Three-stimulus Paradigm

Figure 5.14 Scalp distribution of alpha, theta and delta coefficients in the standards of the three-stimulus paradigm for each time window.

50

Figure 5.15 Scalp distribution of alpha, theta and delta coefficients in the targets of the three-stimulus paradigm for each time window.
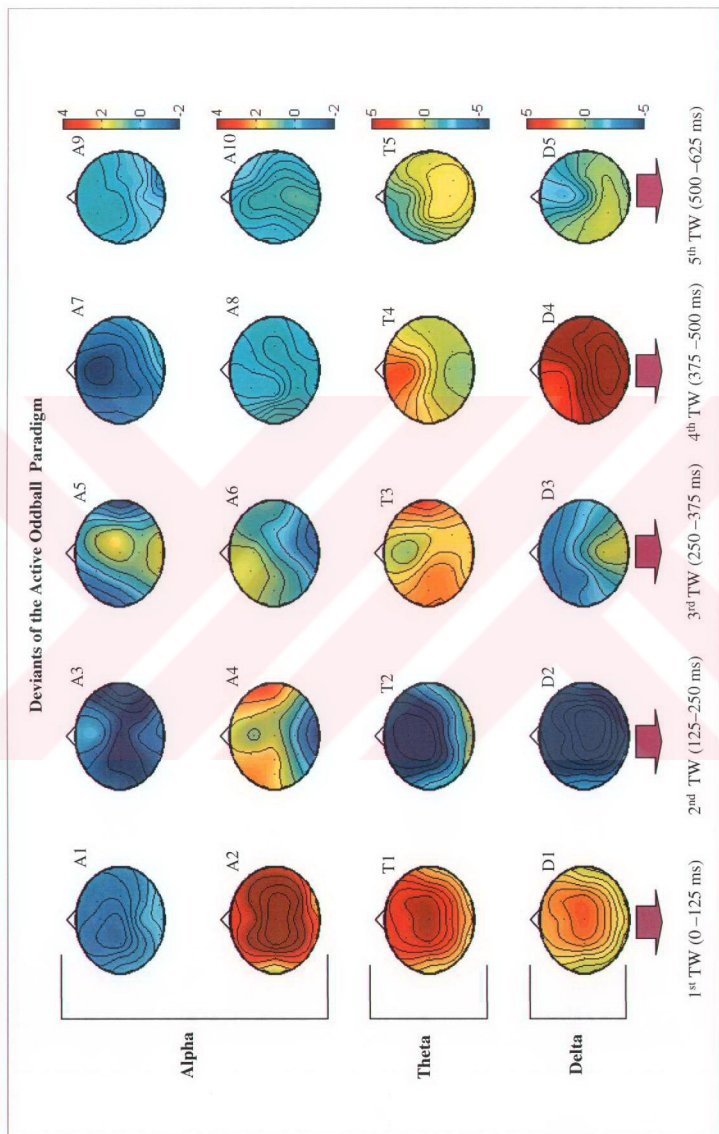
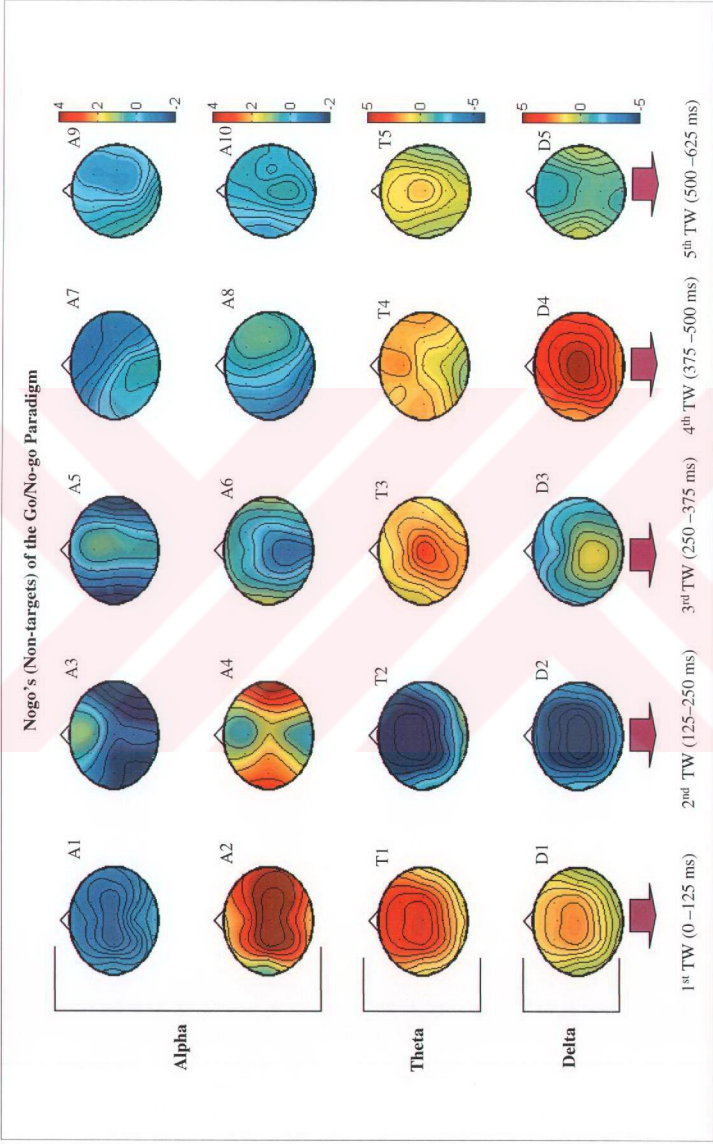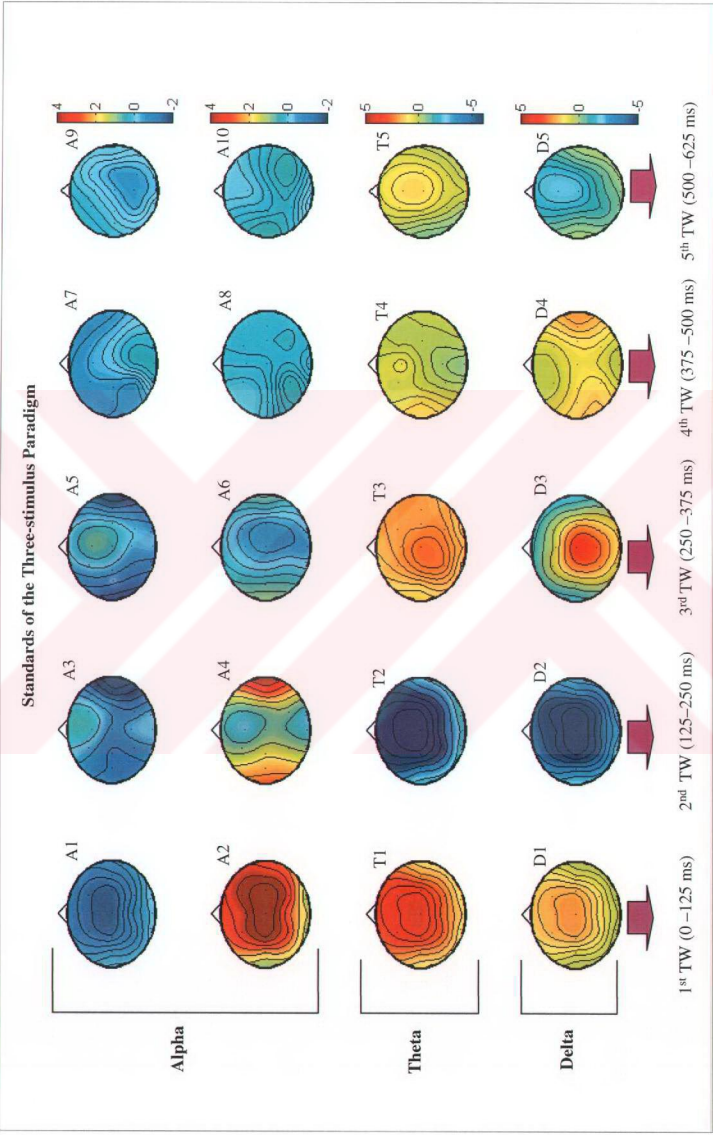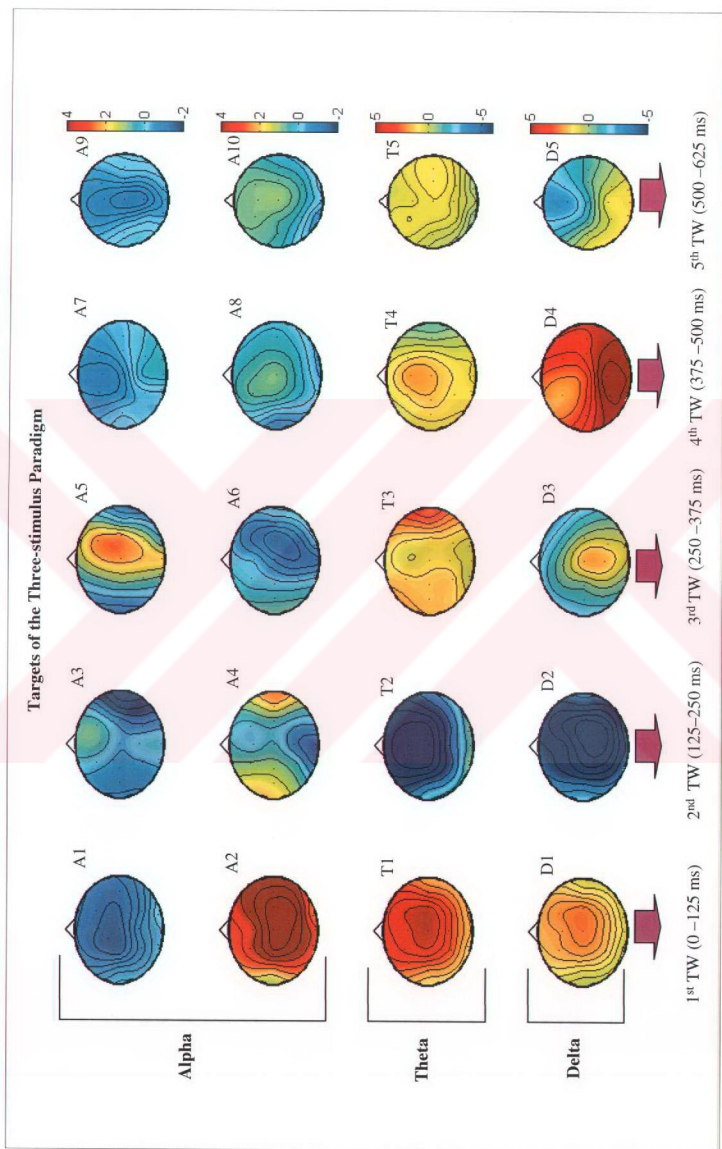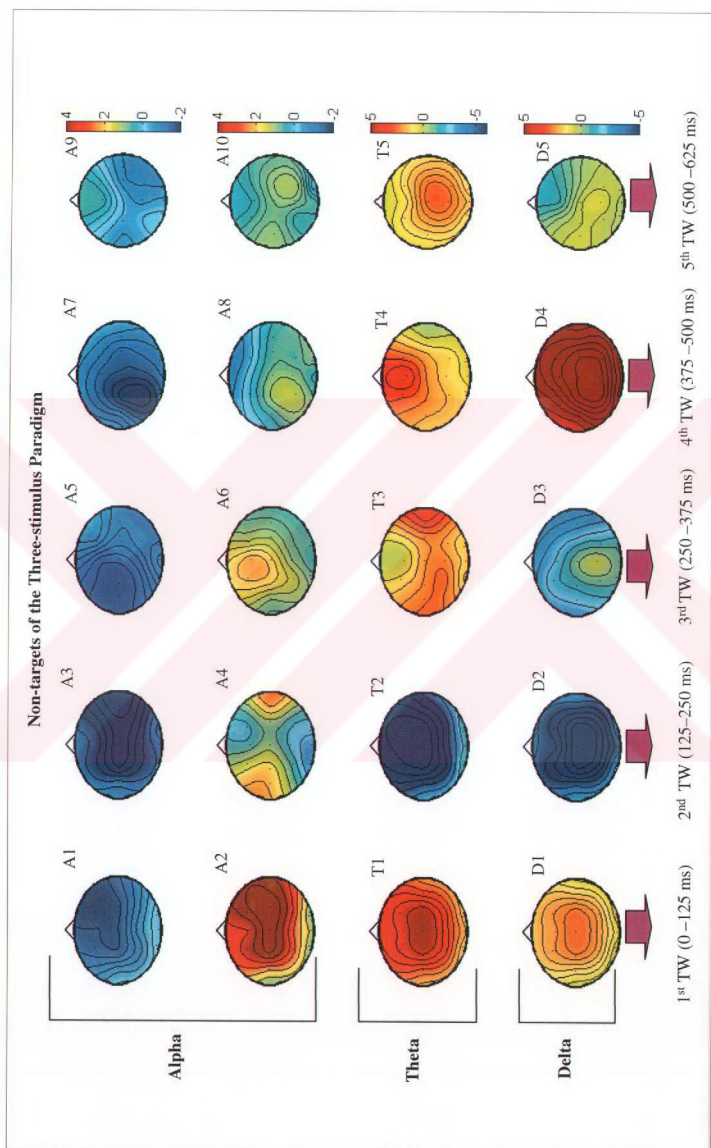**Figure 5.16** Scalp distribution of alpha, theta and delta coefficients in the non-targets of the three-stimulus paradigm for each time window.

6. DISCUSSION

In this study, designed paradigms had both similar and dissimilar cognitive properties. Since the cognitive constructs, for which we aim to find the electrophysiological correlates might also partially overlap with each other or share some common sub-functions, each time-frequency component found in the electrophysiological domain sometimes may not reflect a purely specific cognitive effect.

One of the most prominent findings of the time-frequency domain analysis is the general suppression of the alpha coefficients in the presence of signal discrimination. This suppression of the A1-8 coefficients in discrimination conditions seems to be the result of the need to allocate more attentional resources for the discrimination of different types of stimuli. Especially, their presence in the form of oscillatory patterns with a slow damping (see Figure 5.6 and 5.7; first 2 rows, each successive coefficient has a different polarity) in the single-stimulus paradigms, is a good example of an induced rhythm. Considering the literature on the functional meaning of the on-going alpha rhythm as the sign of the idling of specific brain areas [66, 67], it seems to be meaningful that this rhythm is more suppressed in the conditions where signal discrimination was engaged, hence the activation of wider brain areas are needed. On the other hand, since signal discrimination decreased alpha coefficients more prominently over the central scalp region, as recently suggested, alpha activity may reflect a "surrounding inhibition" process rather than idling and most probably it is controlled by the thalamo-cortical loops and reticular formation [68, 69].

In contrast to the rhythmic pattern along the first 8 alpha coefficients obtained in the single-stimulus conditions, in the conditions, which require signal discrimination, a transient topographic pattern of A3 to A5 coefficients appears to be significant. In all conditions other than single-stimulus experiments, both A3 to A5 coefficients showed very clear bitemporal maxima, whereas their magnitude on the midline electrodes decreased significantly. It seems that this topographic pattern is specific for the signal discrimination process. Considering that especially the A4 corresponds to the P200 latency range, it is possible that the bitemporal A4 coefficients reflect an important sub-process in the P200 latency range that is purely related to signal discrimination. A recent study on the cellular

correlates of the P200 wave with depth electrodes in animal cortex showed that P200 mainly reflects inhibition of the cortical areas responsible for the processing of the stimuli of other categories [70]. The authors showed in a study design consisting of face and word stimuli, that face-specific cells are maximally inhibited by words and vice versa, and that this inhibition process corresponds roughly to the P200 time window. As in our experiments all stimulus categories consist of sounds of different frequencies, it seems to be plausible that the bitemporal A4 topography reflects the inhibition of frequency selective neurons that are responsive to the other stimulus category in the signal discrimination conditions. The interesting point is that the P200 wave in the time domain shows a midline centro-parietal maximum (Figure 5.3), whereas the A4 coefficient, that reflects a sub-process in the P200 latency range shows a clear-cut bitemporal topography, which closely corresponds to the results in [70] with monkey brain using depth electrodes and to the results of the source localization studies in human [47]. Considering that signals in the alpha frequency range may reflect inhibition of specific brain areas, it seems to be very meaningful that the active inhibition effect shown in [70] is reflected to the alpha frequency component on the scalp.

The time domain analysis revealed that the amplitude of the P200 potential was significantly higher in the absence of signal discrimination task (in the active and the passive single-stimulus paradigms). Such a P200 difference between the single stimulus paradigm and the oddball paradigm was reported in many studies but it was not discussed [53-56]. The time-frequency analysis showed that in addition to the A4, D3 and particularly T3 coefficient, which was specifically affected by the signal discrimination, seem to reflect the P200 amplitude effect between the discrimination vs. non-discrimination conditions.

Presence of the motor response requirement decreased D3 to the negative values especially over the anterior scalp regions. Replacement of the positivity into the fronto-central negativity with motor response task in this delta range might reflect the occurrence of the processing negativity with increase in the allocation of attentional resources [3]. Consequently, the difference in P200 potential between the paradigms expressed as the only decrease in the amplitude of the P200 in the time domain analysis, but time-frequency

analysis revealed that the different sub-components were affected by different processes and then the summation of these effects created a final amplitude decrement.

Fronto-centrally distributed early components, D1 and T1, were affected similarly by the signal discrimination, motor response and context updating operations. Thus, these components might be in part of general processes in the early period of the stimulus processing that are probably related with automatic attention.

The amplitude of the D2 was prominently affected by the presence of the context updating process especially over the centro-parietal scalp region and the presence of the both motor response and the context updating made D2 more negative. This component should be related to the selective attention in order to discriminate infrequent, task relevant stimuli from the other ones. Because of its latency range (125-250 ms) and task-context updating interaction suggest that D2 may correspond or contribute the attention related negativity, processing negativity with D3 coefficient.

As previous studies already pointed out, parietally distributed D4 coefficient was suggested to be the basic P300 component, because it was affected by the same factors and it was mostly associated with the signal matching and decision making operation [18-22]. In the present study, this delta coefficient and P300 potential were affected by the motor response task, context updating and inhibition similarly, therefore this component seems to reflect a more general process in P300 latency range rather than a specific process. Prominent fronto-central effect of inhibition on the magnitude of D4 caused the occurrence of the more centrally distributed D4 mainly in the no-go response of the go/no-go and the non-target response of the three-stimulus paradigm as can be seen for P300 amplitude.

Additional theta activity to P300 seems possible, but this additional theta showed different patterns throughout the paradigm set. As can be seen in Figures 5.10, 5.14 and 5.13, T4 coefficient disappeared almost completely in the standard stimuli of the active oddball and the three-stimulus paradigm, and partially in the no-go response of the go/no-go paradigm. Such suppression in this coefficient as a response to the task irrelevant stimuli may suggest the selective inhibition of the responses to these stimuli. However, this coefficient occurred with similar fronto-central scalp distribution in both passive and active

single-stimulus paradigms, where no signal discrimination is needed, and in the passive oddball paradigm where the two types of stimuli were not task-relevant. Hence, this component shows an interesting complex reactivity pattern: It disappears only in the conditions where frequent, task-irrelevant stimuli are to be discriminated from different stimulus categories. It can be considered that the disappearance of this component reflects an active inhibition process during the processing of the task irrelevant signals, which however occur frequently and therefore contribute to the general context of the experiment. However, this theta response to an unexpected stimulus both in terms of its quality (very low frequency tones compared with the standards and targets) or its low probability such as the non-target stimulus in the three-stimulus paradigm cannot be inhibited, and a strong T4 is observed especially in frontal areas. Therefore, the presence of a high expectation or certainty in terms of the high frequency of the stimuli seems to be an important factor that determines the suppression of the T4. In contrast the presence of T4, especially on the central area, is extremely strong in go-responses of the go/no-go paradigm, which shows that the task-relevance of stimuli that are to be discriminated with a low certainty (probability of the target stimuli is 50% in the go/no-go paradigm) maximally activates the neural groups that are responsible of the generation of T4 component.

Although T5 coefficient was smaller in the non-discrimination conditions in general, the presence of the motor response in the non-discrimination conditions (i.e. active single-stimulus paradigm) increased the magnitude of this coefficient. This theta coefficient also showed different activation patterns in the different paradigms. This patterns were statistically detected as context updating and inhibition effect on T5. This late mostly centro-parietal theta activity was more prominent for the non-targets of the three-stimulus paradigm, active single-stimulus paradigm and partially for the no-go response of the go/no-go paradigm and the targets of the oddball paradigm. It seems difficult to associate this coefficient with a specific cognitive function however, because the scalp recorded theta activity was previously related with the hippocampo-cortical feedback loops and memory [9], this late theta coefficient might be reflect post operative processes like evaluation of the response.

D5 coefficient of discrimination task showed a sharp fronto-parietal difference towards to positive values in the parietal region. The presence of additional motor response

enhanced this effect. Enhancement of this component with signal discrimination and motor task may suggest that this component may be a late P300 component especially in the condition where both signal discrimination and motor response are present.

7. CONCLUSION

In this study, time-frequency analysis of data using WT displayed distinct and detailed time-frequency characteristics of the different stimulus types in the paradigms, in addition to parallel findings with the time domain analysis. However, we failed to find pure electrophysiological correlates of the defined cognitive constructs. This may be due to the partial overlapping of these processes or the paradigms, or due to the applied statistical design. Some of the effects that can be easily seen in the topographic distribution of the wavelet coefficients, as a response to different conditions could not be detected with the designed statistical analysis. This is because of the fact that prominent effects seen in one stimulus type covered by a moderate effect in another stimulus type, which was classified in the same group with the previous one.

Applying statistical analysis to small groups or paired comparison, on the other hand, will make the interpretation of the results difficult in terms of cognitive construct. Further analysis should and in fact will be done, in order to clarify found differences and their relation with cognitive processes.

Some of the coefficients found showed similar topographic patterns across conditions and they differed between conditions only in their intensity. Yet, some of the obtained coefficients showed different topography patterns across conditions, they may not reflect separate functional components, rather they may reflect more than one functional component. Although WT is an efficient method to investigate time-frequency characteristics of the ERPs with optimal time and frequency resolution, spatially overlapping events could not be easily distinguished by this method. Hence, for a more accurate decomposition of ERPs into distinct sub-components, spatial decomposition methods should also be incorporated to time-frequency analysis.

APPENDIX

Table A.1

Coefficients of the truncated decomposition filters h, g (IIR) and reconstruction filters p^2, q^2 (FIR) for quadratic B-spline wavelet [13].

k	$h(k)$	$g(k)$	$p^2(k)$	$q^4(k)$
−10	+0.00157	−0.00388		
−9	+0.01909	−0.03416		
−8	−0.00503	+0.00901		
−7	−0.04440	+0.07933		
−6	+0.01165	−0.02096		
−5	+0.10328	−0.18408		
−4	−0.02593	+0.04977		+1/480
−3	−0.24373	+0.42390		−29/480
−2	+0.03398	−0.14034	+1/4	+147/480
−1	+0.65523	−0.90044	+3/4	−303/480
0	+0.65523	+0.90044	+3/4	+303/480
1	+0.03398	+0.14034	+1/4	−147/480
2	−0.24373	−0.42390		+29/480
3	−0.02593	−0.04977		−1/480
4	+0.10328	+0.18408		
5	+0.01165	+0.02096		
6	−0.04440	−0.07933		
7	−0.00503	−0.00901		
8	+0.01909	+0.03416		
9	+0.00157	+0.00388		

8. REFERENCES

1. Donchin, E., and M. Coles, "Is The P300 Component a Manifestation of Context Updating?" *Behav. Brain Sci.*, Vol. 11, pp. 357-374, 1988.

2. Näätänen, R., "The Role of Attention in Auditory Information Processing as Revealed by Event Related Potentials and Other Brain Measures of Cognitive Function," *Behav. Brain Sci.*, Vol. 13, pp. 201-288, 1990.

3. Näätänen, R., "Processing Negativity: An Evoked Potential Reflection of the Attention," *Psychological Bulletin*, Vol. 92, pp. 605- 640, 1982.

4. Rosler, F., and D. Manzey, "Principal Components and Varimax-Rotated Components in Event-Related Potential Research: Some Remarks on Their Interpretation," *Biol. Psychol.*, Vol. 13, pp. 3-26, 1981.

5. Makeig, S., M. Westerfield, T. P. Jung, J. Covington, J. Townsend, T. J. Sejnowski, and E. Courchesne, "Functionally Independent Components of the Late Positive Event-Related Potential During Visual Spatial Attention," *J. Neurosci.*, Vol. 19, pp. 2665-2680, 1999.

6. Pritchard, W. S., M. E., Houlihan, and J. H., Robinson, "P300 and Response Selection: A New Look Using Independent-Components Analysis," *Brain Topogr.*, Vol. 12, pp. 31-37, 1999.

7. Steriade, M., P. Gloor, R. Llinás, F. H. Lopes da Silva, and M. Mesulam, "Basic Mechanisms of Cerebral Rhythmic Activities," *Electroenceph. Clin. Neurophysiol.*, Vol. 76, pp. 481-508, 1990.

8. Lopes da Silva, F. H., "Neural Mechanisms Underlying Brain Waves: From Neural Membranes to Networks," *Electroenceph. Clin. Neurophysiol.*, Vol. 79, pp. 81-93, 1991.

9. Klimesch, W., "EEG Alpha and Theta Oscillations Reflect Cognitive and Memory Performance: A Review and Analysis," *Brain Res. Rev.*, Vol. 29, pp. 169-195, 1999.

10. Basar-Eroglu, C., E. Basar, T. Demiralp, and M. Schürmann, "P300 Response: Possible Psychophysiological Correlates in Delta and Theta Frequency Channels," *Int. J. Psychophysiol.*, Vol. 13, pp. 161-179, 1992.

11. Basar, E., *EEG-Brain Dynamics Relation Between EEG and Brain Evoked Potentials*, Elsevier, Amsterdam, 1980.

12. Sinkkonen, J., H. Tiitinen, and R. Näätänen, "Gabor Filters: An Informative Way for Analyzing Event-Related Brain Activity," *J. Neurosci. Methods,* Vol. 56, pp. 99-104, 1995.

13. Ademoğlu, A., "Analysis of Averaged and Single Evoked Potentials Using Damped Sinusoids and Wavelet Basis Functions," Ph.D. Dissertation, Department of Biomedical Engineering, Boğaziçi University, Istanbul, Turkey, 1995.

14. Ademoglu, A., T. Demiralp, J. Yordanova, V. Kolev, and M. Devrim, "Decomposition of Event-Related Brain Potentials Into Multicomponents Using Wavelet Transform," *Appl. Signal Proc.*, Vol. 5, pp. 142-151, 1998.

15. Samar, V. J., K. P. Swartz, and M.R. Raghuveer, "Multiresolution Analysis of Event-Related Potentials by Wavelet Decomposition," *Brain. Cogn.*, Vol. 27, pp. 398-438, 1995.

16. Samar, V. J., A. Bopardikar, R. Rao, and K. Swartz, "Wavelet Analysis of Neuroelectric Waveforms: A Conceptual Tutorial," *Brain Lang.*, Vol. 66, pp. 7-60, 1999.

17. Schiff, S., A. Aldroubi, M. Unser, and S. Sato, "Fast Wavelet Transformation of EEG," *Electroenceph. Clin. Neurophysiol.*, Vol. 91, pp. 442-455, 1994.

18. Kolev, V., T. Demiralp, J. Yordanova, A. Ademoglu, and Ü. Isoglu-Alkac, "Time-Frequency Analysis Reveals Multiple Functional Components During Oddball P300," *NeuroReport*, Vol. 8, pp. 2061-2065, 1997.

19. Demiralp, T., J. Yordanova, V. Kolev, A. Ademoglu, M. Devrim, and V. Samar, "Time-Frequency Analysis of Single-Sweep Event-Related Potentials by Means of Fast Wavelet Transform," *Brain Lang.*, Vol. 66, pp. 129-145, 1999.

20. Demiralp, T., and A. Ademoglu, "Decomposition of Event-Related Brain Potentials into Multiple Functional Components Using Wavelet Transform," *Clinical Electro-encephalography*, Vol. 32, pp. 122-138, 2001.

21. Demiralp, T., A. Ademoglu, M. Schürmann, C. Basar-Eroglu, and E. Basar, "Detection of P300 Waves in Single Trials by the Wavelet Transform," *Brain Lang.*, Vol. 66, pp. 108-128, 1999.

22. Yordonova, J., M. Devrim, V. Kolev, A. Ademoglu, and T. Demiralp, "Multiple Time-Frequency Components Account for the Complex Functional Reactivity of P300," *Neuroreport*, Vol. 11, pp. 1097-1103, 2000.

23. Demiralp, T., A. Ademoglu, M. Comerchero, and J.Polich, "Wavelet Analysis of P3a and P3b," *Brain Topogr.*, Vol. 13, pp. 251-267, 2001.

24. Polich, J., "Frequency, Intensity, and Duration as Determinants of P300 from Auditory Stimuli," *J. Clin. Neurophysiol*, Vol. 6, pp. 277-286, 1989.

25. Polich, J., P. C. Ellerson, and J. Cohen, "P300, Stimulus Intensity, Modality, and Probability," *Int. J. Psychophysiol.*, Vol. 23, pp. 55-62, 1996.

26. Polich, J., "Attention, Probability, and Task Demands as Determinants of P300 Latency from Auditory Stimuli," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 63, pp. 251-259, 1986.

27. Polich, J., "Task Difficulty, Probability, and Inter-Stimulus Interval as Determinants of P300 from Auditory Stimuli," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 68, pp. 311-320, 1987.

28. Katayama, J., and J. Polich, "Stimulus Context Determines P3a and P3b," *Psychophysiology*, Vol. 35, pp. 23-33, 1998.

29. Picton, T. W., "The P300 Wave of the Human Event-Related Potential," *J. Clin. Neurophysiol.*, Vol. 9, pp. 456-479, 1992.

30. Polich, J., and A. Kok, "Cognitive and Biological Determinants of P300: An Integrative Review," *Biol. Psychol.*, Vol. 41, pp. 103–146, 1995.

31. Polich, J., "*P300 in Clinical Applications: Meaning, Method, and Measurements,*" in E. Neidermeyer and F. H. Lopes da Silva (Eds), *Electroencephalography: Basic Principles, Clinical Applications, and Related Fields,* pp. 1073-1091, Baltimore: Williams & Wilkins, 1999.

32. Ford, J. M., "Schizophrenia: the Broken P300 and Beyond," *Psychophysiology,* Vol. 36(6), pp. 667-82, 1999.

33. Picton, T. W., and S. A. Hillyard, "Human Auditory Evoked Potentials II. Effects of Attention," *Electroencephalogr. Clin. Neurophysiol,* Vol. 36, pp. 191-199, 1974.

34. Näätänen, R., and P. T. Michie, "Early Selective-Attention Effects on the Evoked Potential: A Critical Review and Reinterpretation," *Biol. Psychol.* Vol. 8, pp. 81-136, 1979.

35. Coles, M. G. H., and M. D. Rugg, "*Event-Related Brain Potential: An Introduction,*" in M. G. H. Coles and M. D. Rugg (Eds), *Electrophysiology of Mind, Event Related Brain Potentials and Cognition,* pp. 1-26, Oxford: Oxford University Press, 1995.

36. Sutton, S., M. Braren, J. Zubin, and E. R. John, "Evoked-Potential Correlates of Stimulus Uncertainty," *Science,* Vol. 150, pp. 1187-1188, 1965.

37. Donchin, E, "Presidential Address, 1980. Surprise!...Surprise?," *Psychophysiology,* Vol. 18, pp. 493-513, 1981.

38. Squires, N., K. Squires, and S. Hillyard, "Two Varieties of Long-Latency Positive Waves Evoked by Unpredictable Auditory Stimuli in Man," *Electroencephalogr. Clin. Neurophysiol.,* Vol. 38, pp. 387-401, 1975.

39. Courchesne, E., S. A Hillyard, and R. Galambos, "Stimulus Novelty, Task Relevance, and the Visual Evoked Potential in Man," *Electroencephalogr. Clin. Neurophysiol.* Vol. 39, pp. 131-143, 1975.

40. Courchesne, E, R. Y. Courchesne, and S. A. Hillyard, "The Effect of Stimulus Deviation on P3 Waves to Easily Recognized Stimuli," *Neuropsychologia,* Vol. 16, pp. 189-199, 1978.

41. Knight, R., "Decreased Response to Novel Stimuli After Prefrontal Lesions in Man," *Electroencephalogr. Clin. Neurophysiol.,* Vol. 59, pp. 9-20, 1984.

42. Knight, R., D. Scabini, D. Woods, and C. Clayworth, "Contributions of Temporal-parietal Junction to the Human Auditory P3," *Brain Res.*, Vol. 502, pp. 109-116, 1989.

43. Knight, R., "Contribution of Human Hippocampal Region to Novelty Detection," *Nature,* Vol. 383, pp. 256-259, 1996.

44. McCarthy, G., C. Wood, P. Williamson, and D. Spencer, "Task-Dependent Field Potentials in Human Hippocampal Formation," *J. Neurosci.,* Vol. 9, pp. 4253-4268, 1989.

45. Menon, V., J. Ford, K. Lim, G. Glover, and A. Pfefferbaum, "Combined Event-Related fMRI and EEG Evidence for Temporal-Parietal Cortex Activation During Target Detection," *NeuroReport,* Vol. 8, pp. 3029-3037, 1997.

46. McCarthy, G., M. Luby, J Gore, and P. Goldman-Rakic, "Infrequent Events Transiently Activate Human Prefrontal and Parietal Cortex as Measured by Functional MRI," *J. Neurophysiol.,* Vol. 77, pp. 1630-1634, 1997.

47. Tarkka, I. M., D. S. Stokic, L. F. Basile, and A. C. Papanicolaou, "Electric Source Localization of the Auditory P300 Agrees with Magnetic Source Localization," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 96, pp.538-545, 1995.

48. Scherg, M., and D. Von Cramon, "Evoked Dipole Source Potentials of the Human Auditory Cortex," *Electroencephalogr. Clin. Neurophysiol.,* Vol. 65, pp. 344-360, 1986.

49. Rif, J., R. Hari, M. S. Hamalainen, and M. Sams, "Auditory Attention Affects Two Different Areas in Human Supratemporal Cortex," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 79, pp. 464-472, 1991.

50. Siedenberg, R., D. S. Goodin, M. J. Aminoff, H. A. Rowley, and T. P. L. Roberts, "Comparison of Late Components in Simultaneously Recorded Event- Related Electrical Potentials and Event-Related Magnetic Fields," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 99, pp. 191-197, 1996.

51. Hackley, S. A., M. Woldorff, and S. A. Hillyard, "Cross-Modal Selective Attention Effects on Retinal, Myogenic, Brainstem, and Cerebral Evoked Potentials," *Psychophysiology,* Vol. 27, pp. 195–208, 1990.

52. Luck, S. J., and S. A. Hillyard, "Electrophysiological Correlates of Feature Analysis During Visual Search," *Psychophysiology*, Vol. 31, pp. 291–308, 1994.

53. Polich, J., S. E. Eischen, and G. E. Collins, "P300 from a Single Auditory Stimulus," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 92, pp. 253-61, 1994.

54. Polich, J., and C. Margala, "P300 and Probability: Comparison of Oddball and Single-Stimulus Paradigms," *Int. J. Psychophysiol.* Vol. 25, pp. 169-176, 1995.

55. Mertens, R., and J. Polich, "P300 From A Single-Stimulus Paradigm: Passive Versus Active Tasks and Stimulus Modality," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 104, pp. 488-97, 1997.

56. Zenker, F., and J. J. Barajas, "Auditory P300 Development from an Active, Passive and Single-Tone Paradigms," *Int. J. Psychophysiol.*, Vol. 33, pp. 99-111, 1999.

57. Polich, J., "P300 from a Passive Auditory Paradigm," *Electroencephalogr. Clin. Neurophysiol.*, Vol. 74(4), pp. 312-20, 1989.

58. Bruin, K. J., and A. A. Wijers, "Inhibition, Response Mode, and Stimulus Probability: A Comparative Event-Related Potential Study," *Clin. Neurophysiol.*, Vol. 113, pp. 1172-1182, 2002.

59. Bokura, H., S. Yamaguchi, and S. Kobayashi, "Electrophysiological Correlates for Response Inhibition in a Go/NoGo Task," *Clin. Neurophysiol.*, Vol. 112, pp. 2224-2232, 2001.

60. Fallgatter, A. J., and W. K. Strik, "The NoGo-Anteriorization as a Neurophysiological Standard-Index for Cognitive Response Control," *Int. J. Psychophysiol.*, Vol. 32, pp. 233–238, 1999.

61. Katayama, J., and J. Polich, "Auditory and Visual P300 Topography from a 3 Stimulus Paradigm," *Clin. Neurophysiol.*, Vol. 110, pp. 463-468, 1999.

62. Daubechies, I., "Orthonormal Bases of Compactly Supported Wavelets," *Comm. Pure Appl. Math.*, Vol. 41, pp. 909-996, 1988.

63. Mallat, S., "A theory For Multiresolution Signal Decomposition: the Wavelet Representation," *IEEE Trans. Patt. Analysis Mach. Intell.*, Vol. 11, pp. 674-693, 1989.

64. Eckhorn, R., R. Bauer, W. Jordan, M. Brosch, W. Kruse, M. Munck, and H. J. Reitboeck, "Coherent Oscillations: A Mechanism of Feature Linking in the Visual Cortex?," *Biol. Cybern.,* Vol. 60, pp. 121-130, 1988.

65. Unser, M., A. Aldroubi, and M. Eden, "On the Asymptotic Convergence of B-Spline Wavelets to Gabor Functions," *IEEE Trans. Info. Theory,* Vol. 38, pp. 864-872, 1992.

66. Pfurtscheller, G., A. Jr. Stancak, and C. Neuper, "Event-Related Synchronization (ERS) in the Alpha Band an Electrophysiological Correlate of Cortical Idling: A Review," *Int. J. Psychophysiol.,* Vol. 24, pp. 39-46, 1996.

67. Adrian, E. D., and B. H. C. Matthews, "The Berger Rhythm: Potential Changes From the Occipital Lobes in Man," *Brain,* Vol. 57, pp. 354-385, 1934.

68. Cooper, N, R., R. J. Croft, S. J. Dominey, A. P. Burgess, and J. H. Gruzelier, "Paradox Lost? Exploring the Role of Alpha Oscillations During Externally vs. Internally Directed Attention and the Implications for Idling and Inhibition Hypotheses," *Int. J. Psychophysiol.,* Vol. 47, pp. 65-74, 2003.

69. Suffczynski, P., S. Kalitzin, G. Pfurtscheller, and F. H. Lopes da Silva, "Computational Model of Thalamo-Cortical Networks: Dynamical Control of Alpha Rhythms In Relation to Focal Attention," *Int. J. Psychophysiol.,* Vol. 43, pp. 25-40, 2001.

70. Allison, T., A. Puce, and G. McCarthy, "Category-Sensitive Excitatory and Inhibitory Processes In Human extrastriate Cortex," *J. Neurophysiol.,* Vol. 88, pp. 2864-68, 2002.