Tangram solved? Prefrontal cortex activation analysis during geometric problem solving

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Abstract— Recent neuroimaging studies have implicated prefrontal and parietal cortices for mathematical problem solving. Mental arithmetic tasks have been used extensively to study neural correlates of mathematical reasoning. In the present study we used geometric problem sets (tangram tasks) that require executive planning and visuospatial reasoning without any linguistic representation interference. We used portable optical brain imaging (functional near infrared spectroscopy - fNIR) to monitor hemodynamic changes within anterior prefrontal cortex during tangram tasks. Twelve healthy subjects were asked to solve a series of computerized tangram puzzles and control tasks that required same geometric shape manipulation without problem solving. Total hemoglobin (HbT) concentration changes indicated a significant increase during tangram problem solving in the right hemisphere. Moreover, HbT changes during failed trials (when no solution found) were significantly higher compared to successful trials. These preliminary results suggest that fNIR can be used to assess cortical activation changes induced by geometric problem solving. Since fNIR is safe, wearable and can be used in ecologically valid environments such as classrooms, this neuroimaging tool may help to improve and optimize learning in educational settings.

I. INTRODUCTION

Problem solving is an essential mental process of intellectual functioning and represents a component of higher order cognition. Neuroanatomical models of mathematical problem solving until recently, have been largely based on human brain lesion studies [1]. The advent of noninvasive neuroimaging enabled mapping functional neuroanatomy of mathematical reasoning [2-4].

Studies using functional magnetic resonance imaging (fMRI) with healthy participants have recently identified a number of brain regions involved in performance of mental arithmetic tasks. During elementary arithmetic tasks a reproducible set of parietal and prefrontal areas are systematically activated [2, 5, 6]. However, the role of linguistic representation in mathematical thinking has been a highly debated topic. Dehaene et al. [2] suggested that exact calculation is language dependent, whereas numerical approximation relies on nonverbal visuospatial cerebral networks.

Studies using optical brain imaging (functional near infrared spectroscopy – fNIR) have confirmed the role of prefrontal cortex and parietal involvement during mental arithmetic [7-13]. For example, Pfurtscheller et al. [7] reported a bilateral increase of oxygenated hemoglobin (oxy-Hb) concentration change within the dorsolateral prefrontal cortex during the performance of simple arithmetic tasks. Richter et al. [8] investigated the involvement of the parietal cortex and reported higher oxy-Hb change in parietal brain regions of both hemispheres for the arithmetic calculation compared to the reading-only condition that was used as a control. Also, Tanida et al. [11] reported an increase in total hemoglobin concentration change in the right prefrontal cortex during mental arithmetic. Dresler et al. [9] investigated whether near-infrared spectroscopy can be used to measure the processing of arithmetic problems in school children and reported that calculations resulted in greater average oxygenation in parietal and posterior frontal regions. More recently, Meiri et al. [13] reported frontal lobe involvement during simple mathematical processing in adults and fNIR results showed differentiation of mathematical abilities as well as under varying arithmetical operations and difficulty levels.

In an earlier study, Hoshi and Tamura [14] used complex math problems that required not only mental arithmetic but also mathematical reasoning. The type and domain of the problems they used varied from calculations to proving statements in Euclidian geometry. Using optical brain imaging, they compared spatiotemporal changes in prefrontal brain activation during the problem solving periods and reported varying patterns of activation for different problems suggesting that the pattern of activation is related to problem domain and hence a different subset of brain regions might be involved with different type of problem solving.

Reasoning, in general, is a key part of executive decision-making and problem solving. Recent evidence from fMRI supports the hypothesis that a fronto-parietal network contributes to adaptive behavior, at least in part, by supporting reasoning [15]. However, the mechanisms by which this is achieved remain poorly understood [15]. Various tasks have been used to study visuospatial reasoning such as Tower of London task [16-19] and Tower of Hanoi task [19, 20] to assess planning and decision making.

In this study, our aim was to assess the involvement of prefrontal cortex during problem solving that required visuospatial reasoning. As problem sets, we used geometric puzzles (tangram tasks) that required visual object manipulation. We used a wearable optical brain imaging technology, fNIR, which allowed data acquisition in more ecologically valid environments. As we described in [21-23] optical brain imaging can be translated for use in educational settings to improve and optimize training and potentially advance reasoning and math learning skills.

A. fNIR Data Acquisition

Throughout the experiment duration, the prefrontal cortex of each participant was monitored using a continuous wave fNIR system developed at Drexel University (Philadelphia, PA), manufactured and supplied by fNIR Devices LLC (Potomac, MD; www.fnirdevices.com). The system was described in our recent report in [24] and is composed of three modules: a flexible headband (sensor pad), which holds light sources and detectors to enable a fast placement of all 16 optodes; a control box for hardware management; and a computer that runs the COBI Studio software [25] for data acquisition (See Fig. 1). The 2.5 cm source-detector separation on the sensor allowed for approximately 1.25 cm penetration depth.
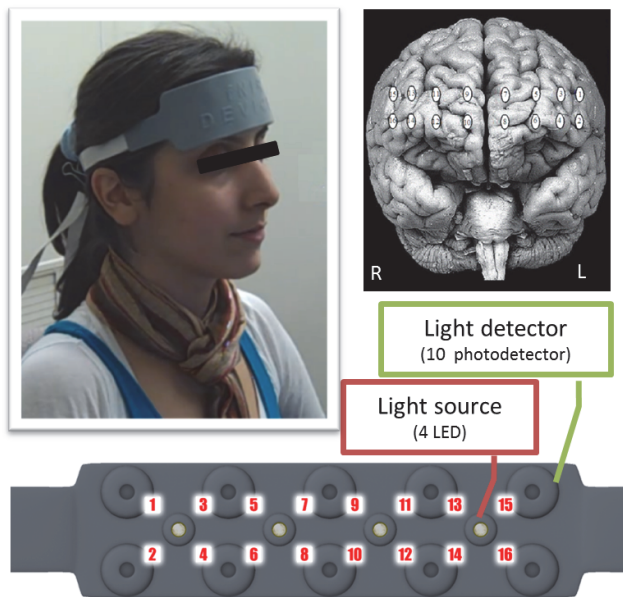

Figure 1. fNIR sensor (top, left), projection of measurement locations (optodes) on brain surface image [26] (top, right), optodes identified on sensor (bottom)

B. Participants

Twelve right-handed volunteers (6 males, Edinburgh Handedness Laterality Quotient = 73.2 ± 21.1) participated in the study. One subject was excluded due to poor signal quality. All participants stated that they have no neurological or psychiatric history and gave written informed consent approved by the institutional review board of Drexel University for the experiment.

C. Experiment Protocol

During the experiment, participants were asked to solve computerized tangram tasks (see Figure 2) that required moving and rotating seven 2D shapes (pieces) to form a specific larger shape in a given time. Participants used mouse button clicks to select and mouse cursor movement to drag selected pieces. For rotation of selected objects, keyboard buttons z and x were used for counter-clockwise and clockwise directions, respectively. All inputs (piece movements/rotation/selection) were recorded in log files.

Tangram tasks were designed and rendered using SAN Suite software (Drexel University) that has separate tools for automated protocol execution.

Participants completed the experiment in one session. Before starting the tasks, each participant was allowed to familiarize themselves with the user interface and control options until they confirm they are ready. The experiment consisted of three phases. The first phase involved three repetitions of control tasks with 30 second rest periods before each task. The control task requires all shape manipulation and control elements without any need for problem solving since each target location for each piece are identified (first window at the upper left corner in Figure 2). Participants completed a 5 minute long psycho-motor vigilance task [27] (PVT) before they proceeded to the next phase. PVT task was intended to divert the subject's attention away from the tangram task between the experiment's phases.
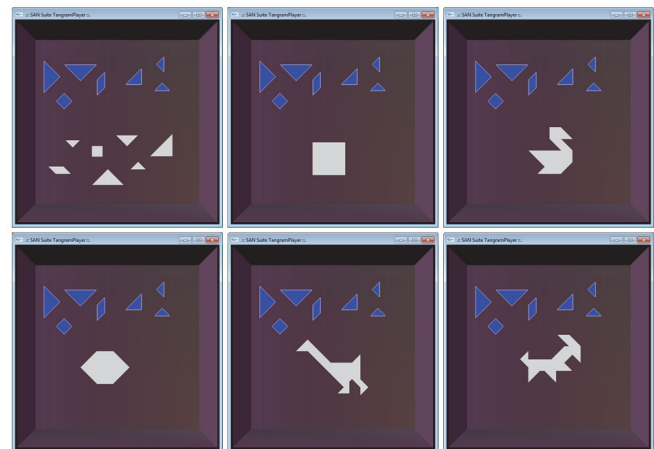

Figure 2. Tangram task windows that contain blue movable pieces that need to fit in the white area. Top row: control, square, swan; Bottom row: hexagon, duck and dog puzzles.

The second session of the experiment protocol, called acquisition, consisted of pseudo random sequential execution of three tangram tasks (duck, dog and hexagon) each with two repetitions (bottom row windows in Figure 2). Hence, acquisition phase included six puzzles in total together with six respective 30 seconds rest-periods. Each puzzle also had a 3 minute timeout and a warning of 30 seconds before timeout by changing the background color.

The third and last phase, called transfer, consisted of two tangram (square and swan) executions which were not practiced before in the acquisition (last two windows on the top row of Figure 2). There were 30 seconds rest periods before each transfer phase tasks.

Throughout the experiment, all tangram activities were recorded in log files on the presentation computer. Task start and end times information was sent by using unique single byte markers to fNIR data acquisition computer through RS232 serial port communication.

D. Data Analysis

For each participant, raw fNIR data (16 optodes×2 wavelengths) were low-pass filtered with a finite impulse response, linear phase filter with order 20 and cut-off frequency of 0.1 Hz to attenuate the high frequency noise,

respiration and cardiac cycle effects [24]. Saturated channels (if any), in which light intensity at the detector was higher than the analog-to-digital converter limit were excluded. fNIR data epochs for the rest and task periods were extracted from the continuous data using time synchronization markers. Blood oxygenation and volume changes within each 16 optodes were calculated using the modified Beer-Lambert Law for task periods with respect to rest periods at beginning of each task with fnirSoft software [28].

The main effect for task was tested using one-way repeated measures analysis of variance (ANOVA), with Subject and Task Type designated as fixed effects. Geisser–Greenhouse (G–G) correction was used when violations of sphericity occurred in the omnibus tests. Tukey's post hoc tests were used to determine the locus of the main effects. A complex post-hoc contrast of control vs acquisition and transfer were used to assess problem-solving with a 0.05 significance criterion for all analyses. Acquisition and transfer tasks were also analyzed based on performance outcome, success and failure. Number Cruncher Statistical Software (NCSS) 2007 (www.ncss.com) was used for the statistical tests.

III. RESULTS

The average total hemoglobin (HbT) concentration changes throughout all tasks (control / acquisition/ transfer) were analyzed using one-way repeated measures ANOVA. Oxygenated hemoglobin (HbO) concentration changes also indicated similar results to HbT. A main effect of task was found for optodes 9 [$F_{(2,20)}$= 5.37, p=0.014], 11[$F_{(2,20)}$= 3.65, p=0.049] and 15[$F_{(2,20)}$= 24.26, p <0.001]. Post-hoc Tukey tests showed a $q_{(20,0.05/2)}$ = 3.578 with the control tasks lower HbT changes (mean± SD; -0.349 ± 0.414 μmolar) than the acquisition tasks (-0.029 ± 0.587 μmolar) for optode 9. For optode 15, Tukey's post-hoc test showed a monotonic increase in activation across control (-0.018 ± 0.370 μmolar, acquisition (0.133 ± 0.716 μmolar) and transfer (0.423 ± 0.486 μmolar).
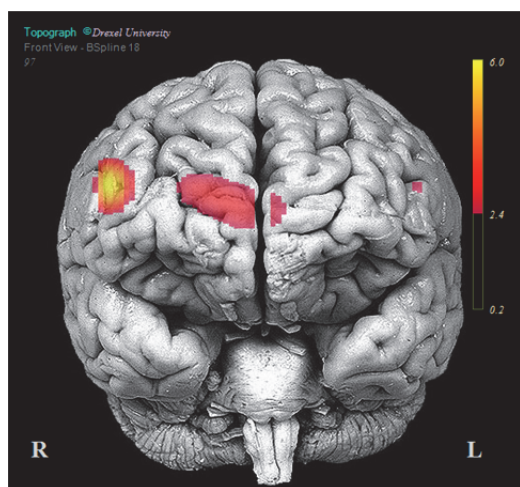

Figure 3. Projection of t-statistics map on brain surface image indicates right hemisphere dominance. Based on [26], BSpline interpolation was used to generate surface representation from t values of comparisons of each control vs. task conditions along with thresholding by significance limit p<0.05. (Brain surface image is from Digital Anatomist Project, University of Washington).

For the complex contrast, control task averages were compared with all task averages (acquisition and transfer) to identify significant differences due to problem solving. Contrast t values for each optode location were used to generate a t-statistics map, which were then registered onto a brain surface image as described in [26]. Resultant activation map in Figure 3 indicates right hemisphere dominance for the problem solving component.

The most significant optodes 11 and 15 are graphed below in Figures 4 and 5 respectively indicating higher activation levels during both acquisition and transfer task periods compared to control tasks.
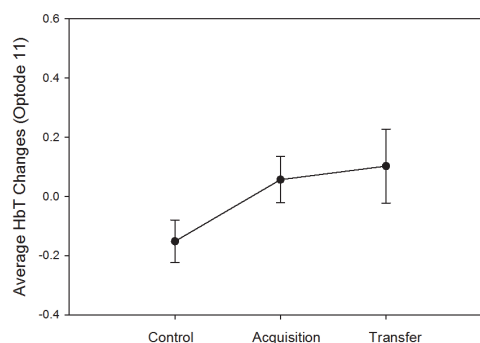

Figure 4. Average HbT changes at optode 11. Error bars are standard error of the mean (SEM)
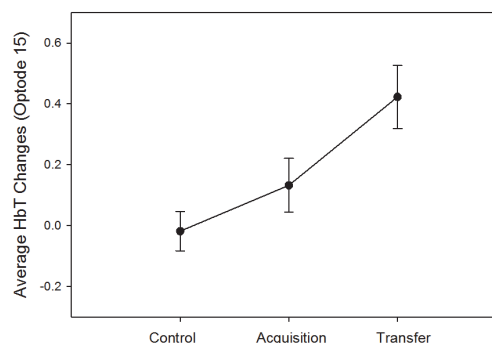

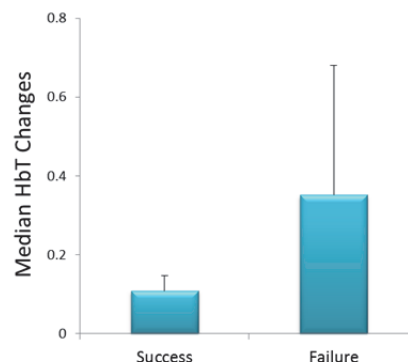Figure 5. Average HbT changes at optode 15. Error bars are SEM

Figure 6. Comparison of HbT changes for success versus failed task periods at optode 15. Error bars are Interquartile Deviation.

Next, within the acquisition and transfer task periods, successful and failed task periods were compared using a two-tailed Wilcoxon Rank sum test for median differences [Z=3.416, p < 0.001]. There were higher HbT concentration changes for failure (0.352 μ molar) periods compared to successful (0.109 μ molar) periods. There were 30 failed

attempts out of 88 puzzles. Figure 6 displays the median HbT changes for the most significant optode 15.

IV. DISCUSSION

Hemispheric involvement in reasoning abilities has been a topic of discussion for some time, and it remains unclear whether the involvement of the right hemisphere in problem solving is modality specific or dependent on the type of spatial reasoning required [29]. In this study, we used tangram tasks that required executive planning and visuospatial reasoning without any linguistic representation interference as in mental arithmetic tasks. Results indicate that optical imaging by fNIR was able to capture differences in brain activation elicited by the increased cognitive workload during problem solving similar to our earlier results using working memory and attention related cognitive tasks [24]. Comparison of measurement locations revealed that most significant differences in brain activation occurred in right hemisphere (Figure 3), consistent with previous fMRI meta-analysis of cerebral lateralization of spatial abilities and fluid reasoning [15, 30]. Given the qualities of fNIR that it can measure localized brain activity and track hemodynamic response with safe and wearable sensors, future applications building on this work will investigate deployment in ecologically valid environments. An example of this application could include classrooms in which this approach could be used to help improve and optimize learning in educational settings.

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