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Investigating Brain Hemodynamics of ADHD Patients by Functional Near Infrared Spectroscopy

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***Abstract*—Inhibition of prepotent response is an executive function and is subserved by prefrontal cortex of the brain in healthy subjects. Damage to these regions results in response inhibition deficits. Response inhibition deficits have been linked to several neurological disorders. Some disorders like ADHD(Attention Deficit Hyperactivity Disorder) is associated with general cognitive impairments in addition to inhibitory deficits. In this study, attentional processes in ADHD have been examined using matching Stroop task and fNIRS(functional near-infrared spectroscopy).**

I. INTRODUCTION

People can easily stop talking, walking, singing and so on, in response to changes in internal or environmental states. The ability to respond to a specific dimension of a stimulus while suppressing simultaneous inappropriate or no longer required competing stimulus is known as interference effect. Intelligent behavior in rapidly changing environment requires continual monitoring and updating of our actions. Response inhibition is the ability to suppress behaviors that are inappropriate, unsafe or no longer required and is a key determinant of successful cognitive and motor control. This ability to inhibit inappropriate or irrelevant responses is a hallmark of executive control [3]. Inhibition of this prepotent response requires a fast control mechanism that prevents the execution of the motor response. Cognitive interference occurs during this inhibition of competing responses. In some neurological disorders, like ADHD and autism there have been impairments in triggering of inhibitory process. Response inhibition allows measurement of both the speed of the behavioral inhibitory process and the ability to effectively trigger inhibitory process. In the traditional Stroop task, one dimension of the stimulus has to be named while the other dimension is being suppressed. Subjects generate a response to match one dimension of a stimulus while suppressing the irrelevant dimension. In doing this, response preparation and interference processes are within the same modality (verbal) and one cannot exclude that these two processes confound each other. The stimuli interfere at the response preparation level [1].

II. METHODS

A. Subjects

In this study, 12 ADHD patients and 12 age and gender matched healthy volunteers as control group were participated. Patients and controls did not differ significantly regarding their mean age level (age 30.2 ± 10.4 versus 32.6 ± 8.3 respectively). Ratios of male to female participants between two groups were matched (2/3). All subjects had normal or corrected-to-normal vision and normal color vision and were self-reported right-handers. Control subjects had no history of psychiatric or neurological disorders.

B. Materials

Experiments were performed using a near infrared spectroscopy device, NIROXCOPE 301 (Hemosoft Inc., Ankara, Turkey). The fNIRS system, houses a flexible forehead probe that consists of 4 LED light sources and 10 detectors. Data were taken in three different wavelengths, 730 nm, 805 nm and 850 nm. Several studies showed that if light range is selected between 700-900 nm then light scattering will be minimized. Data were taken from 16 regions over the prefrontal cortex. Changes in oxyhaemoglobin and deoxyhaemoglobin concentrations were calculated according to modified Beer-Lambert Law for each of the 16 channels. Modified Beer- Lambert Law is an empirical description of optical attenuation in highly scattered medium.

C. Task

Controls and patients were evaluated during a color–word matching STROOP task which is known to activate particularly the frontal lobe. Three types of stimuli namely incongruent stimuli (is), neutral stimuli (ns) and congruent stimuli (cs) are applied randomly.

During Stroop task two rows of letters appeared on the screen and subjects were instructed to identify the color of the top word which could be flanked the distracters that triggered the same response (congruent), opposite response (incongruent), no response (neutral).

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Response was given by pressing the right button of a mouse with index finger (YES-response) and left button of a mouse with middle finger (NO-response) of the right hand. During the neutral trials, the letters in the top row were “XXXX” printed in red, green, blue or yellow, and the bottom row consisted of Turkish names of color words of “RED”, “GREEN”, “BLUE” and “YELLOW” printed in white. For congruent trials, the top row consisted of Turkish names of color words of “RED”, “GREEN”, “BLUE” and “YELLOW” printed in congruent color. For the incongruent condition, the color word was printed in different color to produce interference between coloring the word and naming it.

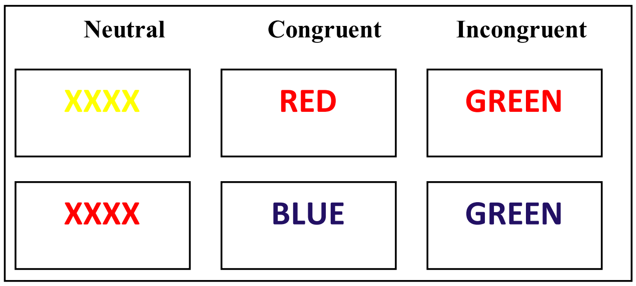

Figure 1. Examples of single trials for the neutral, congruent and incongruent condition of the color–word matching Stroop task. For the upper three examples color of the upper word does not match with the meaning of the lower word, but for the lower three examples it does.

D. *Analysis*

Preprocessed data were processed and analyzed in MATLAB environment. Analysis of hemodynamic signals was performed in the frequency domain. After the calculation of oxy-Hb and deoxy-Hb signals, the Butterworth low pass filter with cut off frequency of 0.25 Hz was used to remove baseline drift and to eliminate the fluctuations due to heart rate, respiration etc.. Fourth order band pass Butterworth filter was used to separate the oxy-Hb and deoxy-Hb signals into very low frequency (VLF) (0.02-0.05 Hz), low frequency (LF) (0.08-0.12 Hz), and high frequency (HF) (0.12-0.18 Hz) bands.

Statistical analyses were done in SPSS environment. Statistical evaluation was based on the differences between the means of two groups. Since the group variances were different, ANOVA Welch was used to test the statistical significance between groups. The statistically significant level of difference was considered to be at $p < 0.05$.

III. RESULTS

A. *Behavioral Results*

Behavioral results were studied in two parts. In the first part mean reaction times and error rates were compared within the group and between the subjects. Studying reaction time is important because it is a measure of cognitive difficulty and efficiency of processing.

As expected prior to analyses mean reaction times were found shorter in controls then ADHD patients. Also within the groups mean reaction times were shorter in neutral than in the congruent or incongruent conditions for controls and shorter in congruent than in neutral or incongruent conditions for AHDH respectively. Reaction times were calculated as the average of answered questions; not answered questions were not included in the reaction times because we did not know whether the subject spend more than 4 seconds on the task or just shift the attention towards something else. As shown in Table I, reaction times did not differed significantly for both groups. The interference effect between congruent and incongruent remained significant over the entire period of the experiment for both controls and ADHD. The mean error rates of ADHD patients are higher than that of control groups (Table I), but only in incongruent stimulus significant difference was seen. This was because the hemodynamic response was stronger during incongruent compared to congruent and neutral trials of the Stroop task in the lateral prefrontal cortex bilaterally. This stronger hemodynamic response was interpreted as stronger brain activation during incongruent trials of the Stroop task.

TABLE I. REACTION TIME AND ERROR RATES FOR THE STROOP TASK AVERAGED OVER ALL SUBJECTS

Reaction Times	ADHD_off			Controls		Anova Results	
	Mean	Std. Dev.		Mean	Std. Dev.	F Value	P Value
Neutral Stimulus	1,45	0,3		1,09	0,27	6,44	p>0,05
Congruent Stimulus	1,34	0,26		1,32	0,36	0,263	p>0,05
Incongruent Stimulus	1,625	0,41		1,36	0,35	2,582	p>0,05
Error Rates	Mean	Std. Dev.		Mean	Std. Dev.		
Neutral Stimulus	0,04	0,04		0,03	0,02	2,8	p>0,05
Congruent Stimulus	0,08	0,1		0,04	0,05	3,01	p>0,05
Incongruent Stimulus	0,35	0,2		0,08	0,08	14,27	p<0,05

In the second part response inhibition, which is a measurement of both the speed of behavioral inhibitory process and the ability to effectively trigger inhibitory process, were analyzed. ANOVA was used to determine whether ADHD is associated with impaired response inhibition. As shown in Table II patients with ADHD presented with increased stop signal reaction time, suggesting slower inhibitory processes

TABLE II. SUMMARY DATA FOR RESPONSE INHIBITION VARIABLES

Response Inhibition Index			Anova Results	
	Mean	Std. Dev.	F value	P value
Control	0.104	0.146	4.483	0.045
ADHD_Off	0.225	0.138		

B. *fNIRS Results*

The underlying idea of calculating response inhibition by using reaction times and energies were the same. In calculating response inhibition using reaction times we averaged RTs in all detectors, so it gives us an overall idea of inhibition occurred in the whole prefrontal cortex. Calculating response inhibition using energies makes us to differentiate prefrontal cortex in four regions, and makes it easier to understand if some part of the brain region is more responsible for inhibitory behavior.

Adapted version of the Stroop task helps us to separate response preparation and interference process. In the traditional Stroop task, generating the verbal response to match a stimulus is interfered by the second dimension of the stimulus (or the dimension of a second stimulus). Response preparation and the interference process itself are confounded by this. With the presently used task, these processes are separated. The manual response preparation processes are separated from the matching process, where interference has to be reduced.

As shown in Figure 3, in bi-group comparison all significant results were found in VLF and LF bands, which show us inhibition occurs in low or very low frequency energies.

HbO	VLF	LF	HF
1-4	0.038	0.997	0.148
5-8	0.782	0.514	0.203
9-12	0.852	0.447	0.286
13-16	0.636	0.938	0.683

Hb	VLF	LF	HF
1-4	0.249	0.144	0.178
5-8	0.904	0.760	0.260
9-12	0.512	0.679	0.298
13-16	0.545	0.448	0.502

Figure 3. Summary of response inhibition energies for detector quadruples for VLF,LF and HF energy bands in deoxy-hemoglobin and oxy-hemoglobin for controls and ADHD unmedicated.

IV. DISCUSSION & CONCLUSION

In this study a multichannel fNIRS device and a variation of the Stroop task was used to compare ADHD patients with those healthy controls during cognitive task. In this Color-Word Matching Stroop version, interference takes place at a conceptual level and is separated from the response preparation. An additional matching process added and subjects gave a constant response (button press), which was neither a color nor a word. The modality of the behavioral component of the task is independent of the interfering dimensions. Varying the dimension of the first word (neutral, congruent, or incongruent words to the presented color) allows for the investigation of the interference effects[2]. The conceptual interference between the two dimensions of a within a matching process was separated from the response preparation and execution process. The main difference between the two tasks is that subjects in the Matching Stroop task compare two attributes of a stimulus while in the traditional Stroop task they generate a response to match one attribute of a stimulus [3]. The results were somehow consistent with the previous studies which show us ADHD is directly related to response inhibition. We also found impaired response inhibition in ADHD too, but seeing significant result just in one region leads us to conclusion that whether only lateral prefrontal regions are responsible for response inhibition or there are other proceses confounded our results.

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