Neuroscience Letters 510 (2012) 43–47

Contents lists available at SciVerse ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Frontal lobe role in simple arithmetic calculations: An fNIR study

Hedva Meiri[a,*], Itamar Sela[a,b], Pearla Nesher[a], Meltem Izzetoglu[b], Kurtulus Izzetoglu[b], Banu Onaral[b], Zvia Breznitz[a]

[a] The Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, University of Haifa, Haifa, Israel
[b] School of Biomedical Engineering, Science & Health Systems, Drexel University, Philadelphia, PA, United States

ARTICLE INFO

Article history:
Received 3 November 2011
Received in revised form
18 December 2011
Accepted 30 December 2011

Keywords:
fNIR
Frontal lobe
Calculation
Arithmetic processing

ABSTRACT

This study aimed to affirm the use of functional near-infrared spectroscopy (fNIR) in examining frontal lobe role during automatic (i.e., requires retrieval from long-term memory) and method-based (i.e., requires calculation) arithmetic processing. Adult university students (math difficulties [MD] and control) performed simple arithmetic calculations while monitored using an fNIR system designed to image regions within the frontal cortices. Addition and subtraction problems presented on a computer screen belonged to one of three categories: triples "under 10" (e.g., 2 + 3 = ?, 5 – 3 = ?), triples that "break 10" (e.g., 5 + 8 = ?, 13 – 5 = ?), or triples "including 10" (e.g., 10 + 7 = ?, 17 – 10 = ?). fNIR recordings indicated significant interactions between type of triple, operation, and group over left frontal lobe, and between type of triple and group over right frontal lobe.

Within-group differences among controls were found in the "break 10" triples with higher DeOxyHb level recorded during subtraction processing. Between-group differences were found in the "break 10" and "including 10" triples for subtraction with higher levels of DeOxyHb recorded among controls. Results imply that among adults frontal lobe is still involved during simple mathematical processing and fNIR recordings can differentiate its role in adults of varying mathematical ability.

1. Introduction

Research on performing arithmetical operations in specific regions of the brain has mainly been demonstrated by fMRI and neuroimaging studies [3,5,14]. These studies have drawn a clear distinction between automatic retrieval of well-practiced facts consisting of one-digit numbers (associated with the parietal lobe) and problems demanding calculation and use of other strategies (associated with more frontal areas [14,4,8,13]).

This study aimed to replicate and expand findings concerning frontal lobe role in arithmetic calculation and retrieval using functional near-infrared spectroscopy (fNIR). fNIR uses specific wavelengths of light to measure levels of oxygenated and deoxygenated hemoglobin in brain blood flow while participants perform various tasks [2,9,15]. This study utilized an fNIR machine over the frontal lobe (see Fig. 1; fNIR Devices LLC; http://www.fnirdevieces.com).

Stimuli selected for this study distinguished between operations performed by retrieval from long-term memory (e.g., addition of one-digit numbers) and those not retrieved automatically, such as complement subtraction in the same range of numbers (e.g., 4 + 5 = 9; 9 – 4 = 5). Subtraction is supposedly harder and processed with several different strategies [7]. For most adults with strong mathematical skills retrieval of one-digit addition facts up to 18 is processed automatically. However, young children and students weak in math usually use different strategies for addition problems that "break" 10, such as decomposition to a known problem (e.g., '7 + 9' becomes '7 + 7 + 2') or completing first to 10 ('8 + 7' becomes '8 + 2 + 5' [8,11]). A third kind of simple addition is adding one-digit numbers to 10 itself (e.g., 10 + 6). It seems simple but involves knowledge of the place value system's syntactic structure [6,16].

The research groups chosen for this study include students with math difficulties and an age-matched control group. The researchers hypothesize that fNIR results for both groups will be similar for stimuli which demand automatic retrieval of mathematic facts, but different when calculations demand more involvement from the frontal lobe. It is expected that participants with math difficulties will display more variability in frontal lobe blood oxygenation in response to specific kinds of stimuli.

2. Materials and methods

2.1. Participants

University-aged students (Control group: mean age = 25.79 ± 3.22, five males; experimental group: mean

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* Corresponding author at: Education Building Rm. 264, Department of Learning Disabilities, University of Haifa, Mt. Carmel, Haifa 31905, Israel.
Tel.: +972 4 828 8433; fax: +972 4 824 9835.
E-mail address: hedva.meiri@gmail.com (H. Meiri).

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doi:10.1016/j.neulet.2011.12.066

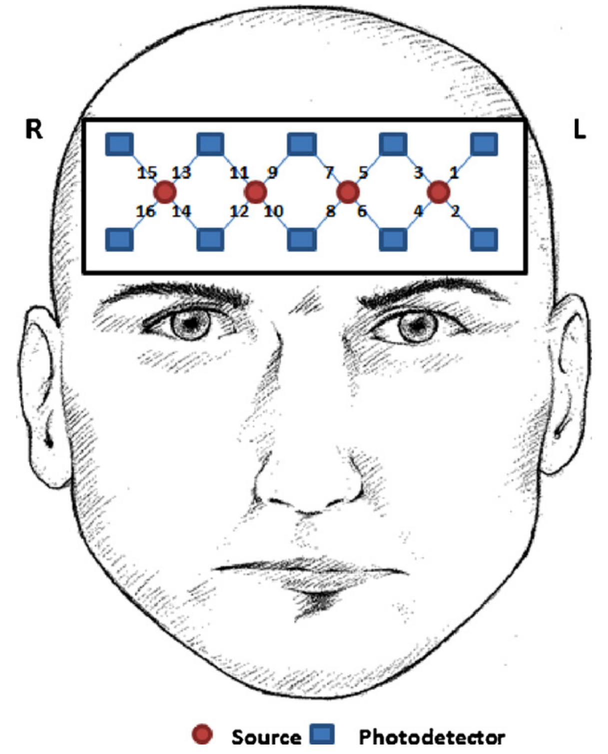

Fig. 1. The fNIR machine utilized in this study included a head-piece with sources and photoreceptors to measure activity in brain frontal regions.

age = 25.93 ± 3.39, four males) were recruited by advertisements placed around campus and sent through email. One ad requested participants without any forms of learning disabilities. Another requested participants with documented or self-reported ms difficulties in mathematics. All participants were paid volunteers with normal or corrected-to-normal vision and normal intelligence as measured by sub-tests of the Wechsler Adult Intelligence Scale III (WAIS-III). Group differences were found on the Digit Symbol and Digit Span sub-tests (see Table 1). With the exception of one participant, none presented with Attention Deficit/Hyperactivity Disorder (ADHD) as defined by the DSM-IV guidelines. To be classified into the experimental or control group participants completed the Two-Minute Test ([TMT]; [12]; see description below) which examines calculation abilities. A natural split occurred where 19 controls were able to complete at least 62 correct calculations (mean = 72.00 ± 5.96) in the allotted time and 15 participants with math difficulties (MD) completed no more than 54 correct calculations (mean = 45.40 ± 9.05; see Fig. 2).

2.2. Two-Minute Test (TMT)

The TMT is a questionnaire consisting of 80 open-ended math facts employing the four basic mathematical operations (e.g., 2 + 2 = ?, 5 − 3 = ?, 3 × 3 = ?, and 10:2 = ?). Participants have two minutes to complete as many of the 80 questions as possible while working quickly and accurately. Questions must be completed in order and are presented in increasing difficulty.

Table 1
Standard scores of experimental and control groups on sub-tests of the WAIS-III. Both groups scored within normal range.

	Mean (SD)		$t(32)$
	Control ($n = 19$)	MD ($n = 15$)	
Digit symbol	11.79 (2.53)	9.73 (2.52)	2.36*
Digit span	11.95 (2.78)	9.87 (3.04)	2.08*
Block design	13.21 (2.95)	11.80 (3.05)	n.s.
Similarities	12.26 (2.54)	11.33 (1.88)	n.s.

* $p < .05$, ** $p < .01$, *** $p < .001$

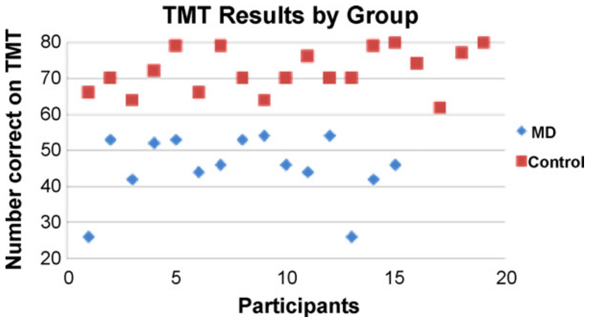

Fig. 2. Results of TMT. Participants in the MD group scored no more than 54 correct. Participants in the control group scored a minimum of 62 correct.

2.3. Apparatus

Experimental measures were collected using two computers. The first presented stimuli using E-Prime software (Psychology Software Tools, Inc., http://www.pstnet.com) and collected reaction times. The second hosted the fNIR system. The fNIR device used in this study was composed of two main parts – a head-piece which held light sources and detectors and a control box for data acquisition (sampling rate of 2 Hz). The flexible fNIR sensor consists of four light sources and ten detectors designed to image dorsolateral and inferior frontal cortices. With a fixed source-detector separation of 2.5 cm, this configuration results in a total of 16 channels. The control box was connected to the computer for data collection and storage utilized by COBI studio software (Drexel University). Synchronization of the computers was achieved with a COM cable which sent online event triggers from E-Prime to the COBI studio software. Signal processing and data preparation for statistical analysis was done with Matlab (Version 2010a, The Mathworks, Natick, MA). Statistical analysis was performed with IBM SPSS Statistics (Version 19, IBM SPSS Inc., Chicago, IL).

2.4. Task and stimuli

Participants completed one of two counter-balanced versions of the experimental task. The task consisted of 54 basic one- and two-digit addition and subtraction questions based on mathematical triples – eighteen in the “under 10” category, where addition between the two smaller terms yielded a third term less than 10 (e.g., [2,3, 5]; [3,4, 7]), twenty that “broke” 10 (e.g., [4,7, 11]; [5,8, 13]), and sixteen including the number 10 (e.g., [7,10, 17]). Each trial contained two addends or a minuend and subtrahend, and a missing solution. The largest two-digit number presented in a problem or as a possible solution was 19. The smallest solution was 1. Questions were presented in the middle of a computer screen for 1000 ms, followed by a blank screen for 500 ms. A screen with three possible answers was then presented for 4000 ms, followed by a blank screen for 9500 ms. Participants used the E-Prime Serial Response Box to choose the correct answer. They could answer from the time the choices appeared on-screen until the next trial was presented. The three possible answers always contained the correct solution, an erroneous solution with a magnitude of 1 more or less than the correct solution, and an erroneous solution that would have been correct had the operation been subtraction in an addition problem, and vice versa. Onscreen position of correct and erroneous answers was counterbalanced.

Table 2
RT (ms) means and standard errors (mean (SE)) for the interactions type of triple × group and type of triple × operation.

		Type of triple		
		Under 10	Break 10	Including 10
Group	Control	720 (60)	930 (90)	760 (60)
	MD	790 (70)	1220 (100)	720 (60)
Operation	Addition	700 (40)	910 (60)	720 (40)
	Subtraction	810 (60)	1230 (90)	760 (60)

2.5. Data processing and feature extraction

Data processing began with the removal of heart pulsation, respiration and movement artifacts from the fNIRS intensity measurements by using a finite impulse response low-pass filter with a cut-off set to .14 Hz. fNIR intensity measurements at 730 and 850 nm wavelengths were then converted to relative changes in hemodynamic responses in terms of oxygenated (OxyHb) and deoxygenated hemoglobin (DeOxyHb) using the modified Beer–Lambert law [10]. Epochs were segmented from the stimuli onset to 15 s later for each trial. fNIR features maximum and mean values were extracted for each trial epoch, channel and participant. For the statistical analyses, each parameter was averaged over trials per participant. Noisy segments, mainly due to movement artifacts, were excluded.

3. Results

Statistical analyses were carried out with respect to type of triples (i.e., “under 10”, “break 10”, or “including 10”), operation (addition or subtraction), and group (MD or control).

3.1. Behavioral measures

3.1.1. Accuracy (ACC)

3 × 2 × 2 repeated measures ANOVAs (type of triple × operation × group) revealed a main effect of type of triple ($F(2, 64) = 9.77$, $p < .001$), with ACC in the “break 10” triples (mean = 91.50 ± 1.31) significantly lower than ACC in the “under 10” (mean = 95.39 ± 1.25, $F(2, 31) = 9.21$, $p < .02$) and “including 10” (mean = 97.81 ± 60, $F(2, 31) = 9.21$, $p < .001$) triples. A group effect was also found ($F(1, 32) = 5.49$, $p < .05$), with overall ACC lower for the MD (mean = 93.21 ± 1.08) than control group (mean = 96.59 ± 96). Independent *t*-test analyses revealed a significant difference in accuracy between control (mean = 95.26 ± 8.42) and MD (mean = 86.67 ± 11.75) groups in the “break 10” triples for subtraction ($t(32) = -2.49$, $p < .05$).

3.1.2. Reaction time (RT)

3 × 2 × 2 repeated measures ANOVAs (type of triple × operation × group) revealed main effects of type of triple ($F(1, 27) = 34.85$, $p < .001$) and operation ($F(1, 27) = 18.57$, $p < .001$). The main effect of type of triple was further analyzed with post hoc Bonferroni pairwise comparisons.

RT for the “break 10” triples (mean = 1070 ± 70 ms) was significantly longer than for the “under 10” (mean = 753 ± 40 ms, $F(2, 26) = 22.61$, $p < .001$) and “including 10” triples (mean = 738 ± 40 ms, $F(2, 26) = 22.61$, $p < .001$). RT for addition (mean = 780 ± 40 ms) was significantly shorter than RT for subtraction (mean = 930 ± 60 ms, $F(1, 27) = 18.57$, $p < .001$).

ANOVAs also revealed interactions between type of triple and group ($F(1, 27) = 6.74$, $p < .02$) and type of triple and operation ($F(1, 27) = 11.05$, $p < .01$). Table 2 provides means and standard errors for these parameters. Independent *t*-test analyses revealed significant differences existed in the “break 10” triples between the control ($\text{mean}_{\text{addition}} = 813 \pm 26$ ms, $\text{mean}_{\text{subtraction}} = 1108 \pm 44$ ms) and MD ($\text{mean}_{\text{addition}} = 1106 \pm 46$ ms, $\text{mean}_{\text{subtraction}} = 1499 \pm 58$ ms) groups for both addition ($t(32) = 2.35$, $p < .05$) and subtraction ($t(32) = 2.24$, $p < .05$).

3.1.3. fNIR results

fNIR statistical analyses were employed on the mean and max attributes of the OxyHb and DeOxyHb measures. Analyses revealed that most significant differences between experimental groups, operation, type of triple and interactions occurred in the DeOxyHb measure. Thus, results are reported with respect to DeOxyHb.

Repeated measures ANOVAs were carried out separately for each channel in a 3 × 2 design (type of triple × operation) with experimental group as between-subjects variable. No significant main effects were found. However, type of triple × operation × group interactions were found for DeOxyHb-Mean at channel 3 ($F(2, 54) = 4.62$, $p < .02$), and DeOxyHb-Max at channels 3 ($F(2, 54) = 3.71$, $p < .05$) and 7 ($F(2, 54) = 3.78$, $p < .05$). Operation × group interactions were found for DeOxyHb-Max at channels 6 ($F(1, 27) = 5.51$, $p < .05$) and 7 ($F(1, 27) = 5.42$, $p < .05$). Finally, type of triple × group interactions were found at channel 10 for DeOxyHb-Mean ($F(2, 54) = 6.15$, $p < .01$) and DeOxyHb-Max ($F(2, 54) = 5.59$, $p < .01$).

In order to further examine interactions, independent and paired *t*-tests were applied to these channels. Independent *t*-tests revealed between-group differences in addition within the “including 10” triples in DeOxyHb-Max at channel 3 ($t(23.84) = -2.197$, $p < .05$), and in subtraction within the “break 10” triple in DeOxyHb-Max at channels 6 ($t(32) = -2.286$, $p < .05$) and 7 ($t(30.82) = -3.096$, $p < .01$); within the “including 10” triples in DeOxyHb-Max at channels 6 ($t(29) = -2.872$, $p < .01$), 7 ($t(23.17) = -2.931$, $p < .01$), and 10 ($t(29) = -3.209$, $p < .01$); and within the “including 10” triples in the DeOxyHb-Mean feature at channel 10 ($t(29) = -2.696$, $p < .02$).

Significant results for paired *t*-tests examining differences between addition and subtraction within groups and type of triple were found within the MD group, within the “including 10” triples in DeOxyHb-Max at channel 3 ($t(13) = -2.338$, $p < .05$) and 6 ($t(13) = 3.145$, $p < .01$). Within the control group, significant differences were found at channel 7 in the “break 10” triples for both DeOxyHb-Max ($t(18) = -2.900$, $p = .01$) and DeOxyHb-Mean ($t(18) = -3.151$, $p < .01$).

A more global view of the fNIR results is presented in Table 3. It lists means and SDs of DeOxyHb-Max and -Mean for channels 3, 6, 7, and 10 where significant results from *t*-tests were obtained. Values in bold were significant in the independent *t*-tests and highlight differences between groups within operation and within type of triple. Italicized values were significant in paired *t*-tests and highlight within-group differences within type of triple and between operations. No significant differences were found between or within groups in the “under 10” condition, while the “break 10” and “including 10” condition were considerable sources of between-group differences in subtraction. The “break 10” condition contributed to within-group differences among the controls, while the “including 10” condition contributed to differences among the MD group.

Table 3
Means and SDs of channels which revealed significant interactions in rmANOVA analyses. Values in bold represent between-group differences, while italicized values represent within-group differences.

Ch	Feat	Grp	Triple					
			Under 10		Break 10		Including 10	
			+	−	+	−	+	−
3	Max	Control	.128(.071)	.100(.042)	.096(.051)	.108(.062)	**.115(.088)**	.121(.054)
		MD	.096(.041)	.094(.057)	.102(.071)	.075(.041)	***.067(.032)***	*.095(.045)*
	Mean	Control	.012(.036)	−.001(.038)	−.004(.038)	−.003(.038)	−.011(.042)	.021(.081)
		MD	.004(.048)	.005(.038)	.012(.041)	−.016(.035)	−.029(.069)	−.001(.039)
6	Max	Control	.118(.067)	.096(.035)	.098(.037)	**.115(.043)**	.086(.064)	**.126(.087)**
		MD	.086(.034)	.088(.033)	.080(.031)	**.083(.037)**	*.090(.034)*	***.058(.031)***
	Mean	Control	.014(.041)	.003(.028)	−.002(.034)	.015(.031)	−.009(.053)	.006(.074)
		MD	.012(.031)	.007(.027)	.000(.032)	.005(.032)	.002(.037)	−.015(.042)
7	Max	Control	.148(.092)	.121(.050)	*.098(.049)*	***.160(.088)***	.126(.091)	**.140(.074)**
		MD	.115(.054)	.104(.063)	.105(.066)	**.083(.056)**	.111(.082)	**.078(.040)**
	Mean	Control	.021(.044)	.013(.044)	*−.012(.040)*	***.040(.061)***	.015(.064)	.012(.070)
		MD	.022(.042)	.008(.042)	.007(.049)	−**.008(.045)**	−.001(.066)	−.031(.123
10	Max	Control	.129(.079)	.106(.041)	.092(.033)	.109(.053)	.115(.086)	**.129(.055)**
		MD	.102(.056)	.085(.056)	.101(.057)	.101(.057)	.079(.037)	**.078(.028)**
	Mean	Control	.022(.039)	.013(.036)	−.004(.030)	.008(.041)	.016(.053)	**.027(.043)**
		MD	.005(.047)	−.002(.041)	.012(.056)	.002(.042)	−.020(.050)	−**.012(.038)**

4. Discussion

The purpose of this experiment was to examine differences in cognitive activity in the frontal lobe between two populations performing simple mathematical calculations. fNIR was used to provide information about blood flow and oxygen consumption. Young adults with and without mathematical difficulties participated in the study. In addition to differences between the research groups, differences between addition and subtraction and types of stimuli were examined.

Use of fNIR enabled the researchers to pinpoint several differences between control and MD participants beyond the behavioral differences found in accuracy and reaction time in the "break 10" triples. Despite the calculations being fairly easy (as evidenced by high accuracy rate among both groups), frontal lobe activity appears to differ in young adults with MD during task performance assumed to be automatic or during retrieval of facts assumed to be ingrained. Furthermore, statistical findings in specific channels revealed activation in both left (channels 3, 6, and 7) and right (channel 10) sides of the frontal lobe among both groups. This may suggest that detailed processing occurs on the left and holistic processing on the right, much as the right hemisphere of the brain in general is believed to be responsible for whole or holistic and symbolic processing [3]. From our results it cannot be ascertained whether the observed activation is verbal or not. Future studies using fNIR over Broca's area may be able to clarify this point.

Similarly to Dahaene's findings [3], this study identified differences between the operations learned by rote memory and those that require active calculation abilities. One-digit operations of addition and subtraction were retrieved automatically. However, triples with at least one two-digit number (e.g., [7,10, 17]) required the nonverbal representation and manipulation of number that is seemingly controlled by the right side of the brain. This study's results would indicate that right frontal lobe is responsible for this kind of processing in addition to right parietal lobe.

Use of fNIR in this study allowed the researchers to examine hemodynamic responses to different mathematical conditions. An increase in the value of deoxygenated hemoglobin (DeOxyHb) can be interpreted as an increase in oxygen consumption by neurons. Subtraction caused between-group differences in recorded DeOxyHb in the "break 10" and "including 10" triples. It is likely that between-group differences were not found in the "under 10" condition because it was easy for both groups. Furthermore, it is likely that between-group differences were not found for the addition operation because addition triples represent more automatic mathematical processing than subtraction.

Ansari et al. [1] report on a shift of cognitive functions from the frontal lobe to the parietal lobe that occurs once mathematical fact retrieval is automatized, as seen in adult processing of number. Children in their study activated more frontal regions. It seems that this study's MD group simulated cognitive processing similar to that of children, in that they rely more on frontal regions than students without MD.

Results from this study support the use of fNIR for examining the role of frontal lobe during mathematical calculations. The group differences highlight differential patterns of blood flow to specific areas of the frontal lobe, even among adults. Future studies using fNIR have the potential to identify other automatic and non-automatic mathematical processes, even when the study is based on relatively simple stimuli.

Acknowledgment

Funding for this research project was provided by the Edmond J. Safra Philanthropic Foundation.

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