Predictability of Cognitive Performance Based on Functional Neuroimaging via fNIRS

by

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Predictability of Cognitive Performance Based on Functional Neuroimaging via fNIRS

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ABSTRACT

Predictability of Cognitive Performance Based on Functional Neuroimaging via fNIRS

In neuropsychology many tasks have been used to determine the cognitive ability and/or flexibility of individuals to have any prior knowledge about the psychological condition or to state the level of neuropsychological disease of a person. This study presents the relations between behavioral performances and neuronal activation within and between two cognitive tasks; Tower of London (TOL) and color-word matching Stroop test which are utilize to obtain cognitive flexibility on decision making, attention and planning. Functional Near Infrared Spectroscopy method is used as functional neuroimaging tool. fNIRS results revealed that activations for both tasks mainly located in both left and right lateral side of prefrontal cortex. Behavioral outcomes such as reaction times of interference effect of stroop task and total planning time of TOL tasks were compared with neuroimaging findings. Right superior lateral prefrontal cortex (RSLPFC) activity during incongruent-neutral interference showed positive correlation with difference of mean response times for correct answered incongruent and congruent trials. In addition we also observed negative correlation with activation of 7-move TOL task and reaction time in left and right lateral prefrontal cortex. At last, it has been presented that subjects have negative brain response(NBR) which is related with good performance (according to results of correlation analysis) during stroop task showed relatively positive brain response (PBR) during TOL task which indicates also good performance, whereas, lateral activation during TOL task is reduced for subjects have PBR in stroop task which can be stated as bad performance.

Keywords: Cognitive Tasks, fNIRS, Prefrontal Cortex, Executive Functions,Stroop Task, Tower of London.

ÖZET

iYKAS Fonksiyonel Nörogörüntüleme Tekniği Kullanılarak Bilişsel Performansın Öngörülebilirliği

Günümüze kadar nöropsikolojide birçok ödev, bireylerin bilişsel yeteneğini ve-/veya esnekliğini belirlemek için kullanılmıştır. Bu ödevlerdeki amaç bireylerin psikolojik durumları hakkında herhangi bir önbilgiye sahip olmak ya da kişinin hastalık seviyesini ifade etmektir. Bu çalışma, Londra Kulesi Testi (LKT) ve renk-kelime eşleştirme Stroop testlerinin kendi aralarındaki ve kendi içindeki davranışsal performanslar ve nöronal aktivasyonlar arasındaki ilintiyi sunar. Bu iki test, karar verme, planlama ve dikkat üzerindeki bilişsel esnekliği elde etmeyi amaçlar. işlevsel Yakın Kızılaltı Spektroskopi (iYKAS), nörogörüntüleme aracı olarak kullanılmıştır. iYKAS sonuçları, her iki ödevde de aktivasyonların yoğunluklu olarak hem sağ hem de sol prefrontal korteksin yanal yüzeylerinde görüldüğünü söylemektedir. Bu sonuçlar ile, Londra kulesi görevindeki toplam planlama süresi ve Stroop görevinin girişim etkisinin tepki süreleri gibi davranışsal sonuçların birbirleriyle ilintileri karşılaştırılmıştır. Uyumsuz-nötr girişiminden elde edilen verilerden, sağ üst yanal prefrontal korteks aktivasyonunun, aynı girişimin tepki süreleri arasında positif vir korelasyon izlediği görülmüştür. Bunların yanı sıra, 7-hamleli LKT görevinin sırasında oluşan sağ ve sol yanal prefrontal korteks aktivasyonu ile görevi tamamlama süresi arasında negatif bir ilinti olduğu gözlenmiştir. Son olarak, stroop testinde uyumsuz-nötr girişiminden elde ettiğimiz frontal aktivasyonu negatif olan deneklerin LKT esnasındaki prefrontal korteks aktivasyonlarının göreceli daha poizitif, yine aynı bölge için stroop test esnasındaki frontal aktivasyonu pozitif olan deneklerin, LKT esnasındaki sağ ve sol yanal prefrontal korteks aktivasyonlarının görece daha negatif olduğunu ve yaptığımız analizlere göre bu aktivasyonların Stroop test ve LKT′den elde edilen performans kriterleriyle eşleştiğini gösterdik.

Anahtar Sözcükler: Bilişsel Ödevler, işlevsel Yakın Kızılaltı Spektroskopi, Prefrontal Korteks, Yönetici Fonksiyonlar, Stroop Test, Londra Kulesi Testi.

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PFC	Prefrontal Cortex
DLPFC	Dorsalateral Prefrontal Cortex
LSLFC	Left Superior Lateral Frontal Cortex
LILFC	Left Inferior Lateral Frontal Cortex
LSFP	Left Superior Frontopolar
LIFP	Left Inferior Frontopolar
RSFP	Right Superior Frontopolar
RIFP	Left Inferior Frontopolar
RSLFC	Right Superior Lateral Frontal Cortex
RILFC	Right Inferior Lateral Frontal Cortex
TOL	Tower of London
TOH	Tower of Hanoi
TMS	Transcranial Magnetic Stimulation
EEG	Electroencephalography
HBO_2	Oxygenated Hemoglobin
HB	Deoxygenated Hemoglobin
FC	Frontal Cortex

1. INTRODUCTION

Etymologically " cognition " comes from the Latin verb cognosco, which 'con' means 'with' and 'gnosco' means 'know', itself a cognate of the Ancient Greek verb gnosko meaning 'I know'. However, the term 'cognition' has been used within disciplines such as psychology and cognitive sciences. In cognitive psychology, cognition known as processing of information from sensory inputs by transforming, reducing, storing, recovering, elaborating, and using in an operator's mind or brain. These mental processes can be described as: attention, working memory, comprehending and producing language, calculating, reasoning, problem solving, and decision making [4, 5].

Interests in cognitive processes emerged centuries ago. The opinion that what separates humans from animals is the consciousness, which is a debate that has been ongoing for many years. Humans have been always fascinated about how the brain works and how a decision is made. For instance Aristotle and his interest on mind and the functionality of the brain and his will to answer the question how it affects the human behavior, led him to focus on cognitive areas related to memory, perception, and mental imagery. The Greek philosopher found that his studies should be based on experimental evidence and the information should be gathered through accurate observations and conscientious experimentation [6]. The processes behind such adaptability to the inputs from out of the brain, referred as cognitive control, have been the focus of a growing research area within cognitive psychology [7, 8, 9].

Many experimental protocols which are aimed to get responses to given set of tasks by loading a cognitive work to a person have been designed by researchers. Apart from testing the cognitive power of healthy people, these tools are also used for accurately assessing individuals with questionable dementia, mild cognitive impairment, Alzheimer's disease, schizophrenia, and age-related memory loss.

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Among many experimental protocols, Stroop Task and Tower of London stand out as the ones most studied on. The Stroop task was first published by John Ridley Stroop in English in 1935 [10] as a classical paradigm involving the inhibition of automatic responses and to measure selective attention capacity and skills, as well as, the brain's processing speed. Tower of London task was originally designed in 1982 [11] to assess the deficits in executive functioning and planning abilities is applied to all participants. Today, this task is still frequently used in clinical or research settings for performance impairments assessed relative to normative performance.

Functional Near Infrared Spectroscopy (fNIRS) is used to obtain activations in prefrontal cortex area of subjects. Studies with patients who have frontal lesions [12, 13] or with healthy subjects [14, 15, 16] revealed that the prefrontal cortex region of the brain has large contribution on performing the cognitive tasks. This demonstrated role of the prefrontal cortex in the execution of all forms of actions (somatic movement, eye movement, emotional behavior, intellectual performance, speech, etc.)[17]. Since Tower of London test and Stroop test created to test executive functioning of the brain, fNIRS method is appropriate to be used in this study. In daily life, we face a variety of challenges both emotionaly and cognitively. Each individual has a unique way of coping with these challenges. The intricacy of the strategies explored depend on the cognitive abilities of the individual. We claimed that the cognitive ability or flexibility of a person can be quantified by fNIRS derived parameter during a cognitive task and that information would lead us to predict his/her cognitive ability in another task. We believe that efficiency in completing a task is as important as getting the work done. For instance every participant has completed the TOL tasks in a given time while the brain responses were not the same. This study aims to predict a person's cognitive ability from neuroimaging data during a cognitive tasks.

2. BACKGROUND

2.1 Evolution of Neuroimaging

In the earlier stage of cognitive studies with the advances in neuroimaging tools the evidence was only the behavioral responses. However, scientists have begun to do new researches on detecting the activity of brain. In 1918's the method called ventriculography was introduced [18]. X-ray images of the ventricular system within the brain were obtained by injection of filtered air directly into one or both lateral ventricles of the brain. It prevents to image the blood vessels in the brain. Until 1960's the tomographic images were taken by X-ray devices. In 1960's the investigations on radioactive imaging techniques were performed, and after the first positron emission tomography (PET) scanner was developed in 1973 by Paul Lauterbur, and Niels A. Lassen has published his work [19] based on the functional brain imaging. This approach relies on the idea of capturing the emission of positrons from injected molecules to the human blood vessels, so images could be created based on regional blood flow within the tissue. Since active neurons needs a robust blood supply, which is the main idea of neurovascular coupling phenomena [20], PET allows to make regional maps of brain activity indirectly during various neuropsychological tasks. Downside is that getting a PET image costs higher than other neuroimaging techniques.

Furthermore PET scanning is invasive since it does involve exposure to ionizing radiation. Another imaging method used in neuroimaging is magnetic resonance imaging (MRI). Since Wolfgang Ernst Pauli has made the suggestion that atomic nuclei should have magnetically related spins [21], many exploration has been made on the principles of magnetic resonance. After many researches, a device which can create an image by using the variation in signals produced by protons in the body when the tissue is placed in a magnetic field is produced [22]. Seiji Ogawa recognized that blood flow to activated brain regions could be used to augment MRI, since the magnetic properties of oxygenated hemoglobin (HBO_2) and deoxygenated-hemoglobin (HB) are different, it

would cause changes in the MRI signal. Blood-oxygen-level dependent (BOLD) is the MRI contrast of dHb, discovered in 1990 by Ogawa [23] and first functional magnetic resonance fMRI image in 1990 [24]. On the other hand, the application of this modality is not easy because the mobility and portability of MR devices are limited due to its huge size and furthermore it is costly.

One of another functional neuroimaging technique for mapping brain activity is Magnetoencephalography (MEG). MEG images are generated by recording magnetic fields produced by electrical currents occurring in the brain. Due to its size and cost it is also not convenient to be used conventionally. Apart from these expensive techniques, Electroencephalography (EEG) stands out as relatively more applicable than other techniques for the recording of neuronal activity of the brain [25]. EEG measures voltage fluctuations along the scalp resulting from ionic current flows within the neurons of the brain.

2.2 Functional Near Infrared Spectroscopy fNIRS

The more compatible, easy to use, relatively cheap way of neuroimaging technique that we used in this study is Functional Near Infrared Spectroscopy (fNIRS) which was first proposed in 1977 [26] as a non-invasive neuroimaging method which measures related changes of HBO_2 and HB in localized cerebral blood flow caused by neuronal activity. It has been demonstrated that skin, tissue, and bone are mostly transparent to NIR spectrum [27](see figure 2.1). Hence these changes, also called as hemodynamic responses are obtained by the measurement of near infrared (NIR) light attenuation. Since HBO_2 and HB are stronger absorbers of light NIR light in the spectrum of 700-900 nm. fNIRS signals are highly correlated with fMRI BOLD signals [28]. fNIRS and fMRI are sensitive to similar physiologic changes and are often comparative methods. Studies relating fMRI and fNIRS show highly correlated results in cognitive tasks [29]. fNIRS has several advantages in cost and portability over fMRI, but cannot be used to measure cortical activity more than 4 cm deep due to limitations in light emitter power and has more limited spatial resolution.

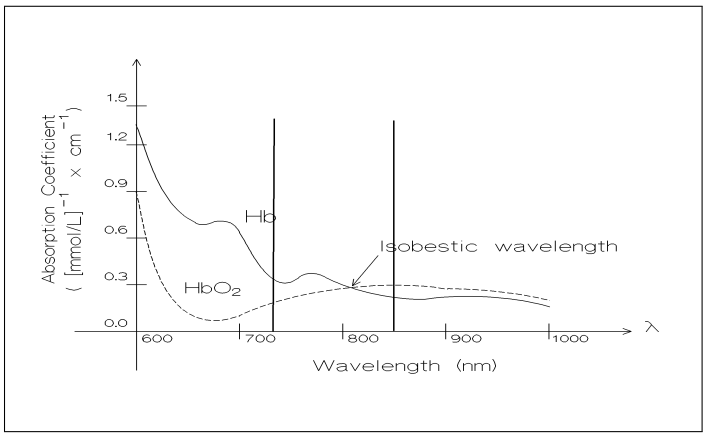

Figure 2.1 Frequency spectrum of absorbtion coefficients of HBO_2 and HB [1].

2.3 Cognitive Tasks with fNIRS

In this study 26 subjects performed the Stroop test [10] which is one of the cognitive task commonly used in psychology. Stroop effect is a demonstration of interference in the reaction time of the trials. Performance on the Stroop task relies on executive attention to maintain the goal of naming the color of the letters and aims to determine the partipicant's cognitive ability on selective attention of conflict questions. A first outcome is semantic interference, which states that naming the color of neutral stimuli (when the color and word do not interfere with each other) is faster than in incongruent conditions. The second finding, semantic facilitation, explains the finding that naming the color of congruent stimuli is faster (e.g. when the ink color and the word match) than neutral stimuli (when the ink is black, but the word describes a color). The third finding is that both semantic interference and facilitation disappear when the task consists of reading the word instead of naming the ink. For the test to be reliable, participants should respond faster to neutral questions than congruent and incongruent questions.

It has been sometimes called Stroop asynchrony, and has been explained by a reduced automatization when naming colors compared to reading words [30]. Many neuroimaging research has been conducted in neural correlates of Stroop task. However only few of them is performed via fNIRS. One of the fNIRS studies revealed task related frontal activations in left inferior frontal cortex during stroop task [31]. They have

found specific increase in concentration of oxy- and total-hemoglobin but they have not observed any task-related changes in the concentration of deoxyhemoglobin during incongruent trials. Another two studies in adults showed the hemodynamic increase of stroop interference effect in both right and left sides in the lateral prefrontal cortex areas [32, 33]. There are also studies with patiens; One of the stroop task with NIRS study with dyslexic children and healthy children revealed that the dysfunction of the PFC in conflict resolution for patient group cause reduced bilateral prefrontal activation. In one study of both control subjects and schizophrenia patients, increased activation has been reported in the bilateral PFC of healthy control subjects during performance of the Stroop task [34]. They also found that schizophrenia patients showed reduced activation in the prefrontal cortex during Stroop task.

Other cognitive task Tower of London(TOL) is applied in this study to all subjects who have performed stroop task. TOL task has been utilized in large amount of studies as a test of planning ability in neuropsychological patients as well as normal partipicants. In TOL tasks Subjects are asked to preplan a set of displacement of disks to reconstruct a given goal structure and then start to move disks one by one. Response planning is consisted of complex executive functions so that several studies investigated the involvement of response inhibition [35, 36] and working memory [37] in TOL task. This test basically measures latency time(time between start and first move), average execution time (time spent on applying the plan) and extra moves (number of moves excess of the minimum required moves to solve the task). Zhu et al. 2010[38] have performed TOL task measurements via fNIRS method. They have found an activation during TOL task compared with control condition in superior frontopolar and inferior lateral side of right prefrontal cortex (RPFC) and left lateral prefrontal cortex (LLPFC) area in healthy subjects. In same study they have observed reduced activation in schizophrenia patients in left lateral and left rostrolateral prefrontal cortex areas. Although there is no sufficient amount of fNIRS studies which have performed TOL task, there are couple of near infrared spectroscopy studies that have performed working memory tasks [39, 40]. These studies demonstrated the feasibility of NIRS-based detection of neuronal activation differences during complex cognitive tasks between healthy subjects and patients.

3. METHOD

3.1 Subjects

26 healthy voluntary subjects (16 females, 10 males) mean age 25.52±4.98, education year 14.77±4.67 were recruited for the study. Subjects had no reported any neurological, medical, and psychiatric disorders. None of subjects were taking medications at the time of measurements. Written informed consent was obtained from all subjects before the measurements. The experiments are done in Istanbul university and experimental protocol was approved by the Ethics Committee of Istanbul University, School of Medicine.

3.2 Experimental Design

3.2.1 Stroop Task

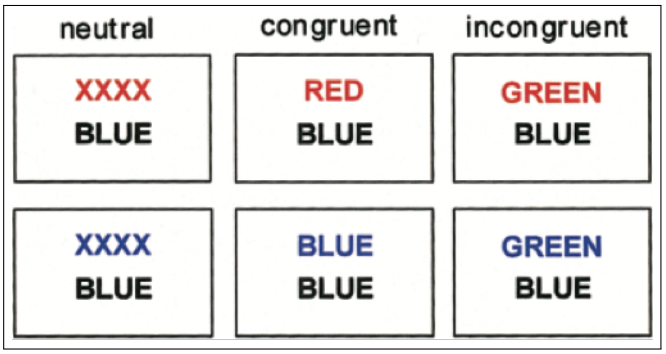

Figure 3.1 Stroop task design presentation [2].

Subjects were asked to perform color-word matching Stroop task whose trials are the Turkish versions of Zysset et al.[2]. Two words have been shown, one written above the other (see figure 3.1). The top one was written in ink color whereas the bottom one was in white (over a black background). Subjects were asked to judge whether the word written below correctly denotes the color of the upper word or not. If color and

word match, then subjects were to press on the left mouse button with their forefinger, and if not, to press on the right mouse button with their middle finger. Subjects were informed to perform the task as quickly and correctly as possible. The words stayed on the screen until the response was given with a maximum time of 2s. The screen with a fixation cross between the trials was presented. The experiment consisted of neutral, congruent and incongruent trials. In the neutral condition, upper word consisted of four X's (XXXX) in ink color. In the congruent condition ink color of the upper word and the word itself were the same, whereas in the incongruent condition, they were different. The trials were presented in a semi-blocked manner. Each block consisted of six stimuli. Interstimulus interval within the trials (blocks) was 4s and the blocks were placed 20s apart in time. The trial type within a block was homogeneous (but the arrangements of false and correct trials were altering). There were five blocks of each type(5xNeutral, 5xCongruent, 5xIncongruent). Experiments were performed in a silent, lightly dimmed room. Words were presented via an LCD screen that was approximately 0.5 m away from the subjects.

3.2.2 Tower of London Task

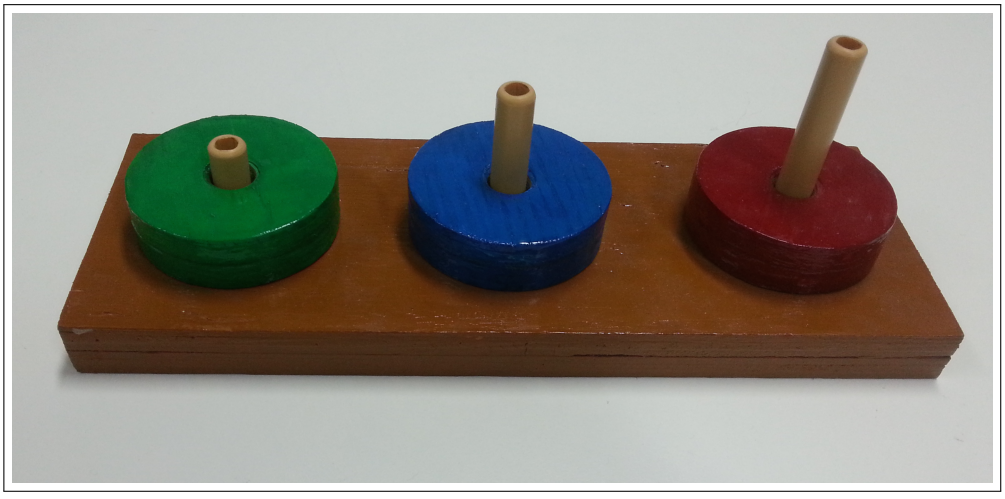

Figure 3.2 London Tower tasks tools.

Subjects have also performed a plain version of the Tower of London task[11]. Two sets of Tower of London Tool with three disks and three rods with different length attached on a board is used in this version of TOL task see Figure 3.2. Participants

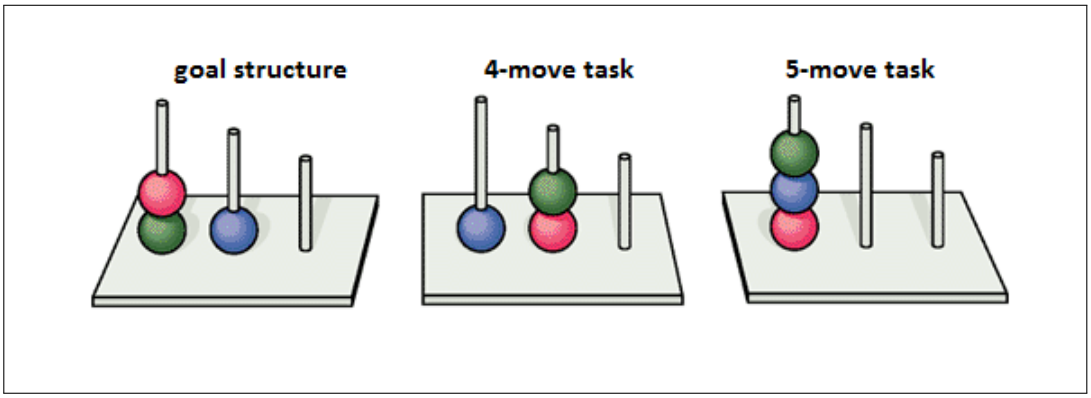

Figure 3.3 Presentation of goal structure with 4-moves and 5-moves tasks [3].

have been asked to build the same construction of disks which is presented in the other set of disks. Each set was composed of three coloured disk (red, blue, green) passed into any of three rods which could only contain one, two, or three disks depending on the length of rods. On each trial, the sample set of coloured disks have been appeared in predetermined locations. The goal of the task was to reproduce, in a minimum number of moves. There was two main rules to be followed when displacing disks: (1) a disk could only be moved if there is another disk above it in the rod; (2) a disk could not be moved into an empty space if there was a vacant position beneath it. All subject should use their dominant hand and they will repeat the task with an increasing level of difficulty depending on minimum required number of moves. Individuals have performed 10 tasks which have 4 difficulty level(2 x 4-move, 3 x 5-move 3 x 6-move, 2 x 7-move) and started to task after 2 minute resting state period. Between the levels they have asked to do random motor movement.

3.3 Data Acquisition

3.3.1 Behavioral data

Behavioral responses of Stroop test such as response times, response types (correct- wrong match etc..) and error rates are saved as log file via MATLAB. Behavioral responses for London Tower Test is recorded by hand. Thinking time motor

execution time, task sequence and number of moves for every individual task is written to a sheet for every subject. Total average reaction times of TOL tasks are presented in table 4.2

3.3.2 fNIRS Data Acquisition and Filtering

Figure 3.4 ARGES Cerebro functional near infrared spectroscopy device.

fNIRS Data acquisition was performed with a continuous wave, dual wavelength functional near infrared spectroscopy device , ARGES Cerebro (Hemosoft Inc) (see figure3.4). The system houses 10 detectors and 4 LED sources with a fixed distance between source and detector of 2.5 cm. The near-infrared light transmission occurs at two wavelengths (730 and 850 nm). The probe was attached to the head over the prefrontal area. The sampling frequency was 2.4 Hz.

3.3.3 Pre-Processing

In order to clear signal from physiological noise and baseline drifts 4th order Butter-worth filter band-pass filter with the frequency range of 0.01-0.2 Hz is utilized[41, 42]. Unprocessed and Processed data is shown in figure 3.5.

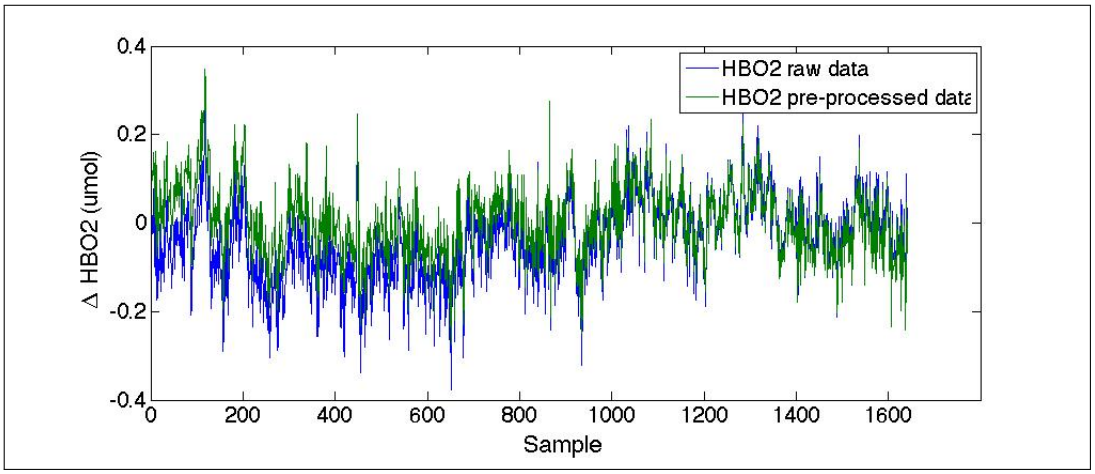

Figure 3.5 Demonstration of Pre-processed (green) and frequency filtered (blue) data.

3.3.4 Noisy Data Elemination

We decide not to include subjects with unreasonably high noisy channels into the analysis. Noisy channels are detected by visually inspecting the fNIRS signal. Data of 4 subjects had unexpected peaks or out of range values like shown in Figure 3.6.

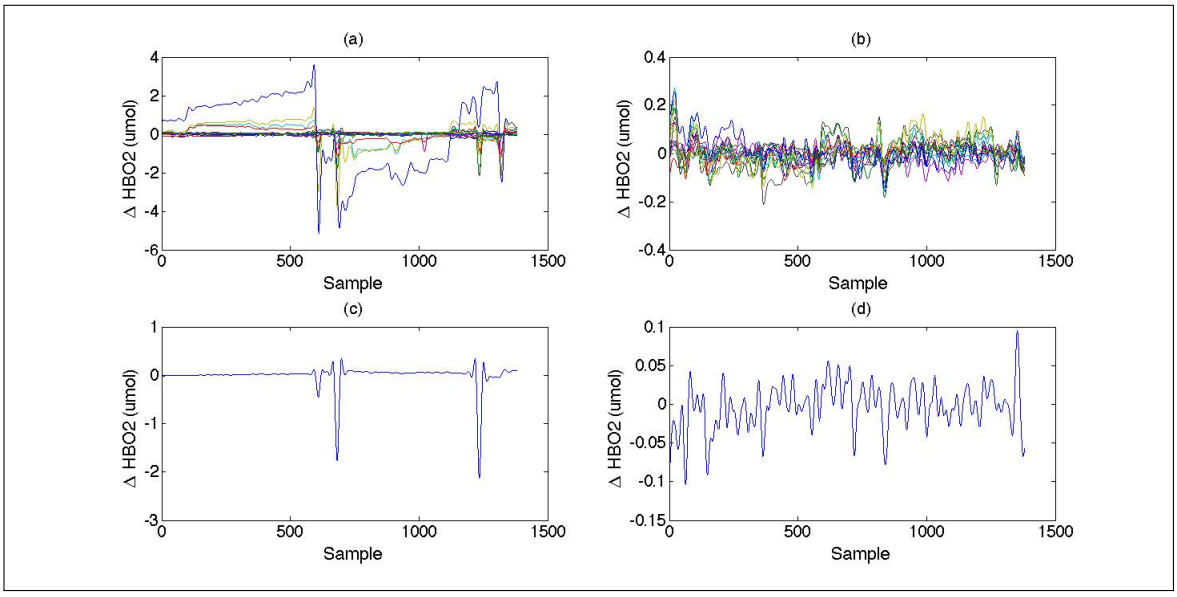

Figure 3.6 Representation of health and noisy HBO_2 data (a) A subject with high noise content in all channels (b) A subject with minimum noise in all channels (c) A single channel from noisy subject (d) A single channel from health subject.

3.4 Detecting the Activation

We have used one of the common regression analysis method to extract the features based on the task dependent activation. The basic idea of this model is to convolve Hemodynamic Response Function (HRF)[43] with the task pattern, and statistically obtain a parameter which indicates the activation by fitting the raw date with constructed model. Generalized Linear Model(GLM) is utilized to do multiple regression.

3.4.1 Generalized Linear Model (GLM)

The general linear model can be seen as an extension of linear multiple regression for a single dependent variable. The general purpose of multiple regression is to quantify the relationship between several independent or predictor variables, in our case it is modeled data, and a dependent or criterion variable which is fNIRS data.

$$\begin{bmatrix} Y_1 \\ . \\ . \\ . \\ . \\ . \\ Y_n \end{bmatrix} = \begin{bmatrix} X_{11} & ... & ... & ... & ... & X_{1k} \\ . & ... & ... & ... & ... & . \\ . & ... & ... & ... & ... & . \\ . & ... & ... & ... & ... & . \\ . & ... & ... & ... & ... & . \\ . & ... & ... & ... & ... & . \\ X_{11} & ... & ... & ... & ... & X_{nk} \end{bmatrix} \begin{bmatrix} \beta_1 \\ . \\ . \\ . \\ . \\ . \\ \beta_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ . \\ . \\ . \\ . \\ . \\ \varepsilon_n \end{bmatrix}$$

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k \tag{3.1}$$

The regression coefficients (or βcoefficients) in equation 3.1 represent the contributions of each independent variable to the prediction of the dependent variable. The regression surface (a line in simple regression or a plane or higher-dimensional surface) expresses the best prediction of the dependent variable (Y), given the independent variables (X's). However, there is important variation of the observed points from the fitted regression surface. The deviation of the points from the nearest points on the predicted regression

surface is called as the residual value. Since the goal of linear regression procedures is to fit a surface, which is a linear function of the X variables, as closely as possible to the dependent Y variable, the residual values for the observed points can be used to devise a criterion for the "best fit." Specifically, in regression problems the surface is computed for which the sum of the squared deviations of the observed points from that surface are minimized. Thus, this procedure is sometimes referred to as least squares estimation.

The multiple regression model can be expressed as,

$$Y = X\beta + \varepsilon \tag{3.2}$$

Where β is a column vector of k unknown regression coefficients. Recall that the goal of multiple regression is to minimize the sum of the squared residuals. Regression coefficients that satisfy this criterion are found by solving the set of normal equations shown below

$$X'X\beta = X'Y \tag{3.3}$$

$$\beta = pinv(X'X)^{-1}X'Y \tag{3.4}$$

This β coefficients give us the information about the direction and the strength of the brain activation for a single channel during individual task intervals. These tasks intervals are separated as neutral congruent incongruent and rest for strop test while as 4-5-6-7 move problems and rest for Tower of London test. After β values are calculated, in order to see the significance level we performed statistical t-test which compares the slope of two group in this case the slope is β values calculated in eq.2.5. The groups will be described in detail in further sections.

3.4.2 Statistical Analysis of GLM results

$$t = \frac{\text{difference of regression coefficients}}{\text{standard error of difference of regression slopes}} \tag{3.5}$$

$$\mathrm{t} = \frac{\beta_1 - \beta_2}{S_{\beta_1 - \beta_2}} \tag{3.6}$$

$S_{\beta_1-\beta_2}$ is the standard error of the difference of two regression and can be calculated as;

$$S_{\beta_1-\beta_2} = \sqrt{\frac{S^2_{yx_p}}{(n_1-1)(S_{X1}^2)} + \frac{S^2_{yx_p}}{(n_2-1)(S_{X2}^2)}} \tag{3.7}$$

However the length of two group is not same all the time. Therefore we calculated the pooled estimate of variance S_{yx_p} as,

$$S_{yx_p} = \frac{(n_1-2)(S_{yx_1})^2 + (n_2-2)(S_{yx_2})^2}{n_1 - n_2 - 4} \tag{3.8}$$

n_1, n_2 are the length of the first and second group respectively. The square root of the standard error estimate of the first and second group about the regression surfaces S_{yx_1} and S_{yx_2} are related to the standard deviations of the dependent and independent variables and the slope of the regression line and can be calculated as,

$$S_{yx_1} = \sqrt{\frac{n_1-1}{n_1-2}(S^2_{Y_1} - \beta^2 S_{X1}^2)} \qquad \text{and} \qquad S_{yx_2} = \sqrt{\frac{n_2-1}{n_2-2}(S^2_{Y_2} - \beta^2 S_{X2}^2)} \tag{3.9}$$

Equation 3.9 is an estimate of the actual variability about the surface of samples σ_{yx}, where S_{Y_1} and S_{Y_2} are the standard deviation of raw data and S_{X_1} and S_{X_2} are the standard deviation of the modeled data for the group1 and group2 respectively. Activation parameter represents the interference of brain activation during two condition(for instance incongruent and neutral). Selection of those conditions varied depending on the performed task. For instance to observe the interference effect in strop test, we compared the activation of Incongruent questions with Neutral questions. On the other hand for TOL task activation during each task is compared with the activation during

resting condition. After pooled estimated error is calculated (see equation 3.8) t-score of every channel is evaluated.

4. RESULTS

4.1 Behavioral Results

A. Stroop Test

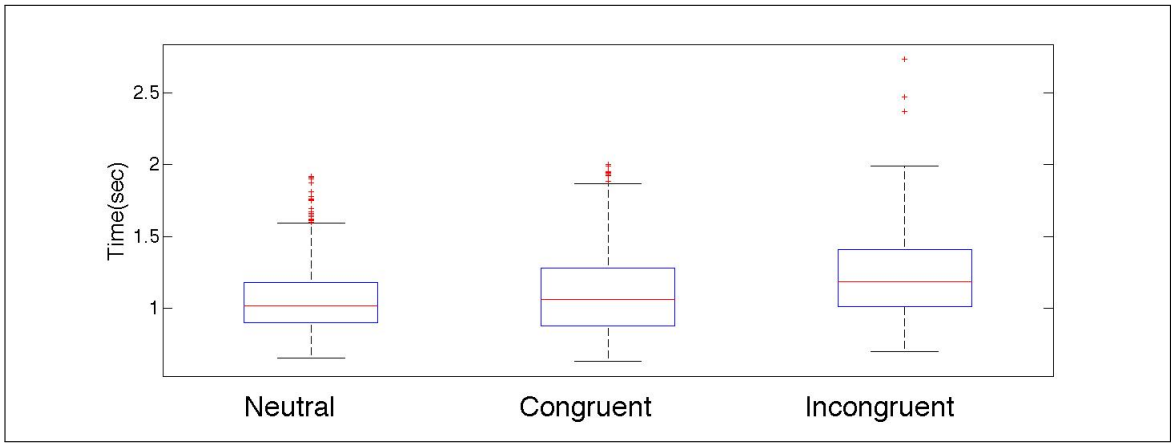

Figure 4.1 Boxplot representation of reaction time of correct answered Neutral Congruent and Incongruent questions.

Mean responses times are 1.0558±0.1335 for neutral where 1.1102±0.1578 for congruent 1.2484±0.1836 in seconds for incongruent questions (see figure 4.1). Mean error rates are %1.6 , %3.8 , %8.3 calculated for neutral, congruent, incongruent trials

Table 4.1
Statistical values which represents the significant difference between trials.*significant.

Trials	Response Time	Error Rate
Incongruent-Congruent	**t=5.9639*** **p=6.4138e-006**	t=1.0368 p=0.145
Incongruent-Neutral	**t=8.2680*** **p= 4.8363e-008**	**t=3.4868*** **p=0.0022**

respectively. To eliminate the outlier in terms of response time and error rate we used the 3 SD away from the means. One subject was assigned as outlier (due to high error rate). There was a significant difference between response times of incongruent and neutral trials (t(21)=8.42 p«0.00001) and incongruent and congruent triasl(t(21)=5.79 p«0.00001) observed.

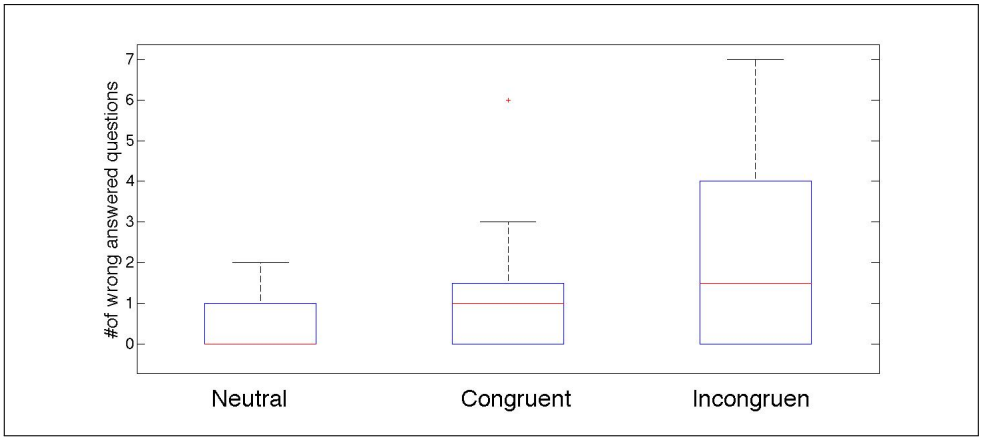

Figure 4.2 Boxplot representation of number of wrong answered Neutral Congruent and Incongruent questions.

B. Tower of London test Similar outcomes were obtained from Tower of London task, the response times were increased in proportion to the degree of task difficulty as expected. These results verify the consistency of applied task. One subject stood out by our outlier analysis due to number of excessive moves. Hence our analysis was performed on 20 subjects.

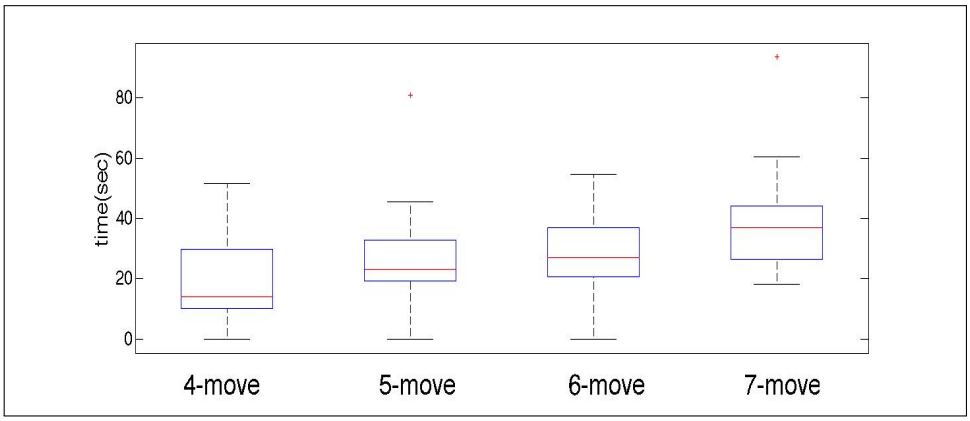

Figure 4.3 Boxplot representation of response times of correct answered 4-move 5-move 6-move 7-move problems.

Table 4.2
Mean and standard deviations of Reaction time, Thinking time and number of moves which excessed the minimum required move of 4-5-6-7 moves TOL tasks.

	Raction time(sec.)	Thinking time (sec.) (latenc to first move)	Number of excessed moves
4-move	30.72±14.56	6.12±5.27	3.47±2.87
5-move	39.31 ±14.22	7.75±6.46	3.86±2.70
6-moves	43.73 ±8.88	7.38±4.17	3.83±2.42
7-moves	46.20 ±27.37	7.67±5.81	3.72±4.26

4.2 fNIRS Results

In order to model data we used canonical hemodynamic function (HRF) generated by MATLAB see figure4.4.Task pattern formed by the correct answered questions. This pattern is convolved with HRF to obtain the model of desired data see figure4.5.

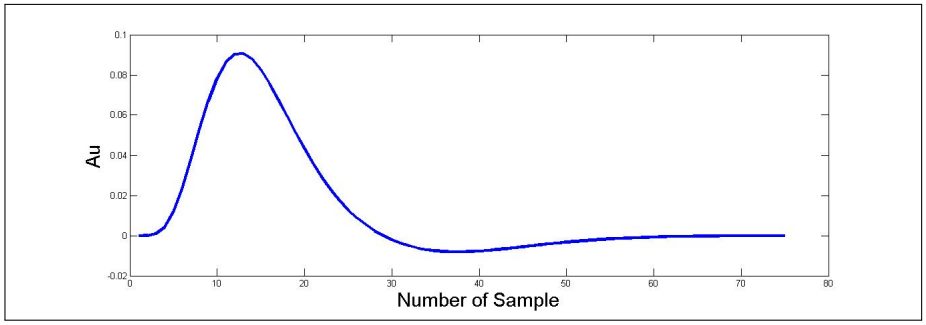

Figure 4.4 Utilized canonical hemodynamic response function (HRF) (Fs=2.3Hz).

The t scores for desired contrast was transformed to the unit normal distribution and converted to z-scores. Due to the spatial resolution of fNIRS we did not applied second level group analysis, instead, percentage of active regions over subjects are calculated. Detectors are placed to cover prefrontal cortex area and probe is divided into 8 PFC area; 1) (channel:1,3) left superior lateral frontal cortex (LSLFC), (channel: 5 and 7) left superior frontopolar (LSFP) , (channel: 9 and 11) right superior frontopolar (RSFP), (channel:13,15) right superior lateral frontal cortex (RSLFC), (channel:2 and

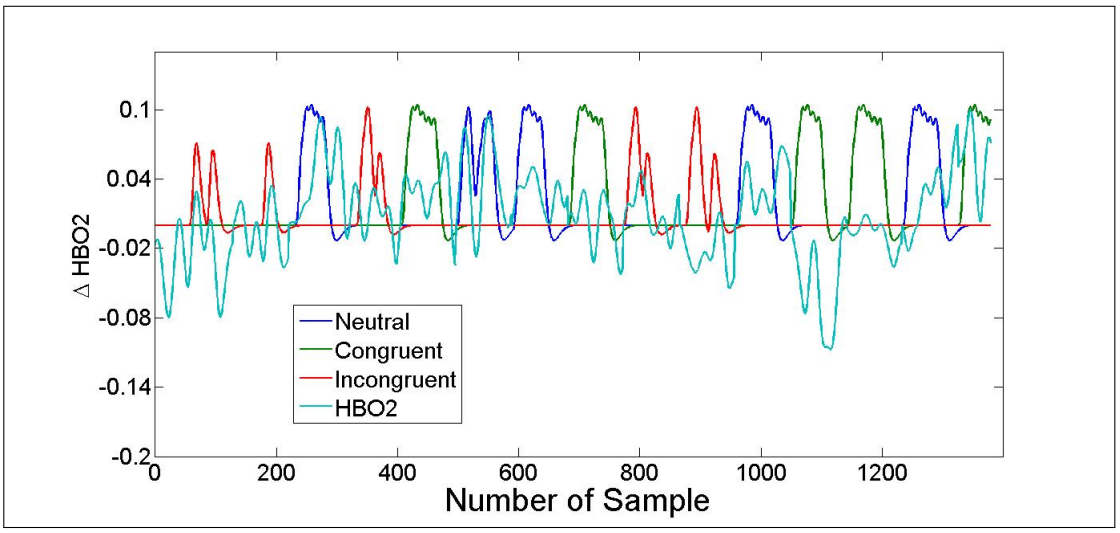

Figure 4.5 Modeled and Processed Data of HBO_2.

4) left inferior lateral frontal cortex (LILFC), (channel: 6 and 8) left inferior frontopolar (LIFP),(channel: 10 and 12) right inferior frontopolar (RIFP), (channel:14,16) right inferior lateral frontal cortex (RILFC) figure 4.13 illustrates the channel locations. According to this specified locations z-scores over the threshold value($p<0.05$) were averaged, the percentage of active regions for stroop task within subjects are showed in figure 4.6. We observed that in more than %80 of the 20 subjects showed activation in the LSPFC for Neutral-Incongruent interference, also LIPFC, RIPFC revealed activated in %70 of subjects. In this study the Tower of London test in different levels

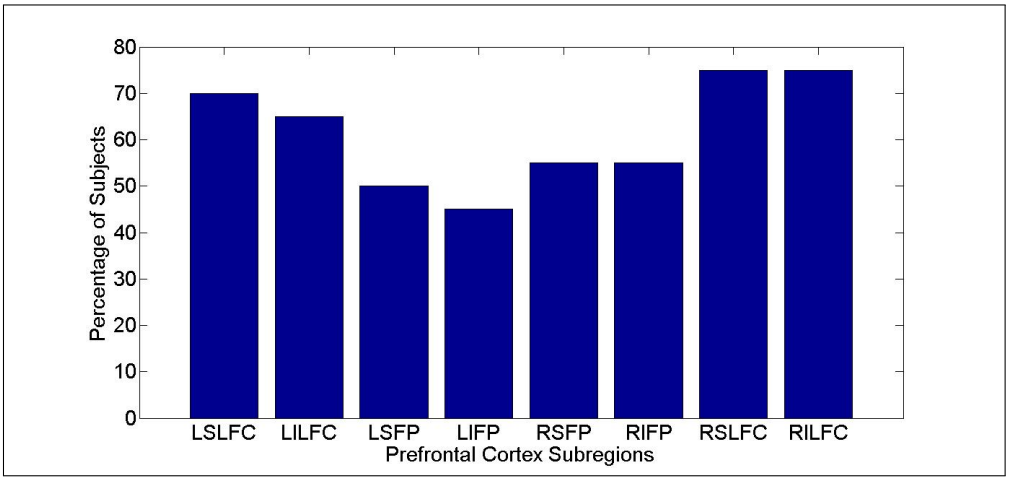

Figure 4.6 Percentage of Active Regions for STROOP task Neutral-Incongruent interferance. The z-scores above significancy level are averaged for specified regions. Figure illustrates the percentage of subject who remained above the threshold.

(4-7 move tasks) is applied. However subjects have not solved the task with same concentration and consistency. Therefore we decided to deal with only the highest level (7-move) task. Figure 4.7 presents the percentage of active regions within the 20 subjects.LIPFC, RSPFC are showed activation in %90 of the subjects.

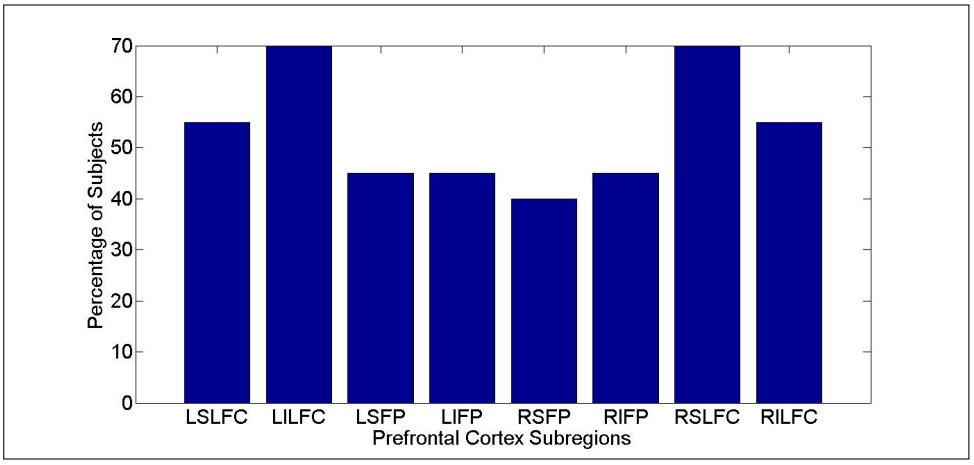

Figure 4.7 Percentage of Active Regions for 7-move TOL task. The z-scores above significancy level are averaged for specified regions. Figure illustrates the percentage of subject who remained above the threshold.

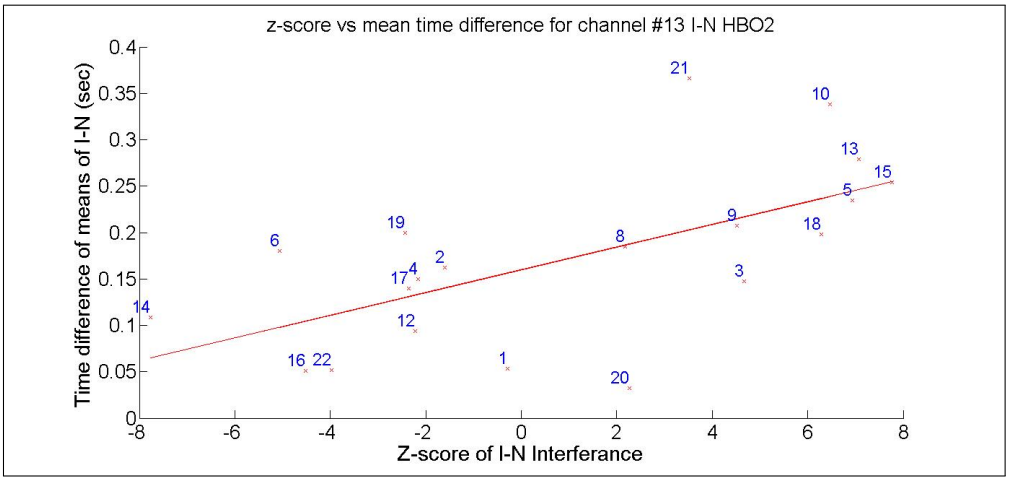

Figure 4.8 Correlation between reaction time difference and I-N (Incongruent-Neutral) interferance z-score for channel 13. Numbers are subject identifiers.

In previous results we showed the activation based on the idea that neuronal activation consumes ATP and O_2 hence HBO_2 level should increase [44]. Nevertheless in some regions there is an decrement in HBO_2 level. Although some studies suggest that this reduction in HBO_2 level is associated with the âstealingâ effect in which blood

is directed to the most active areas cause decrement of cerebral blood volume (CBV) at neighbor areas [45], some studies support the idea of suppressed neuronal activity may cause negative blood oxygenation[46, 47, 48]. In the light of these studies we decided not to cut out the activation parameters which are below the threshold value. In this respect we applied basic correlation analysis to see how behavioral data is correlated with the neuroimaging data. We have calculated the correlation parameters channel by channel. Significant correlation ($p<0.01$) between the mean response time difference of correct answered incongruent and neutral questions, and z-scores which indicate the congruent-neutral interference activation (see figure4.8) is observed only in 13.th channel. The correlation constant is $r=0.57$.

Similar analysis are performed for the TOL task and there was again a positive correlation between the response time (time spent to finish the related task) of 7-move task and the activation parameters. However there was a negative correlation in channel1 ($p<0.05$) and channel 16($p<0.02$) with the correlation coefficient $r=-0.48$ $r=-0.55$ respectively.(see figure 4.9 and 4.10)

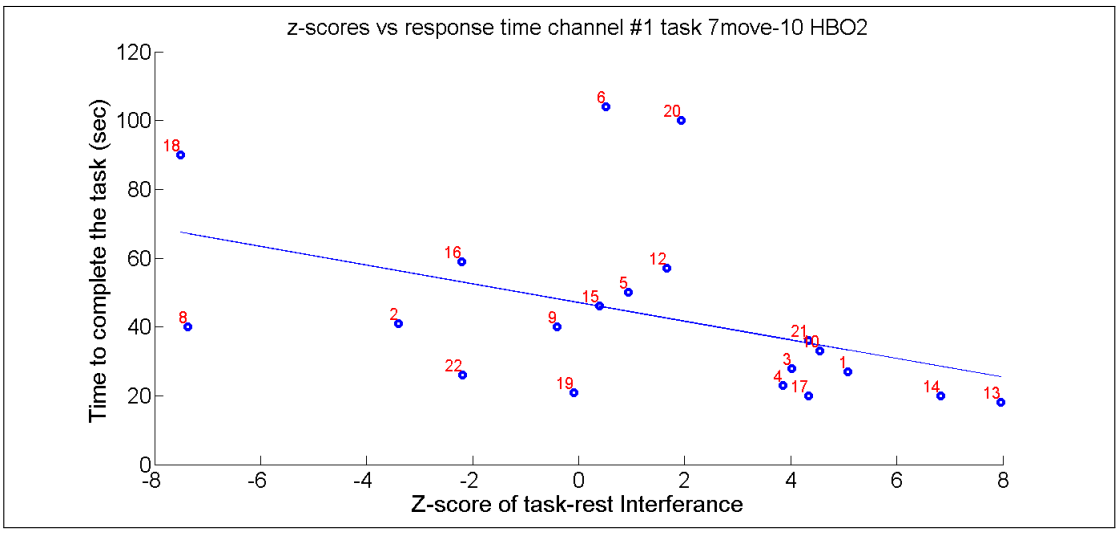

Figure 4.9 Correlation between reaction time of 7-moves task and z-score for channel 1.

Figure 4.12 illustrates the z-score of subjects of channel 13 for stroop task and channel 16 for 7-moves TOL task. Figure 4.11 illustrates the z-score of subjects of channel 13 for stroop task and channel 1 for 7-moves TOL task. We have observed that

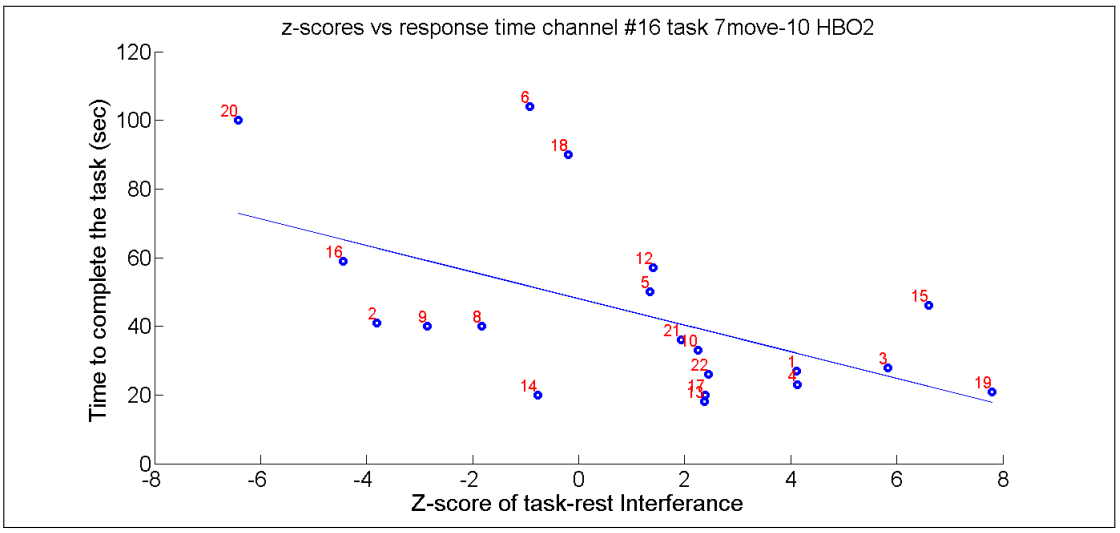

Figure 4.10 Correlation between reaction time of 7-moves task and z-score for channel 16.

subjects who have negative z-scores at channel 13 of stroop interference have respectively more positive(increased) z-scores for the TOL 7-moves task whereas, subjects with positive z-score of stroop effect have respectively more negative(reduced) z-scores for planning task. Upward arrows indicates raise in negative valued z-scores obtained from stroop interference, downward arrows represent the decrease in positive valued z-score for stroop task. Unlike this trend two subject revealed opposite tendency and other two subject did not showed any change in z-scores.

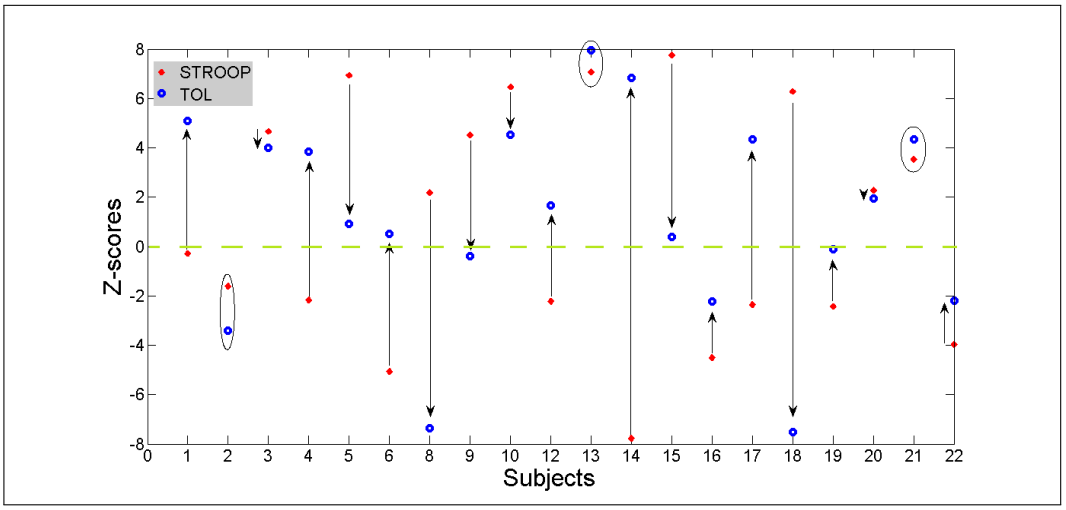

Figure 4.11 Z-score of outcomes from Stroop (Channel13) and TOL(channel1). Red labels are z-score of stroop interference where blue dots obtained from 1th channel during 7-move TOL task. Upper arrows are for negative z-score of stroop interference, downword arrows are for positive valued z-scores of stroop interference. Elipses are representing the subject whose z-score have not fit the trend.

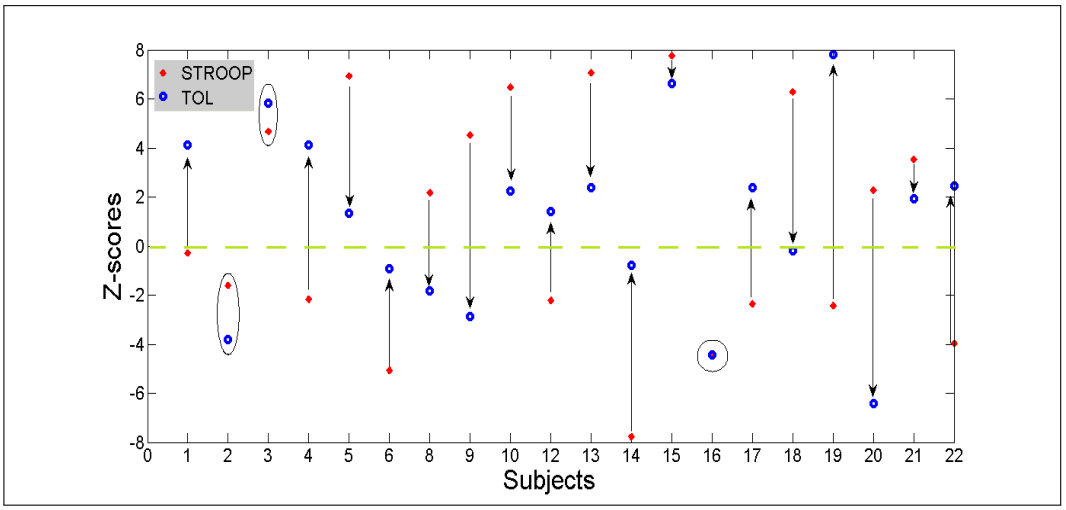

Figure 4.12 Z-score of outcomes from Stroop (Channel13) and TOL(channel16). Red labels are z-score of stroop interference where blue dots obtained from 16th channel during 7-move TOL task. Upper arrows are for negative z-score of stroop interference, downward arrows are for positive valued z-scores of stroop interference. Elipses are representing the subject whose z-score have not fit the trend.

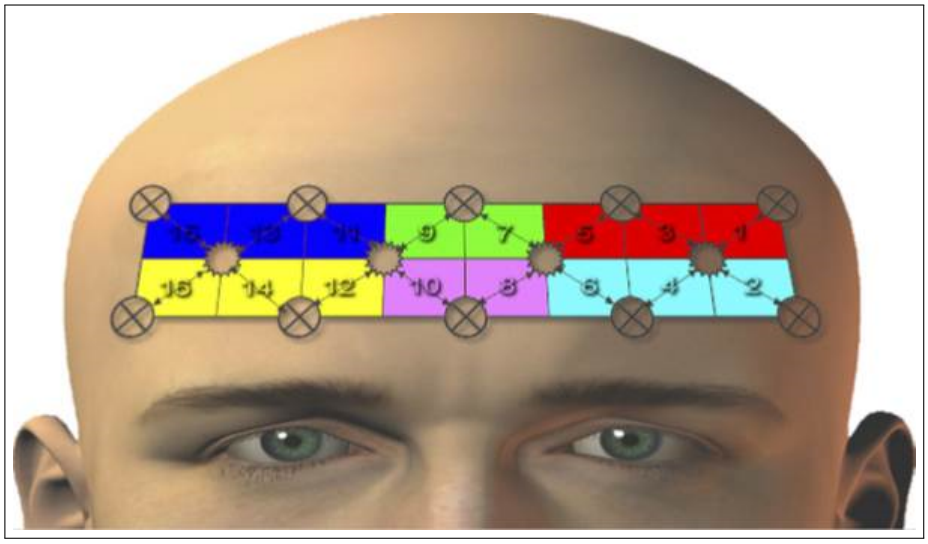

Figure 4.13 Location of Channels.

5. DISCUSSION

Behavioral results of Stroop task from the present study showed that significant differences between the trials are present in response times of correct answered questions but not in error rates. In order to validate participants performance during the task, we compared performance findings for incongruent-congruent and incongruent-neutral correct answered trials. Participants responded significantly faster in neutral and congruent trials than incongruent trials (table 4.1). However there was no significant difference in accuracy between congruent and incongruent trial types which means that although subjects had more difficulty when reading the word which is written in different color than reading the word written in same color they answered correctly but with longer response time for incongruent trials. Those findings are consistent with other studies which are investigated in detail in a rewiev article [49].

TOL task has been utilized in many studies with different task patterns. Computerized version of TOL task has been utilized in fMRI studies through restriction of movement in fMRI machine, for those studies subjects has been asked to compute required number of moves to solve the presented task. It lacks procedures to provide information about thinking time and execution time. On the other hand task procedure which is used in current study did not let us to keep the error rates because apart from other TOL task designs the maximum time allowed to solve the task was quite enough such that all subjects has solved the task in a given time period. Therefore we prefer to investigate the response-time changes with task difficulty. Behavioral outputs of TOL task has revealed that as minimum required movement to solve the task increase the response time increase. We observed neuronal activation patterns during Stroop interference and TOL taks, particularly for oxygenated hemoglobin. Deoxygenated hemoglobin changes did not showed significant changes. In most of the studies HBO_2 indicates activation for event related tasks. Strangman et al. 2002 [50] was found that HBO_2 was a more robust hemodynamic signal and correlated more with fMRI-BOLD response.

PFC is known as one of the important area of brain in executive functioning. Moreover evidence from brain imaging studies [51] or transcranial magnetic stimulus (TMS) studies [52] with planning tasks (TOL,TOH or visuospatial problem-solving) has implicated the involvement of dorsolateral prefrontal cortex (DLPFC) and revealed significant relations between task performance and DLPFC activation. In our study we have demonstrated that the fNIRS can also detect the activations in the LPFC. Especially activation of LIPFC and RSPFC are detected in over %80 of subjects (Figure 4.7).

In some TOL studies behavioral findings have been linked to the brain activation. Most of them were investigating the effect of task complexity. Morris et al. 1995 [53] has introduced new information about correlation of regional cerebral blood flow (rCBF) with response time of TOL task. They found that longer latency times were associated with higher regional cerebral blood flow (rCBF) in the left prefrontal cortex whereas execution time was negatively correlated with both left and right prefrontal rCBF significantly. Our results showed negative correlation between reaction time to complete the 7-move task and prefrontal cortex activation for the channels 1,16 (see figure 4.9 and 4.10). Since subjects were not warned to plan the task carefully before they start reconstructing the goal structure average thinking times stayed much below the total task durations. In fact average latency time (time to plan) of that task which correlation observed was 7.67 ± 5.8 seconds whereas average total task time has 46.2 ± 27.37 seconds. We found that higher lateral activations has led to decrease in total task duration. This finding is consistent with the fMRI-Tower of London experiments which suggests that successful performance of planning is strongly positively correlated with DLPFC activation. The most important finding of their study is the increase of activation in the right DLPFC associated with better participant performance, both during the planning and the execution phase of problem solving tasks. Our results also showed that subjects who respond faster to TOL task have higher DLPFC activation.

Functional neuroimaging results of this study obtained for Stroop interference showed that prefrontal cortex activation due to stroop interference is mainly located at

both lateral sides (see figure 4.6). This evidence is also found in the other neuroimaging studies especially an fMRI study [54] and a study with patients who have frontal lesions [55]. Moreover our outcomes also provides an interpretation of the relationship between PFC activity and reaction time differences of stroop interference. We demonstrated that activation of RSPFC and reaction time difference of incongruent-neutral questions are positively correlated (Figure 4.8). This increased lateral activation shows the effect of conflict-control. Many of fMRI studies demonsrated that the inferior frontal, dorsolateral prefrontal and anterior cingulate cortices are known to play a role in the mechanisms of attention control in which maintaining attentional control over conflicting responses is needed [56, 57, 58]. Consistent with the argument that decreases in DLPFC activity is associated with decreases in the need for attention control, Milham et al. 2003 [59] revealed that those subjects showing a smaller interference effect (reaction time between incongruent and neutral trials) showed a greater percentage of reduction in DLPFC activity, that is, a subject who answers incongruent trials as fast as neutral trials has less lateral prefrontal activation. It is well documented that the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC) are intensively involved in conflict control thus neuronal contribution on conflict control is demonstrated in current study.

The main purpose of this study is to predict the performance of subjects in one task by looking at the outcomes of another task. Although these two tasks seems to be developed to test different cognitive functions, studies have been discussed above showed that there are common areas activated during TOL and stroop tasks. Furthermore Zook at al. 2004 [60] and Welsh et al. 1999 [61] has proposed good correlation between behavioral outcomes of this these tasks. At this point, we can say that the most critical outcome of this study is presented in figure 4.11 and 4.12. We have demonstrated that less lateral activity during stroop interferance means less conflict occurs while subject reading the colored word(incongruent trial). Since there is a significant difference in reaction times of correct answered incongruent and neutral trials, we can say that this fast response for incongruent questions is because of cognitive flexibility and attention ability of individuals. On the other hand we showed that as the time to solve the task decreases lateral neuronal activity increases which means that higher

lateral activity leads to fast responses. We had hypothesized that the subjects with reduced neuronal activity and fast reaction time can be named as good performer for stroop task so that this performance should give us an information about how their performance on TOL task will be. This hypothesis is proved by showing an increase in activation parameters during TOL task of the subjects has negative activation during stroop task and a decrease in activation parameters during TOL task of the subjects has positive activation during stroop task. %90 of the subjects for channel 16 and %90 of subjectsfor channel 1 showed same trend described above. When channel1 and channel16 are considered together, we can see that %75 of subjects followed the trend.

6. CONCLUSION and Future Work

This study provided support for our hypothesis that involvement of PFC in attention control is related with the performance on conflicting color-word matching Stroop trials somehow associated with PFC activation and task performance of another cognitive planning task. The direction of oxygenation in RSPFC during stroop task is providing an information to predict the performance of TOL planning task performance of individuals. We did not produce any method which could model this prediction. However it has been demonstrated that fNIRS is compatible to measure brain activations in boh direction (negatively and positively). In contrast with other studies which suggests that the positive increase in oxygenation refers to an activation, we showed that negative brain response is also related to behavioral performance. Although fundamentals of negative brain response is still unclear. This negative oxygenation may reflect blood stealing by a neighboring region of increased neural activation [62] or suppressed neuronal activation [63]. Since both statements support that as long as the obtained activation is task related, it is safe to say that no matter what is the direction of change is still represents the neuronal activation in the brain. We did not present any algorithm to calculate a parameter of prediction. One of our future investigation will be estimating a constant or defining a level of cognitive flexibility of a person only by measuring the neuronal activations during stroop or any other cognitive tasks. Even though according to the neurovascular coupling phenomena it is has been discussed that neuronal activation needs oxygen, information derived from HBO_2 should be supported with the total hemoglobin and deoxygenated hemoglobin as well as the information of event related potentials measured by Electroencephalography (EEG). Because to know the exact time of neuronal activation by the method with high time resolution such EEG, would let us to model the task related stimuli pattern, which enables to detect the activation related blood flow more accurately.

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