Abstract

In this paper we present an experimental study where we investigated neural correlates of visuospatial reasoning during math problem solving in a computer-based environment to exemplify the potential for conducting interdisciplinary research that incorporates insights from educational research and cognitive neuroscience. Functional near-infrared spectroscopy (fNIRS) technology is used to measure changes in blood oxygenation in the dorsolateral and inferior prefrontal cortex while subjects attempt to solve tangram puzzles. The study aimed to identify which areas in the frontal cortex are responsive to geometric reasoning elicited by tangram puzzles and explored how the activation patterns change in response to problem types and difficulty levels.

Keywords: optical brain imaging, fNIR, visuospatial reasoning, dorsolateral prefrontal cortex

1. Introduction

Recent advances in neuro-imaging technology have opened up exciting possibilities for the exploration of neural mechanisms underlying learning and cognition. The past decade has seen an increasing interest towards connecting research on learning sciences and cognitive neuroscience around various topics of common interest such as language learning, creative problem solving, learning disabilities and development of expertise (Goswami & Szucs, 2009; de Jong et al., 2009). Although the gulf of separation between the way educational researchers and neuroscientists study and treat learning has initially fueled controversy (Bruer, 1997; Varma, Schwartz & McCandliss, 2006), recent studies implicate that as we better understand the functional organization of the brain, the nature and the limits of its plasticity, and the ways brain adapts its circuits in response to socio-cultural influences, we may shed further light into the mechanisms underlying cognitive development as well as the nature of learning disabilities and difficulties.

Neural foundations of learning and mathematical thinking have become an important area of research in cognitive neuroscience. Recent brain imaging studies of mathematical cognition that employ imaging modalities
such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET) have identified specific regions in the prefrontal and parietal cortices that are recruited when subjects are engaged in arithmetic calculation and estimation of numerical quantities (Dehaene, Piazza, Pinel, & Cohen, 2003; Dehaene, 2010). Experimental studies with healthy subjects and case studies of numerical impairments due to brain lesions have associated the parietal regions with recognition of numerical objects and retrieval of arithmetic facts, and the prefrontal regions with the selection and execution of calculation strategies (Grabner et al., 2009; Rivera et al., 2005). This line of empirical work also highlighted the difference between the way brain handles numerical estimation and exact calculation. Given the empirical evidence regarding the presence and the lack thereof arithmetic capabilities in animals, infants, and adults across different cultures, the primate brain is claimed to have an innate organization that gives these species a sense of quantity, i.e. an internalized number line for approximating quantity (Dehaene, 2010). Insights from neuroscience and developmental psychology have led to the hypothesis that exact arithmetic skills exhibited by adults raised in most cultures is facilitated by the language acquisition process, through which the innate circuitry for managing the sense of approximate quantity is transformed to accommodate symbolic processing of quantities.

The influence of visuospatial processes in the development of geometric concepts is another important area in mathematical cognition which can benefit from insights from cognitive neuroscience. Nevertheless, cognitive neuroscience studies of tasks that involve visuospatial reasoning are rather limited in scope as compared to the existing literature on neural correlates of arithmetic skills. Studies related to geometric/visuospatial reasoning focus on identifying cortical areas recruited during tasks like tetris (Haier et al., 1990; Haier et al., 2009) and mental rotation (Cohen et al., 1996; Alivisatos & Petrides, 1996) with fMRI and PET. Mental rotation tasks involve judging whether two images show different rotations of the same object or not. Tetris is a computer game where players fit falling pieces to fill perfect lines by rotating and moving them in a certain amount of time. Therefore, both tasks involve elements of visuospatial processing that are relevant to geometric reasoning.

Mental rotation tasks are found to recruit areas in the left-inferior parietal cortex, which are considered to be a part of the brain circuitry for locating and tracking objects in the visual field (Cohen et al., 1996). Activations in the lateral frontal cortex that are anatomically linked to parietal areas were also reported by these studies. Frontal areas´ involvement during mental rotation is considered to be related to the monitoring within working memory as part of the mental imagery of rotation (Petrides et al., 1993).

Haier et al. (2009) found that areas in the parietal and frontal cortex were involved when subjects were playing tetris. They also found that the level of activation in the frontal areas decreased among subjects who regularly practiced Tetris for three months. Moreover, structural MRI scans indicated that the thickness of those subjects´ left parietal cortex was increased (i.e. Brodmann Areas 6, 22/38) as compared to the control group. The increase in cortical thickness is considered to indicate the formation of circuits dedicated to this visuospatial task. The overall decrease in activation suggests that the brain utilizes its neural resources in a more efficient way as a result of learning. Such functional and anatomical changes can be considered as neural correlates of developing visuospatial reasoning and motor skills relevant to playing tetris.

In light of the discussion above, we conducted an experimental study focusing on the role of prefrontal cortex during a visuospatial reasoning task called tangram by using an optical brain imaging modality called functional near-infrared spectroscopy (fNIR), which is designed to monitor relative changes in the concentrations of oxygenated and deoxygenated hemoglobin at the frontal cortex. Existing PET and fMRI studies suggest that areas in this part of the brain are activated during similar tasks such as tetris and mental rotation. The study aims to replicate and expand some of these findings by using a task that is more relevant to math education and by using an imaging modality that offers important advantages for studying learning.

fNIRS is an emerging imaging modality which provides a good mix of temporal/spatial resolution and allows the production of portable, affordable and easy to use brain imaging devices. In particular, although fNIR has a relatively lower spatial resolution, it offers better temporal resolution as compared to other imaging modalities such as fMRI and PET that also monitor hemodynamic changes due to neural activity. Moreover, fNIR does not require subjects to be placed in confined positions as in fMRI or PET, and it is a non-invasive technique that does not require the injection of radioactive chemicals like PET. Although fNIR’s temporal resolution is lower than modalities like EEG and MEG which monitor electrical activity induced by neurons, it provides higher spatial resolution as compared to such systems. Moreover, fNIR sensors are easier to install as compared to most EEG
systems. Therefore, fNIR is a promising neuroimaging tool for investigating neural correlates of learning in ecological settings.

We chose to focus on tangram tasks due to its relevance for teaching basic geometric concepts in elementary geometry classes (NCTM, 2000; Lee et al., 2009). The particular version of the tangram task we used asked participants to use 7 elementary objects from Euclidean geometry to form a given animal shape or a larger geometric object (e.g. a perfect square or a hexagon). Such tasks are included in elementary geometry classes to help students develop an intuitive understanding of fundamental geometric concepts such as rotation, congruence and area without using formulas.

The goal of this study is to investigate the fNIR signal’s sensitivity to changes in cognitive workload due to variations in task difficulty and problem types, and whether better problem solvers exhibit different brain activation patterns as compared to novices. As part of our experimental study participants were asked to solve a number of tangram puzzles. The subjects’ behavioral performance (measured in terms of accuracy and task completion time) and self-perceived ratings allowed us to classify tangram tasks in terms of their difficulty. Our analysis revealed higher levels of activation during experimental tasks compared to control tasks across the prefrontal cortex, and right hemisphere is particularly responsive to changes in task type and difficulty.

The rest of the paper is organized as follows. The next section describes the theory underlying the optical brain imaging technology based on near-infrared spectroscopy. This is followed by the methods section that describes the experimental setup and the tasks. Results section summarizes the statistical analyses performed on behavioral and fNIR data. The paper concludes with a discussion of the findings and pointers for future work.

2. Functional Near-Infrared (fNIR) Spectroscopy

fNIR is a neuroimaging modality that enables continuous, noninvasive, and portable monitoring of changes in blood oxygenation and blood volume related to human brain function. Neuronal activity is determined with respect to the changes in oxygenation since variation in cerebral hemodynamics are related to functional brain activity through a mechanism which is known as neurovascular coupling (Villringer & Chance, 1997). Over the last decade, studies in the laboratory have established that fNIR spectroscopy provides a veridical measure of oxygenation and blood flow in the brain (Chance et al., 1998). fNIR is not only non-invasive, safe, affordable and portable (Bozkurt & Onaral, 2004; Bozkurt et al., 2005), it also provides a balance between temporal and spatial resolution which makes fNIR a viable option for in-the field neuroimaging.

fNIR technology uses specific wavelengths of light, introduced at the scalp, to enable the non-invasive measurement of changes in the relative ratios of deoxygenated hemoglobin (deoxy-Hb) and oxygenated hemoglobin (oxy-Hb) in the capillary beds during brain activity. Typically, an optical apparatus for fNIR Spectroscopy consists of at least one light source and a light detector that receives light after it has interacted with the tissue. Photons that enter tissue undergo two different types of interaction: absorption and scattering (Strangman et al., 2002). Whereas most biological tissues (including water) are relatively transparent to light in the near infrared range between 700 to 900 nm, hemoglobin is a strong absorber of lightwaves in this range of the spectrum.

Two chromophores, oxy- and deoxy-Hb, are strongly linked to tissue oxygenation and metabolism (Villringer & Chance, 1997). Fortuitously, the absorption spectra of oxy- and deoxy-Hb remain significantly different from each other allowing spectroscopic separation of these compounds to be possible by using only a few sample wavelengths. Once photons are introduced into the human head, they are either scattered by extra- and intracellular boundaries of different layers of the head (skin, skull, cerebrospinal fluid, brain, etc.) or absorbed mainly by oxy- and deoxy-Hb. If a photodetector is placed on the skin surface at a certain distance from the light source, it can collect the photons that are scattered and thus have travelled along a “banana shaped path” (Figure 1) from the source to the detector (Villringer & Chance, 1997; Chance et al., 1998; Hoshi & Tamura, 1997).

Recent studies with fNIR indicate that this modality can effectively monitor cognitive tasks such as attention, working memory, target categorization, and problem solving (Izzetoglu et al., 2007; Ayaz et al., 2011). These experimental outcomes compare favorably with fMRI studies, and in particular, with the blood oxygenation level dependent (BOLD) signal. Since fNIR can be implemented in the form of a wearable and minimally intrusive device, it has the capacity to monitor brain activity under real life conditions and in everyday environments. Moreover, by virtue of its compactness and portability, fNIR systems are amenable to integration with other...
established physiological and neurobehavioral measures, including EEG, eye tracking, pupil reflex, heart rate variability, respiration, and electrodermal activity.

Figure 1: fNIR sensor with 4 light sources and 10 detectors (left) and 16 optode (channel) measurement locations registered on sensor. fNIR sensor positioned on participants’ head (right, top). Optodes 1-8 and 9-16 monitor the left and the right frontal hemispheres respectively. The illustration on the right depicts the banana shaped path which includes the photons scattered back to the photodetector.

3. Materials and Methods

Continuous Wave fNIR System

During our experimental problem solving sessions, the prefrontal cortex of the participants were monitored using a continuous wave fNIR system manufactured by fNIR Devices LLC (Potomac, MD; www.fnirdevices.com), which was first described by Chance et al. (1998) and developed further at the Optical Brain Imaging Laboratory at Drexel University. The system is composed of a flexible headpiece that holds the light sources and the detectors, a control box for hardware management, and a computer that runs the data acquisition software.

The flexible sensor pad contains 4 light-emitting diodes (LED) with built in peak wavelengths at 730, 805, 850 nm and 10 detectors designed to sample cortical areas underlying the forehead (see Figure 1). The sensor has a temporal resolution of 500 milliseconds per scan with 2.5 cm source-detector separation, allowing approximately 1.25 cm penetration depth. During data acquisition LED sources are activated one at a time and the four photodetectors that surround the active source are sampled. The positioning of the light sources and the photodetectors on the sensor pad provide a total of 16 channels that is designed to monitor dorsal and inferior frontal cortical areas underlying the forehead (Ayaz, 2010; Bunce et al., 2006; Izzetoglu et al., 2005).

COBI Studio Software (Drexel University) was used for data acquisition, monitoring and visualization (Ayaz et al., 2011). SAN Protocol Suite (Drexel University) was used for presenting the tangram puzzles to the subjects and logging their actions during the experiments. The protocol and the fNIR data acquisition computers were linked via a serial cable to transfer time synchronization markers for marking the onset of problem solving trials. The problem solving moves of the participants were both screen recorded and logged by the system. Statistical analysis was performed with IBM Inc.’s SPSS software version 19.

Participants

Eight college students between the ages 21 to 34 volunteered to participate in this study. The participants were right-handed and reported no history of neurological disorders. Four of the subjects completed the experiment at the CONQUER Lab at Drexel University, Philadelphia, PA, USA and the remaining half used the facilities at the Human-Computer Interaction Lab at Middle East Technical University (METU), Ankara, Turkey. Drexel and METU groups followed the same experimental protocol, except that the METU group did not take PVT tasks in between experimental phases. Prior to the study, all participants signed informed consent forms.
**Experimental Protocol**

The tangram protocol started with a tutorial section where subjects were introduced to the computer-based environment they would use to solve the puzzles. During this session subjects completed the control task where they were asked to match each tangram piece with the corresponding shapes by dragging and rotating them, so that they would learn the basic moves required for solving real puzzles (see Figure 2). No time limit is enforced during the tutorial and the subjects were encouraged to try all the controls so that they would be comfortable with using them.

The tutorial was followed by the *Control* phase of the experiment, where subjects performed 3 repetitions of eyes open rest, eyes closed rest, the control task (i.e. the same task they used during the tutorial) and a self-report where they rated the difficulty of the task on a scale of 0 to 10. Then subjects completed a 5 minute long psycho-motor vigilance task (PVT) before they proceeded to the *Acquisition* phase. PVT task was intended to divert the subject’s attention away from the tangram task between the experiment’s phases. The METU subjects, which comprise half of the sample, were not given the PVT task to test if having a PVT in between phases would have an effect on problem solving performance and cerebral oxygenation in the frontal cortex.

During the Acquisition phase subjects attempted 3 different tangram puzzles called Hexagon, Duck and Dog. Subjects attempted each of these puzzles twice during this phase of the experiment, so they engaged in a total of 6 tangram puzzles in the following order: Hexagon, Duck, Dog, Duck, Hexagon, and Dog. Each attempt is preceded by eyes open rest and succeeded by a self-report of perceived difficulty. Repetitions were intended to observe if the participants would benefit from attempting a puzzle that they had encountered before, which would allow us to test the influence of memory on problem solving performance.

The acquisition phase was followed by another round of PVT. The experiment concluded with the *Transfer* phase, where subjects attempted two more tangram puzzles called Square and Swan that they had not encountered before. In short, subjects attempted to solve a total of 8 tangram puzzles during the course of the entire experiment. All subjects followed the same sequence of problems. Each phase included a balanced mix of animal and geometric tangram shapes as puzzles. Except the tutorial session, subjects were given 3 minutes to complete each puzzle. The system changes the color of the background 30 seconds before timeout in order to remind the subject.

**Data Analysis**

For the preliminary processing, block analysis was used to identify fNIR data that corresponds to initial eyes closed/eyes open rest periods, PVT and tangram tasks. First, linear phase, finite impulse (FIR) low pass filter with cut-off frequency of 0.14Hz was applied to the 16 voxel raw fNIR data to eliminate high frequency noise due to physiologically irrelevant data (such as respiration and heart pulsation effects) and equipment noise. Then, Sliding Windows Motion Artifact filter (Ayaz et al., 2010) was employed to minimize the effect of motion artifact on the measurements. Finally, modified Beer Lambert Law (Izzetoglu et al., 2005) was applied to the filtered fNIR data to calculate the changes in oxy-hemoglobin and deoxy-hemoglobin concentration.
4. Results

**Behavioral Analysis**

The bar charts in Figure 3 (top-left) displays the number of successful/failed attempts and the mean task completion times (top-right) of all subjects across the sequence of puzzles. Subjects completed the control tasks much quicker than actual puzzles. Only one subject could solve the hexagon puzzle in his/her first attempt, whereas 6 of the 8 subjects could solve it on their second attempt. The square problem was successfully solved by 4 of the 8 subjects. The remaining puzzles were generally solved by most subjects, albeit at different times. Subjects tended to rate the Hexagon and the Square puzzles as the most difficult, which is summarized in the boxplot included in Figure 3 (bottom-left). Subjects’ ratings for each puzzle were positively correlated with their completion times (Spearman’s Rho=0.824, p<0.01, N=86).

Since some subjects exhibited better problem solving performance as compared to others, we decided to split our sample into two ability groups. The first group (good problem solvers) involved subjects who failed 1 or 2 puzzles at most and whose mean task completion time was less than 100 seconds, whereas the remaining group (i.e. average problem solvers) involved participants who failed 2 to 4 puzzles and whose mean task completion time was higher than 100 seconds.

The overall influence of experimental phases, the presence of the PVT task, and ability groups on task completion time was tested with a 3-way mixed ANOVA with experimental phase (control, acquisition, and transfer) as within-subjects and PVT (with PVT vs no PVT) and group (good vs average) as between-subjects factors respectively. Mauchly’s test indicated that the sphericity assumption was tenable (W=0.199, p>0.05). The ANOVA revealed a main effect of experimental phase; F(2,8) = 27.472, p<0.01, η²=0.873. Helmert contrasts among the levels of
experimental phases indicated that the mean task completion time for control tasks is significantly lower than the mean completion time for the experimental phases (i.e., acquisition and transfer combined), $F_{1,4} = 74.034$, $p < 0.01$, $\eta^2 = 0.949$. Nevertheless, no significant difference was found between the acquisition and transfer phases. In addition to this, no significant interaction effects and no main effects of PVT and Group were found. Therefore, having a PVT task in between experimental phases did not have a significant impact on task completion times. Moreover, the ability groups did not significantly differ in terms of their task completion times across the phases of the experiment.

Likewise, the overall influence of experimental phase, PVT, and ability groups on accuracy (i.e., percentage of solved puzzles) was tested with a 3-way mixed ANOVA. Mauchly’s test indicated that the sphericity assumption was tenable ($W = 0.431$, $p > 0.05$). The ANOVA revealed a main effect of experimental phase ($F_{2,8} = 6.565$, $p < 0.05$, $\eta^2 = 0.621$) and a main effect of ability ($F_{2,8} = 8.471$, $p < 0.05$, $\eta^2 = 0.679$). Helmert contrasts indicated that the mean accuracy is significantly higher during the control phase as compared to the experimental phases. No significant difference was found between acquisition and transfer phases. The main effect of ability indicates that better problem solvers have a significantly higher accuracy percentage as compared to average problem solvers.

Paired samples t-tests on the completion times of repeated puzzles during the Acquisition phase revealed no significant difference between the first and second attempts on the same puzzle ($t(7) = 0.776$, $t(7) = -0.118$ and $t(7) = 0.673$ all $p > 0.05$ for Hexagon, Duck and Dog puzzles respectively). Hence, the fact that a subject previously encountered a tangram puzzle did not affect his/her completion time during the second attempt. Qualitative analysis of screen recordings of participants also revealed no clear evidence of repetition among solution sequences performed during first and second attempts. In short, subjects do not seem to have benefited from previously solving the same problem.

The distribution of accuracy percentages and the mean completion times suggest that subjects had more difficulty with Hexagon and Square problems, which can be classified as geometric type tangram puzzles. The remaining puzzles represented animal shapes. This motivated us to test for the effect of problem type (i.e., control, geometric, and animal) over task completion times and accuracy percentages.

A 2-way mixed ANOVA was conducted to investigate the influence of these variables on task completion times. Mauchly’s test indicated that the sphericity assumption was tenable ($W = 0.898$, $\chi^2(2) = 0.537$, $p > 0.05$). The ANOVA analysis revealed a significant main effect of task type ($F_{2,12} = 199.07$, $p < 0.01$, $\eta^2 = 0.971$), a significant main effect of ability group ($F_{1,6} = 17.21$, $p < 0.01$, $\eta^2 = 0.741$), and a marginally significant interaction effect ($F_{2,12} = 3.791$, $p = 0.053$, $\eta^2 = 0.387$). Helmert contrasts indicated that mean accuracy is significantly higher in animal tasks as compared to geometric tasks ($F_{1,6} = 22.193$, $p < 0.01$, $\eta^2 = 0.787$). The main effect of ability groups was not significant at the $p = 0.05$ level ($F_{1,6} = 4.913$, $p = 0.069$).

Figure 4: Better problem solvers were able to solve animal puzzles more quickly as indicated by the means plot on the left. The time gap between completion times of both groups decreases in the case of geometric problems. The mean accuracy percentage is lower in both groups for geometric puzzles.

A 2-way mixed ANOVA with task type as within-subjects and ability group as between-subjects factors over accuracy rate indicated a significant main effect of puzzle type ($F_{1,61} = 28.50$, $p < 0.01$, $\eta^2 = 0.826$, Greenhouse-Geisser $\varepsilon = 0.584$). Helmert contrasts indicated that mean accuracy is significantly higher in animal tasks as compared to geometric tasks ($F_{1,6} = 22.193$, $p < 0.01$, $\eta^2 = 0.787$). The main effect of ability groups was not significant at the $p = 0.05$ level ($F_{1,6} = 4.913$, $p = 0.069$).

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contrasts showed a significant difference among control versus experimental puzzles ($F_{1,6}=229.16$, $p<0.001$, $\eta^2=0.974$), as well as between animal and geometric puzzles ($F_{1,6}=159.693$, $p<0.001$, $\eta^2=0.964$). The means plot in Figure 4 (left) indicates that good problem solvers took roughly the same amount of time to complete control and geometric tasks, but significantly less amount of time to complete animal puzzles as compared to average problem solvers. All subjects tended to spend more time on solving geometric puzzles.

The similarity in completion times for the geometric puzzles across both ability groups is partly due to the maximum time subjects were allowed to work on a puzzle (180 sec.). Good problem solvers were successful in 7 of the 12 attempts, whereas the average group members were successful in 2 out of 12 attempts to solve a geometric puzzle. Thus, better problem solvers had a higher success rate even though they managed to solve the geometric puzzles close to the 3 minutes time limit during those 7 instances. However, the ANOVA conducted over accuracy rates indicated that this difference was not statistically significant at the $p=0.05$ level.

**fNIR Analysis**

Statistical analysis on fNIR data was conducted on mean oxygenation values computed for each subject during each task across 16 channels. Oxygenation refers to the difference between the concentrations of oxygenated and deoxygenated hemoglobin molecules. An increase in oxygenation suggests that there is an increasing level of neural activation under the cerebral region monitored by the corresponding optode.

A 2-way mixed ANOVA was conducted on the fNIR data with experimental phase as the within-subjects and ability group as the between-subjects factors. The analysis revealed main effects of experimental phase at optodes 2 ($F_{2,12}=3.960$, $p<0.05$, $\eta^2=0.398$), 4 ($F_{2,12}=6.876$, $p<0.05$, $\eta^2=0.523$), 5 ($F_{2,12}=4.330$, $p<0.05$, $\eta^2=0.419$), 6 ($F_{2,12}=11.821$, $p<0.01$, $\eta^2=0.663$), 7 ($F_{2,12}=9.25$, $p<0.01$, $\eta^2=0.649$), 8 ($F_{2,12}=9.978$, $p<0.01$, $\eta^2=0.666$), 10 ($F_{2,12}=9.51$, $p<0.01$, $\eta^2=0.655$), 12 ($F_{2,12}=8.68$, $p<0.01$, $\eta^2=0.591$), 14 ($F_{2,12}=8.68$, $p<0.01$, $\eta^2=0.591$), and 16 ($F_{2,12}=7.391$, $p<0.01$, $\eta^2=0.552$). Helmert contrasts indicated that control phase induced significantly less oxygenation as compared to experimental phases at optodes 4 ($F_{1,6}=7.954$, $p<0.05$, $\eta^2=0.570$), 5 ($F_{1,6}=6.461$, $p<0.05$, $\eta^2=0.398$), 6 ($F_{1,6}=13.8$, $p<0.05$, $\eta^2=0.697$), 7 ($F_{1,6}=26.795$, $p<0.01$, $\eta^2=0.843$), 8 ($F_{1,6}=11.772$, $p<0.05$, $\eta^2=0.702$), 10 ($F_{1,6}=11.758$, $p<0.05$, $\eta^2=0.702$), 12 ($F_{1,6}=14.011$, $p<0.05$, $\eta^2=0.70$), 14 ($F_{1,6}=15.436$, $p<0.01$, $\eta^2=0.72$), 16 ($F_{1,6}=9.633$, $p<0.05$, $\eta^2=0.616$). Thus, tangram puzzles induced higher levels of oxygenation as compared to the control tasks, but oxygenation levels during acquisition and transfer phases did not exhibit significant differences at any of the 16 optodes. A significant main effect of ability was observed only at optode 9 ($F_{1,4}=12.94$, $p<0.05$, $\eta^2=0.764$), where better problem solvers had a lower level of oxygenation as compared to average problem solvers (see Figure 5).

In order to investigate whether task type and ability had an effect on the fNIR data a 2-way mixed ANOVA was conducted with task type as within-subjects and ability groups as between-subjects factors. The analysis revealed main effect of puzzle type at optodes 1 ($F_{2,12}=10.172$, $p<0.01$, $\eta^2=0.718$), 4 ($F_{2,12}=7.086$, $p<0.01$, $\eta^2=0.541$), 5
Our results indicated that tangram puzzles elicited significantly higher oxygenation levels in both left and right hemispheres of the prefrontal cortex as compared to the control task. This difference can be attributed to the increasing load on spatial working memory induced by attempting tangram puzzles.

As the subjects continued to work on the puzzles across the acquisition and transfer phases of the experiment, the oxygenation level at optode #9 followed a decreasing pattern for better problem solvers and an increasing pattern for average problem solvers. We posit that these patterns in oxygenation level are meaningful given that at least 73% of the variation in oxygenation level is explained by problem solver type. This differential pattern indicates that better problem solvers increasingly become less dependent on the neural resources in this region as they continue to work on subsequent tangram puzzles.

Our analysis also showed that animal and geometric puzzles elicited significantly different activation patterns at optodes 9, 12, 14 and 16. Analysis of behavioral data indicated that subjects had the most difficulty with solving geometric type puzzles. Optode #9 seems to reflect this pattern as mean oxygenation values observed during geometric puzzles were significantly higher than animal puzzles. The reverse relationship was observed at optodes 12, 14 and 16 where animal tasks induced more oxygenation as compared to geometric tasks. Finally, a significant main effect of ability was observed at optode 9 (F1,5=11.052, p<0.05, η²=0.734) where good problem solvers had significantly lower level of oxygenation as compared to average problem solvers (see Figure 5).

5. Discussion and Future Work

In the future we will expand this study further by focusing on the details of the problem solving process in an effort to better account for the differences observed between the activation patterns elicited by animal and geometric type tangrams. To this end, we will assess the learning curves for the behavioral data and neural data independently. Previous work (Shewokis et al, 2011 – brain in the loop) has shown that learning curve analyses provides insight into the costs and effort associated with learning different types of tasks. We will also aim to observe if detectable changes in oxygenation occur in response to critical moments such as breakdowns in problem solving. We are also planning to incorporate eye tracking technology to our experimental setup to monitor where subjects allocate their attention as they work on the puzzles. Such observations will shed further light into the functional roles fulfilled by the cortical regions that are activated during visuospatial reasoning.

6. References


