How the brain's performance during mathematics and reading fluency tests compare

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Abstract

The purpose of this study was to analyze how participants' levels of hemoglobin as they performed mathematics fluency and reading fluency (reading comprehension) compare. We used Optical Topography (OT, helmet type brain-scanning system, also known as Functional Near-Infrared Spectroscopy or fNIRS) to measure levels of brain activity. A central issue in cognitive neuroscience involves the study of how the human brain encodes and manipulates information. Recently, functional neuro-imaging studies have begun to clarify how the human brain performs mental activities. fNIRS is an imaging technique capable of measuring changes in the relative concentration of hemoglobin the in the cerebral cortex of the brain (Hoshi & Tamura, 1993; Villringer et al., 1993; Koizumi et al., 2003). Near-infrared light of a wavelength between 650 nm and 950 nm can penetrate living tissue where it is specifically absorbed by hemoglobin (Strangman et al., 2002). Changes in the concentrations of oxy- and deoxyhemoglobin were monitored and energy consumption, or activation of the brain region during the performance of cognitive tasks were analyzed. Twelve undergraduate and graduate college-level students participated in scanning session. Brain activity was similar for both mathematics and reading fluency tasks. There were also different levels of oxy-hemoglobin: low, moderate, and high for different participants. Similarly to Ortiz (2010), the levels of activity were related to participants' mental strategies as they solve the exercises. Students who had an easier time with the reading or mathematics tasks tended to show moderate to low hemoglobin oxygenation. These results may have implications for how important fluency in these might be in students' performance. Other results and possible implications are discussed in this article.

Keywords: cognitive neuroscience, mathematics, mental calculations, reading, brain, mind, education.

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Introduction

A central issue in cognitive neuroscience involves the study of how the human brain encodes and manipulates information. Two important components related to this issue are reading fluency (reading comprehension) and mathematics fluency, which provide a good model to investigate fundamental cognitive processes. Recently, functional neuroimaging studies have begun to clarify how the human brain performs the everyday activities that require reading and mental calculation. In the area of mental calculation, we can find studies and reviews by Kazui et al., (2000), Davis et al. (2009), Dresler et al. (2009), and Dehaene et al. (2004). However, most studies have used fMRI to make these new discoveries. The present study used a multi-channel Optical Topography System (OT) or NIRS system by Hitachi Medical Corporation (Maki et al., 1995; Watanabe et al., 1996) to test the hypotheses that there are specific neural networks dedicated to performing mathematics (addition, subtraction, multiplication and division arithmetic) and reading fluency tasks. Due to the fact that the OT system is a non-invasive technology (Fig.1) based on the absorption of near-infrared light by haemoglobin, studies can be performed in a controlled and natural environment.

In an fMRI study, Delazer, Ischebeck, Domahs, Zamarian, Koppelstaetter, Siedentopf, Kaufmann, Benke, and Felber (2005) investigated whether learning new arithmetic operations is reflected by changing cerebral activation patterns, and whether different learning methods lead to differential modifications of brain activation. The participants were trained over a week on two new complex arithmetic operations, one operation trained by the application of back-up strategies (a sequence of arithmetic operations), and the other by drill (learning the association between the operands and the result). Delazer, et al. indicated that in the following fMRI session, new untrained items, items trained by strategy and items trained by drill, were assessed using an event-related design. They found that untrained items as compared to trained items showed large bilateral parietal activations, with the focus of activation along the right intraparietal sulcus. Further foci of activation were found in both inferior frontal gyri. However, the reverse contrast was found involving trained vs. untrained, which showed a more focused activation pattern with activation in both angular gyri.

In another study, Grabner, Ansari, Hoschutnig, Reishofer, Ebner, and Neuper (2009) indicate that while there is consistent evidence from brain imaging studies for an association between the left angular gyrus and mental arithmetic, its specific role in calculation has remained difficult to understand clearly. Grabner et al. carried out an fMRI study, which involved 28 adults, and used trial-by-trial strategy self-reports to identify brain regions underpinning different strategies in arithmetic problem solving. Their analyses revealed stronger activation of the left angular gyrus while solving arithmetic problems for which participants reported fact retrieval; however, the application of procedural strategies was accompanied by widespread activation in a fronto-parietal network. They also indicated that these data directly link the left angular gyrus with arithmetic fact retrieval and show that strategy self-reports can be used to predict differential patterns of brain activation (Grabner, et al.).

Kong, Wang, Kwong, Vangel, Chua and Gollub (2004) carried out a study with a different scanning system involving addition and subtraction (computation with and without renaming), and found that the right inferior parietal lobule, left precuneus and left superior parietal gyrus are relatively specific for performing subtraction; and bilateral medial frontal/cingulated cortex are relatively specific for supporting arithmetic procedure complexity. They also found that greater difficulty level was related with the activation in a brain network (including left inferior intraparietal sulcus, left inferior frontal gyrus and bilateral cingulated). The present study expands on these findings by including multiplication and division, and retrieval of basic facts as another level of complexity in the analyses.

The OT system (see Figs. 1 and 2) measures changes in the relative concentration of oxygenated and deoxygenated hemoglobin in particular areas of the cerebral cortex (Fig. 3). Increasing levels of oxygenated haemoglobin are associated with increased brain activity and task performance. In the field of neurosciences the phenomenon of task- or stimulus-induced changes in blood circulation is also known as "hemodynamic response". In this study, we considered the hemodynamic changes in the concentrations of oxygenated- and de-oxygenated-hemoglobin during the performance of arithmetic and reading comprehension tasks. Hemoglobin (Hb) refers to the oxygen-carrying pigment and predominant protein in the red blood cells. The data were analyzed for the presence or lack of oxygenation as the tasks were performed.

Figure 3 illustrates the basic brain lobes and provides a visual representation of the cortex. The cerebrum or cortex is the largest part of the human brain, associated with higher brain function such as thought, hearing, vision, vision, etc. The cerebral cortex is divided into four sections, called "lobes": the frontal lobe, parietal lobe, occipital lobe, and temporal lobe.

Although it is recognized that the brain works together as a whole, the four sections of the cerebral cortex are associated with specific functions:

- Frontal Lobe - Associated with reasoning, planning, parts of speech, emotions, working memory and problem solving
- Parietal Lobe - Associated with movement, orientation, recognition, perception of stimuli
- Occipital Lobe - Associated with visual processing
- Temporal Lobe - Associated with perception and recognition of auditory stimuli, memory, and speech ("Broca area")

Materials and Methods

This section provides information regarding the instruments, subjects, and other materials and methods used for this study. This study was exploratory in nature, and involved repeated measures to increase the validity and reliability of results.

The OT System ETG-4000. It was the main instrument used for assessing brain activity (Hitachi, 2004; Maki et al., 1995; Watanabe et al., 1996). It uses near-infrared light, a part of natural sunlight to investigate brain activity. The instrument illuminates the surface of the brain, or cerebral cortex with near-infrared light of different wavelengths, 695 nm and 830 nm. This light is low in intensity (4mW) to avoid heating effects. After penetrating the cerebral cortex through an emitting optical fiber (see Fig. 4), the light is absorbed by hemoglobin; the light with a wavelength of 695 nm by deoxy-hemoglobin and light with a wavelength of 830 nm by oxy-hemoglobin. Detector fiber guide the reflected near-infrared light to a photomultiplier and based on the degree of absorption – (low absorption = low hemoglobin concentration; high absorption = high hemoglobin concentration) – relative changes in oxy- and deoxyhemoglobin can be calculated. This does not only allow the observation of changes in the blood flow in the cerebral cortex but also the distinction between oxygen-carrying hemoglobin and hemoglobin which is depleted of oxygen. By monitoring changes in the blood flow, for example during mental processes the OT system can reveal the location in the cerebral cortex where these mental tasks or stimuli are being processed.

Subjects. Twelve healthy, right-and left-handed subjects (8 female and 4 males of ages of at least 18 years) participated in the study after giving written informed consent by the end of the spring 2008 semester. All subjects had completed at least 14 years of education (5 students were at junior year of their bachelor’s degree, 4 master’s degree, and 3 doctoral degree), and a background in teaching methods, and no difficulty calculating the exercises included in this study in the allotted time.

Participants from a university in a Florida metropolitan area had self selected their courses after enrolling in the bachelor’s or master’s education program. Participation in the study was announced in classes and the students provided consent or no consent to participate in the study. Procedures used in this study were approved by the IRB of the institution. A medical doctor prior to participation in the study interviewed participant, and they received approval to participate in the study by this doctor – a note was written for this purpose. Code numbers were used to identify the data collected from participants.

Experimental Design. In this study, we investigated the optical topography of evoked brain activity as participants performed accurate mental calculations at (one-digit addends or factors, and one- digit sums, or products). We included all three operations (addition, subtraction, and multiplication) with whole numbers, and one level of operational procedure complexity (basic facts). Solving the basic fact exercises should only require retrieval from memory directly (Campbell, & Austin, 2002; Dehaene, & Cohen, 1997; Kazui, Kitagaki, & Mori, 2000; Temple, 1991; & van Haskanp, & Cipolotti, 2001). Similar to Kong, Wang, Kwong, Vangel, Chua and Gollub (2005) and Ashcraft (1992), the difficulty level of these problems was such that subjects achieved a high accuracy rate for the study allowing the use of reaction time measures to estimate each operation difficulty. Addition and subtraction were considered to be naturally paired and relate (Piaget, 1997), as well as multiplication and division.

Instructions before the scanning session. Each task had had a 3-minute limit. Time was calculated by the scanning system and a beep at the start and another at the end served as indicator of starting and ending times. Participants used the Subject Response Booklet for the tests (Woodcock, McGrew, and Mather, 2001).

Scoring: 1 = Correct response**,** 0 = Incorrect response**.** I used the Math Fluency scoring guide to score the tests.

Early Finish: If subject finished test items in less than three minutes, I recorded exact finishing time in minutes and seconds on Test Record.

Sample Items:

Math: 1 + 0 = ?, 2 + 3 = ?, 6 – 2 = ?, 8 x 8 = ?, 7 x 0 = ?

Reading:

A.	A cow is an animal.	Y	N
B.	A fish lives on land.	Y	N
C.	An apple is blue.	Y	N
D.	The moon is in the sky.	Y	N

Design for the Study. After the practice exercises, participants had 3 minutes to solve as many exercises as possible for each task with 20 seconds resting periods between tasks.

Experiment:

Waiting time: 10 seconds.

Math Task: 3 minutes. Resting time 1: 20 seconds

Reading Task: 3 minutes. Resting time 2: 20 seconds

The same format was used for the practice and scanning sessions. Items were given on a piece of paper, and each answer was written on them. Participants were expected to solve each item separately trying to further ensure that they actually calculated the problem instead of judging the correctness of given answers (like multiple choice items) using different strategies (Campbell & Austin, 2002). No feedback was given as to the correctness of the answers during scanning sessions. If participants granted consent for video recoding, the scanning sessions were video recorded.

Before scanning, all subjects were required to practice the task until they were confident about the procedure and their ability to perform calculations. They were told that during the scan, all their responses needed to be recorded.

OP Data Acquisition. All brain imaging were performed with the OT system *ETG-4000* (CBCNews, 2007; Hitachi, 2004). During measurement, the optical fibers were placed on the scalp over the brain area to be monitored (around the frontal lobe, see Fig. 1). Near- infrared light was emitted through emitter fibers and reflected light was collected by detector fibers (see Fig. 4). A lock-in amplifier evaluated the changes in oxygen levels and the result was displayed on a computer screen. This device was tested for safety within FDA guidelines. At the conclusion of the scanning session, the optical fibers were removed.

Data Analysis

This section of the article provides details regarding the analysis of the data collected during this study. Relative changes in the absorption of near –infrared light were converted into changes in hemoglobin concentrations and visualized on the system monitor by the system software applying the modified Beer-Lambert law (Delpy et al., 1988).

Hemodynamic (forces involved in the circulation of blood) changes (in the concentrations of oxygenated- and de-oxygenated-hemoglobin) during the performance of arithmetic and reading tasks were studied. Hemoglobin (Hb) refers to the oxygen-carrying pigment and predominant protein in the red blood cells. Almost all participants showed strong activation (increasing oxygenated-Hb concentrations) in the frontal lobe. Individual data of all participants were examined to see whether differences between participants could be detected. Figure 5 shows the standardized 2D-maps of all participants, with participant C007 showing the strongest signals and participants B018 (task A) and C010 task B) the weakest signals. The same 2D-maps are shown projected onto a model wire-frame head (Figure 6). The examination of the individual maps does not show distinct differences in the activation pattern for the mathematical or the verbal task. Differences between the two tasks are only visible in the group analysis (Figs. 8 and Fig. 9), showing stronger signals in the male group than for the female group in both tasks and the signals for the mathematical task appear stronger than for the verbal task. On the individual base, this tendency is less distinct. Comparison of the waveforms of the male and the female group again shows stronger signals in the male group for both tasks (Fig. 7). Figure 8 depicts the same result but in standardized 2D maps and Figure 9 shows the projection of these 2D maps onto a model wire-frame head. Differences in the magnitude of the activation varied from participant to participant and might be explained with personal preferences.

Conclusions

The mathematical task primarily leads to the activation of the left parietal area. However, some participants also show activity in the frontal lobe, which may be due to particular math problems (memory), or increased (intellectual) demand. Group analysis (male vs. female) indicated a higher signal intensity in the male group which could point towards male participants having more difficulties than female participants. However, this assumption is based on only 4 male data sets and future experiments with more participants has to confirm these preliminary results. Differences in terms of students' mental strategies, background and like or dislike of mathematics or reading need to be studied with larger samples.

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Figure 1. Helmet type brain-scanning portion of the Optical Topography system

Figure 2. Computer portion of the Optical Topography system

Figure 3. Basic brain lobes and visual representation of the cortex

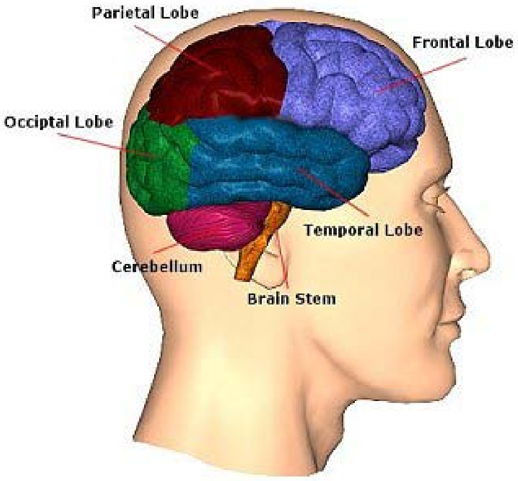

Figure 4. Near-infrared light penetrates the cerebral cortex through an emitting optical fiber and the detector fiber guides the reflected near-infrared light to a photomultiplier

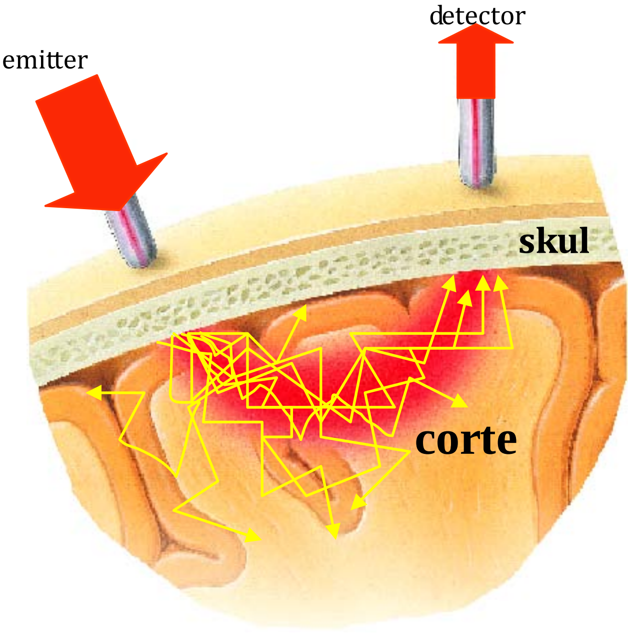

Figure 5.

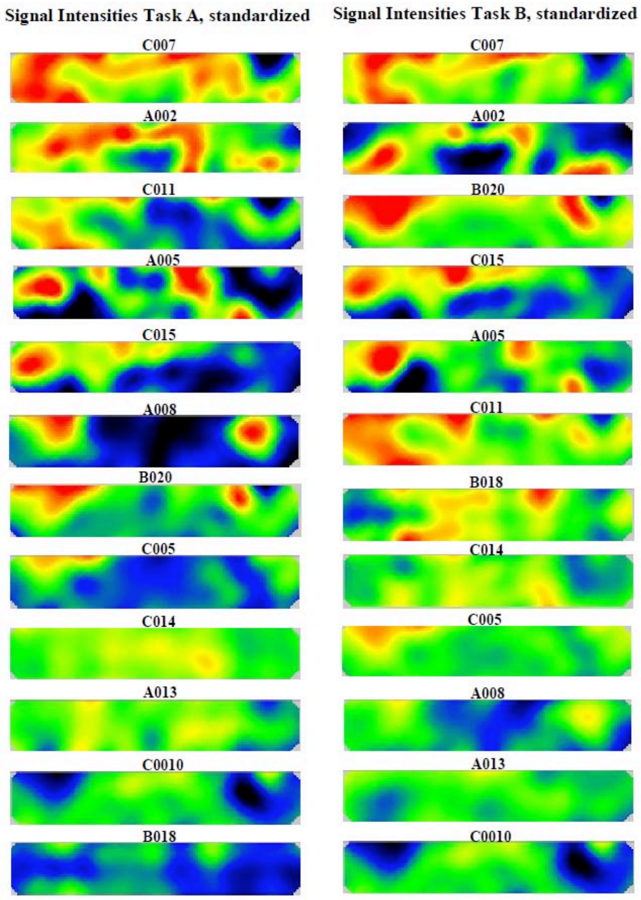

Figure 6.

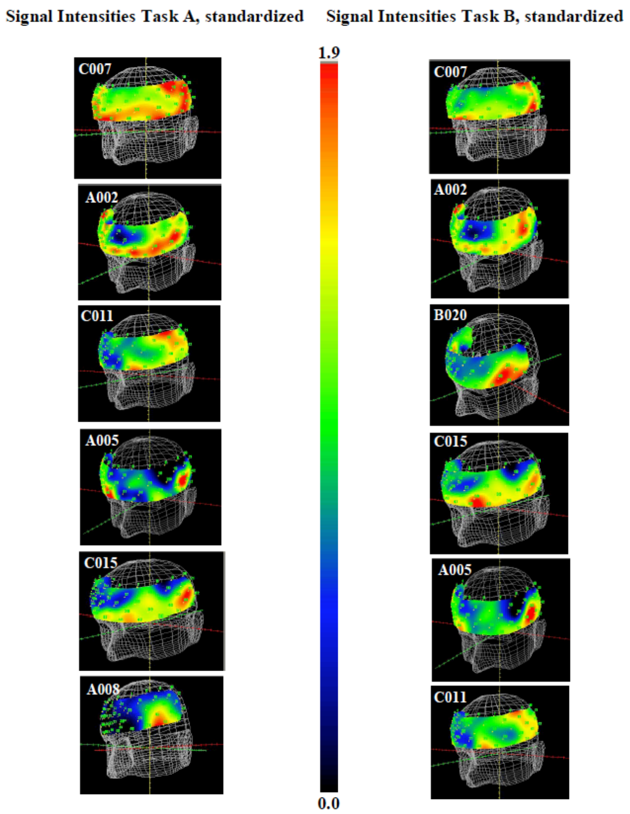

Figure 6 Continued.

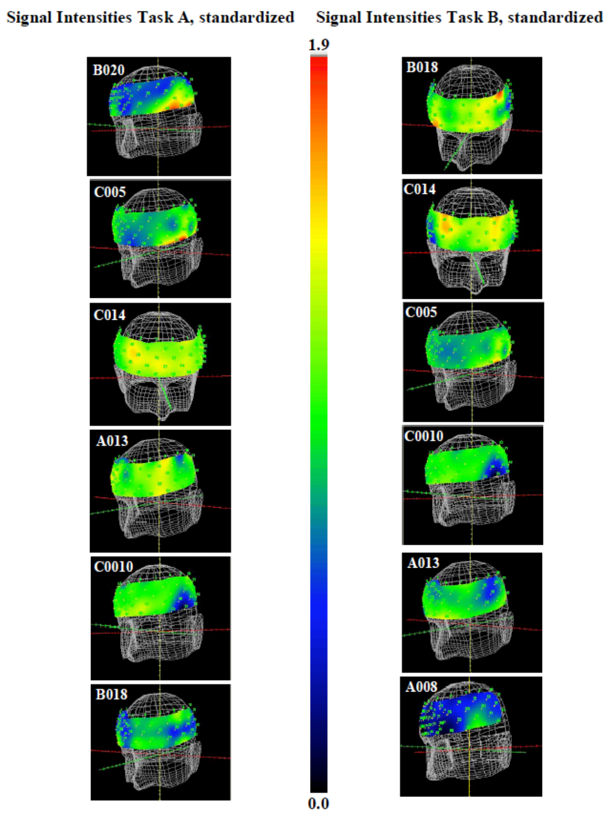

Figure 7.

Figure 8.

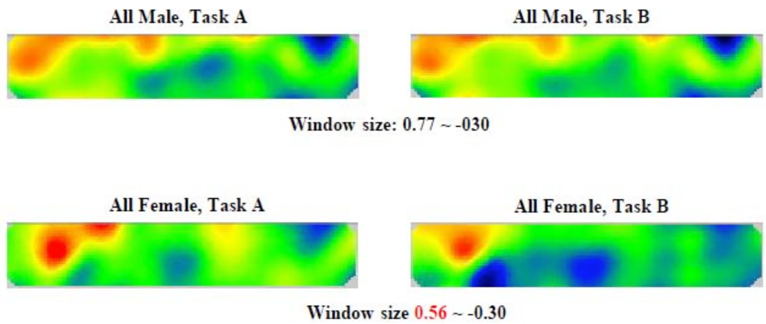

Figure 9.