

Use of Neuroimaging to Clarify How Human Brains Perform Mental Calculations

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Abstract

The purpose of this study was to analyze participants' levels of hemoglobin as they performed arithmetic mental calculations using Optical Topography (OT, helmet type brain-scanning system, also known as Functional Near-Infrared Spectroscopy or fNIRS). A central issue in cognitive neuroscience involves the study of how the human brain encodes and manipulates information, including mental calculation. Recently, functional neuro-imaging studies have begun to clarify how the human brain performs mental calculations. fNIRS is an imaging technique capable of measuring changes in the relative concentration of hemoglobin in the cerebral cortex of the brain (Hoshi & Tamura, 1993; Villringer et al., 1993; Koizumi et al., 2003). It is well known that 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). By illumination the surface of the brain with near-infrared light of two specific wavelengths (695 nm for deoxy- and 830 nm for the oxygen-carrying oxyhemoglobin) changes in the concentrations of oxy- and deoxyhemoglobin can be monitored and allow conclusions about the energy consumption, or activation of the brain region during the performance of cognitive tasks. Twelve undergraduate and graduate college-level students participated in scanning session. Differences in brain activity were found based on mental calculation strategies. There were three different levels of oxy-hemoglobin: low, moderate, and high. The levels of activity were related to participants' mental strategies as they solve the exercises. Students who used more rote memorization tended to show moderate to low hemoglobin oxygenation. These results may have implications for how important rote memorization of arithmetic facts might be. Other results and possible implications are discussed in this article. (Contains 6 tables, and 22 graphs)

Keywords: cognitive neuroscience, mathematics, mental calculations, 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. One important component related to this issue is mental calculation, which involves logical thought and higher order cognition, and provides a good model to investigate fundamental cognitive processes. For several decades, an active field of investigation related to cognitive processes dealing with numbers and arithmetic is mental or cognitive arithmetic (Ashcraft, 1992).

Functionally, we have three distinct specified processes involved in any situation involving accurate mental calculation (Kong, Wang, Kwong, Vangel, Chua & Gollub, 2004). They are the following:

- execution of a calculation operation as can be represented by an arithmetic symbol (+, −, • or ÷),
- execution of supporting arithmetic operation procedures (e.g. carrying, renaming or borrowing during addition, subtraction, multiplication or division computation), and
- retrieval of arithmetic facts from memory (one digit addends with one- or two-digit sums: $3 + 5$ or $9 + 8$) (McCarthy, & Warrington, 1987; McCarthy, & Warrington, 1990; van Haskamp, & Cipolotti, 2001).

Kong, Wang, Kwong, Vangel, Chua and Gollub also indicated that clinical reports of selective deficits in one of these three areas suggest that they may be accompanied by relatively independent and separate subsystems. For example, case studies involving patients who cannot identify arithmetic symbols but can correctly perform the wrong operation.

Recently, functional neuroimaging studies have begun to clarify how the human brain performs the everyday activities that require mental calculation (Kazui et al., 2000; Davis et al., 2009; Dresler et al., 2009; for review: 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 arithmetic operations (addition, subtraction, multiplication and division) with whole numbers, and processes that support more complex calculations (basic facts, computation without renaming and computation with renaming). 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. A previous study (Kong, Wang, Kwong, Vangel, Chua and Gollub (2004) carried out a similar 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/cingulate 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 cingulate). 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 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. Eleven healthy, right-and left-handed subjects (8 female and 3 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 (4 students were at junior year of their bachelor's degree, 5 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- or two-digit addends or factors, and one- or two digit sums, or products). We included all four operations (addition, subtraction, multiplication and division) 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 Haskamp, & 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. We included all four operations in order to have a complete view of the different neural substrate of arithmetic operations and procedure complexity. Addition and subtraction were considered to be naturally paired and relate (Piaget, 1997), as well as multiplication and division.

Instructions before the scanning session. Students were told the following: "Try to avoid sudden movements of the head, hands, and body during the scanning session. There will be an initial

waiting period (10 seconds) before the start of the tasks. When a task is completed look up and focus on the predetermine spot in front of you (black dot printed at the center of a white paper). Try to relax while you wait during resting periods. No talking during the scanning session. You will use a pencil or pen to write the answers to exercises, but solve them using only mental calculations during the tasks. Try to solve as many problems as possible, and as quickly as possible. You might not be able to solve all the problems in the given amount of time, and that is okay. We just want to record using the system what areas of you brain are activated when you solve the exercises. Work in order starting with the top number on the left column added to each number on the top row (from left to right). Please do not skip ahead. The same will be done for subtraction, multiplication and division. For example, add the number on the right to the number on the top of the grid (see Table 1). The division task format is a bit different from the other operations because you need to divide the number on your left by the number on the top (see Table 2).”

Table 1. Example given to students for addition prior to experimental tasks

+	2	0	1	3
4				
2				
3				

Table 2. Example given to students for division prior to experimental tasks

÷	2
4	
12	
30	
16	

Table 3 present the items used for the first addition task. The participants answered as many items as possible by writing the answer on the respective spaces. A similar arrangement was used for subtraction and multiplication. Table 4 presents the items used for the first division task. In addition, our choice of calculation exercises to be included in this study attempted to control for the size effect, a common finding indicates that the difficulty of simple arithmetic problems increases with numerical size of the operands (Ashcraft, 1992) by choosing the same or similar first and second operands for computation exercises with or without renaming for addition and subtraction or multiplication and division combinations.

Table 3. Addition items for mental calculations (From A1)

+	3	5	7	4	6	8
4						
6						
8						
35						
46						
52						
63						

Table 4. Division items for mental calculations (Form D1)

÷	3	÷	5	÷	7	÷	4	÷	6	÷	8
24		45		49		24		66		72	
27		35		42		36		36		32	
12		40		35		32		18		8	
39		30		63		28		42		40	
63		20		14		16		48		24	
18		25		28		12		24		64	
36		15		56		20		54		56	

Design for the Study. After the practice exercises, participants had 30 seconds to solve as many exercises as possible in 30 seconds for each task, and 20 seconds resting periods between tasks. Experiment 1 involved addition and subtraction, and experiment 2 multiplication and division (see Tables 5 and 6).

Table 5. Experiment 1 involved addition and subtraction, and the following steps (for a duration of 300 seconds = 5 minutes)

Waiting time: 10 seconds		
Task A1:	Addition: 30 seconds	Resting Period 1: 20 seconds
Task B1:	Subtraction: 30 seconds	Resting Period 2: 20 seconds
Task A2:	Addition: 30 seconds	Resting Period 3: 20 seconds
Task B2:	Subtraction: 30 seconds	Resting Period 4: 20 seconds
Task A3:	Addition: 30 seconds	Resting Period 5: 20 seconds
Task B3:	Subtraction: 30 seconds	Resting Period 6: 10 seconds

Table 6. Experiment 2 involved multiplication and division, and the following steps (for a duration of 300 seconds = 5 minutes)

Waiting time: 10 seconds		
Task C1:	Multiplication: 30 seconds	Resting Period 1: 20 seconds
Task D1:	Division: 30 seconds	Resting Period 2: 20 seconds
Task C2:	Multiplication: 30 seconds	Resting Period 3: 20 seconds
Task D2:	Division: 30 seconds	Resting Period 4: 20 seconds
Task C3:	Multiplication: 30 seconds	Resting Period 5: 20 seconds
Task D3:	Division: 30 seconds	Resting Period 6: 10 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 a chart. 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 recording, 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. 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).

A general impression analysis was performed prior to the more specific analyses. The data was first analyzed using standard procedures provided by the instrument itself; no additional external analysis software was used.

General impression analysis. First examinations of the data showed specific reactions in the expected areas. Movement during the scanning session can lead to false positive signals or artifacts. To identify possible movement artifacts all sessions were monitored with a video camera. This video camera was directly connected and controlled by the OT-system, thus ensuring the synchronization of data recording with the recording of video footage. Unfortunately, we had to exclude the data from one of the participants (number 008). She tended to vigorously bend her head to her left side. This participant showed strong head movement when she was getting ready to execute the task. This head movement led to a general increase in blood volume in the left hemisphere, as shown in the Hemoglobin (Hb) mapping provided by the OT system. Data from this participant was not included in the analysis. The data from the remaining subjects were clear and suitable for analysis. We were able to include data from a total of 11 participants out 12 participants.

Analysis Methods. Each task (addition, subtraction, multiplication, division) was repeated

five times and data were initially analyzed in the “integral” mode. In the integral mode the data from all repetitions for each task are averaged in order to improve data quality and confidence. As expected, cerebral activation was found in the frontal lobe and in the inferior parietal areas in both hemispheres; after consulting several publications on the effect of solving mathematical problems on brain activity (Castelli, Fulvia, Glaser, Daniel E., & Butterworth, Brian, 2006; Dehaene, S., & Cohen, L., 1997; Kazui, H., Kitagaki, H. & Mori, E., 2000), we paid attention to the inferior parietal area and an area called the “perisylvian region”. This area was covered by the 3 by 11 probe configuration of the scanning system that we used for this study (see Fig. 1), but for future experiments the dual 4 by 4 configuration seems more appropriate.

When looking at the data in the “*integral*” mode for each one of the tasks, only weak signals could be detected. This was mainly due to the high signal intensity in the frontal lobe; when adjusting the signal intensity to the relatively low activity in the parietal area, the signals from the frontal lobes started covering the entire frontal area without discriminating between different activation “hotspots”.

We therefore decided to analyze the data in the “*continuous*” mode (without averaging over a certain number of identical tasks) from left (L) to right (R), and looked closer at the inferior parietal areas and indeed found strong signals in these areas. This mode of the OT system provides a display of the data that comes from combining the data from the different probes into a linear or continuous manner, as well as combining data from the different tasks within an operation: tasks A1, A2 and A3 for addition; tasks B1, B2 and B3 for subtraction; tasks C1, C2 and C3 for multiplication; and tasks D1, D2 and D3 for division. In these OT the mapping, the red color represents oxygenated-Hb, the blue color represents deoxygenated-Hb, and the green color represents total Hb. In the continuous mode, it was also possible to better compare frontal and parietal areas. Figures 5 – 8 provide examples of this type of data display from four participants: one with low levels of oxygenated-Hemoglobin (Hb), two with moderate levels of oxygenated-Hb, and one with high levels of oxygenated-Hb. Similarly, Figures 9 and 10 illustrate the 2D-mapped and integrated hemodynamic changes during the performance of the mental for the eleven participants.

As to the location where the brain processes mathematical problems, the general assumption is that those problems are predominantly solved in the left hemisphere, particularly the inferior parietal area and the intraparietal sulcus (Castelli, Glaser, Butterworth, 2006). Nevertheless, differences between musicians (higher activity in the left hemisphere) and non-musicians (activation in both hemispheres) have been reported (Schmithorst & Holland, 2004), but also the personal characteristics such as handedness, sex, and musical education, may play a very important role and should be considered in the analysis of the data.

Almost all participants showed strong activation (increasing oxygenated-hemoglobin concentrations indicated by the red regions) in the frontal lobe, except for the participants 003, 006 and 012. Participant 003 displayed increasing oxygenated-hemoglobin concentrations only in the right inferior prefrontal/temporal area during all four tasks. The laterality of the cerebral activation could be attributed to the fact that this particular participant is left-handed, whereas all remaining

participants are right-handed. Participant 006 showed only weak activation of the frontal lobe during the tasks B and D; besides the activation of the left inferior prefrontal/temporal area, participant 013 shows activation in the upper frontal region during the tasks A and C. Except for participant 004 all right-handed participants showed a more or less significant increase in oxygenated-hemoglobin in the left hemisphere. Participant 004 is the only participant who shows no lateral activation at all, only a strong activation in the frontal cortex.

Further examination of the fNIRS-data revealed remarkable differences between participants 005 and 009, and participants 003, 012 and to some extent 004. It is remarkable that participants 003 and 012 showed no or only weak activation (increasing oxygenated-hemoglobin concentrations) in the frontal cortex whereas participant 004 shows activation only in the frontal lobe. Participants 005 and 009 display well defined activation in the frontal cortex, reaching to the temporal/parietal area. Participant 003 however showed localized activation in the temporal/parietal cortex regardless of the complexity of the task. It should be noted that participant 003 showed activation exclusively in the right hemisphere, which could be attributed to her being left-handed. All the other participants are right-handed and consequently show major activation in the left hemisphere of their brains.

So far, only positive changes in oxygenated-hemoglobin (increases) were considered in the analysis, but a close look at the “Hb-mapped” data revealed significant decreases in oxygenated-Hb (Fig. 9), accompanied by simultaneous increases of deoxygenated-Hb concentrations in almost all participants (Fig. 10). Only the participants 003 and 009 displayed no changes in deoxygenated-Hb concentrations across the entire measurement area.

When looking closer at the changes in oxygenated-and deoxygenated-Hb in the left temporal/parietal cortex of participant 001 (channel 30; A-task: addition), as shown in Figure 11, it becomes obvious that the concentrations of oxygenated- and deoxygenated-Hb change in opposite directions; the significant increase in deoxygenated-Hb is accompanied by a decrease in oxygenated-Hb. Both concentrations follow an opposite pattern for approximately 7 sec before they change their direction; the deoxygenated-Hb concentration suddenly decreases dramatically while the oxygenated-Hb concentration increases (Fig. 11, participant 001). A possible explanation could be that the task is so demanding for that the consumption of oxygen is faster than the replenishment. Once the participant’s metabolism seems to have adjusted to the increased demand for oxygen, more oxygenated-Hb is supplied leading to a steady increase of oxygenated-Hb and a simultaneous decrease in deoxygenated-Hb.

However, hemodynamic changes in the inferior prefrontal/temporal area have to be interpreted with caution. All tasks had been written tasks and consequently involved a certain degree of movement activating the motor area. The activation of the primary motor area and the task-specific activation in the prefrontal lobe may partially overlap and lead to false results.

In the next step, we looked closer at the integrated “Hb mapping” data, which proved to be quite interesting (see Figs. 12–16). As mentioned above, the closer inspection of the “Hb-mapped” data (oxy-, deoxygenated- and total hemoglobin) revealed that most of the participants showed more or

less significant increases of deoxygenated-Hb in the inferior prefrontal/temporal area. The increasing concentrations of deoxygenated-Hb were almost always accompanied by a decrease in oxygenated-hemoglobin (see Fig. 11). Both concentrations followed an opposite pattern for several seconds, with deoxygenated-Hb lagging a few seconds behind, before they change direction again; the oxygenated-Hb concentration started to increase and a few seconds later the deoxygenated-Hb concentration started to decrease (there were not enough data available to make any conclusions concerning the time lag between deoxygenated- and oxygenated-Hb).

Participant 003 displayed the expected reaction to the different tasks, an increase in oxygenated-Hb and total Hb (Fig. 12A) and, at the same time a decrease in deoxygenated-Hb (Fig. 12B). Participant 004 (Fig. 13) shows activation of the frontal lobe (channels 36, 37, and 46-48), but also a significant drop in oxygenated-Hb in both temporal/parietal lobes (right: channels 22, 23, 33, 34, 43, and 44; left: channels 29, 30, 39, 40, 50, and 51). Participant 012 shows only weak increases in oxygenated-Hb in the frontal lobe during the more demanding tasks C (multiplication) and D (Division) (Fig. 14). Similar to participant 004, participant 012 too shows a drop in oxygenated-Hb concentration, mainly in the right temporal/parietal region (channels 11, 12, 22, 23 and 34). However, the drop in oxygenated-Hb appears only in task B (Subtraction) and is not visible in the tasks A, C and D. The participant 005 (Fig. 15) displays a strong decrease in oxygenated-Hb during the tasks A (Addition) and B (Subtraction) in the right temporal/parietal lobe (channels 22, 23, 33, 34 and 43 - 45) and to a lesser extent in the left hemisphere (channels 30, 40 - 42, 50 and 51). The other control, participant 009 (Fig. 16) only shows increasing oxyhemoglobin concentrations but no decrease of oxygenated-Hb at all.

In the final step, our analysis focused on possible changes in the deoxygenated-Hb concentration. The magnitude of the changes ranged from “significant” (participants 001, 006, 011 and 012) to “none” (participants 003, 009 and 010) (see Figs. 17 and 18). Participant 003 showed no changes in the concentration of deoxygenated-hemoglobin during all four tasks. The participants 001, 004, 005 and 013 showed significant increases in deoxygenated-hemoglobin in the temporal/parietal lobes in both hemispheres of the brain (Figs. 19 and 20).

General findings. Regardless the task, all participants showed activation in the expected areas, the left and right frontal lobes as well as the inferior parietal areas of both hemispheres, with some variation in the intensity of the activation signal. In accordance with previously published results, most of the subjects show a stronger activation in the left hemisphere, with subjects 001 and 004 being the exception. In general, a higher degree of variation could be observed in the frontal lobe, around channels 38, 48, 49 (left side) and 36, 46, 47. Similar to the parietal areas a shift towards one side in the frontal lobe or the other was observed and increased frontal activity was always found on the same side where the stronger parietal activation was detected. These results give a clear indication of the specificity of the task-related brain activation as well as a subject-dependent preference of either the right or the left hemisphere. So far, the different tasks (addition, subtraction, multiplication and division) have not yet been considered in the present data analysis.

Although no differences in the activation of the inferior parietal area could be observed, a certain tendency in the frontal lobe towards diminishing activation when switching from easier (addition, subtraction) to more difficult tasks (multiplication, division) seems to develop (exception subject 007). An explanation for this phenomenon could be that easier mathematical tasks are rather solved searching “memory” areas in the frontal lobe for the correct answer than performing actual calculations (Ischebeck et al., 2006). This theory could be further substantiated by confronting the subjects with more complex tasks; rather “ $341 + 1092$ ” than “ $12 + 5$ ” or rather “ 111×17 ” than “ 3×4 ”, which is in good accordance with previous results (Kwong et al., 2005).

It was remarkable that the increase in deoxygenated-Hb was bilateral with no clear indication of the handedness of the particular participant and that no changes in the frontal lobe were detected. However, the location of increasing deoxygenated-Hb concentration was found to be very consistent, always in an area defined by the measurement channels 13, 23, 24 and 34 (right hemisphere) and the measurement channels 29, 30, 40, 41, 50 and 51 (left hemisphere; Fig. 21). An exception is participant 005 who showed only lateral increases in deoxygenated-hemoglobin during task B; during the tasks C and D a distinct increase of deoxygenated-Hb in the frontal area, around the channels 46 and 47 was observed (Fig. 17). However, a closer look at the “Hb-mapped” data showed the simultaneous increase of both the oxy- and deoxygenated-hemoglobin (Fig. 14), which might indicate a motion artifact. Though no motion artifacts could be seen on the video recordings taken during the performance of the tasks C (Multiplication) and D (Division), these findings should be regarded cautiously until they can be reproduced.

Another interesting observation is the possible difference between male and female participants. It seems that the 3 male subjects in this study barely involve their frontal lobes, regardless the difficulty of the task. Only subject 006 shows some distinct frontal activation during the more difficult tasks. However, the population size of the male group is far too small to support any gender-specific interpretation of the observation. Nevertheless, it is worth further investigating this phenomenon with a larger group of male participants.

Considering the relatively small number of participants, the study provided clear evidence for the task-specific activation of the frontal lobe as well as the inferior prefrontal cortex. Increasing oxygenated-Hb concentrations have been observed in both hemisphere, though a shift to the left hemisphere (right-handed participants) seems obvious, which is in accordance with previous reports by Yun-ting, Z., Quan, Z., Jing, Z., Wei, L. (2005). There were also some indications that the handedness and personal relationship with mathematics (“like” or “dislike”) might influence the task-specific activation of the cortex. In order to answer these questions, a larger number of adequate participants should be involved in future studies.

However, no clear differences based on the complexity from one operation to another could be observed. One would expect to see increasing activation with increasing complexity, from “Plus/Minus” to “Multiplication” and “Division”. The activation pattern (oxygenated-hemoglobin) in participant 001 followed this pattern, but participant 006 however showed the least activation during

task C (Multiplication). Does this mean the participant feels more comfortable with multiplication than with addition or division? This question can only be answered by investigating a larger number of participants and by taking their personal preferences into account; what does he or she like best, does the participant enjoy playing with mathematical problems?

When looking at the deoxygenated-Hb data it was surprising to see no changes in deoxygenated-Hb concentrations in the frontal lobe, but almost all participants showed distinct activation (“activation” = “oxygen consumption” = “increase in deoxygenated-Hb”) in the inferior prefrontal cortex. Differences in the magnitude (Fig. 18) of the activation varied from participant to participant and might be explained with personal preferences (note that participant 006 again showed the least activation during task C!).

References

- Ashcraft, M.H. (1992). “Cognitive arithmetic: A review of data and theory.” *Cognition* **44**, 75–106.
- Campbell, J.I., & Austin, S. (2002). “Effects of response time deadlines on adults’ strategy choices for simple addition.” *Memory Cognition*, **30**, 988–994.
- Castelli, Fulvia, Glaser, Daniel E., & Butterworth, Brian (2006). “Discrete and analogue quantity processing in the parietal lobe: A functional MRI study”. Proceedings of the National Academy of Sciences U S A. Mar 14, 2006. Retrieved November 11, 2008 from <http://en.scientificcommons.org/17427692>
- Hitachi (2007). “Hitachi demonstrates brain-machine interface.” Retrieved December 23, 2007 from CBSNews <http://www.cbc.ca/technology/story/2007/06/22/tech-brain-machine.html>.
- Delpy DT, Cope M, van der Zee P, Arridge SR, Wray SC, Wyatt JS (1988). “Estimation of optical pathlength through tissue from direct time of flight measurement.” *Phys. Med. Biol.* **33**, 1433-1442
- Davis N, Cannistraci CJ, Rogers BP, Gatenby JC, Fuchs LS, Anderson AW, Gore JC (2009). “The neural correlates of calculation ability in children: an fMRI study.” *Magn. Reson. Imaging* **9**, 1187-97
- Dresler T, Obersteiner A, Schecklmann M, Vogel AC, Ehli AC, Richter MM, Plichta MM, Reiss K, Pekrun R, Fallgatter AJ (2009). “Arithmetic tasks in different formats and their influence on behavior and brain oxygenation as assessed with near-infrared spectroscopy (NIRS): a study involving primary and secondary school children.” *J. Neural Transm.* **116**(12), 1689-700
- Dehaene, S., & Cohen, L. (1997). “Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic.” *Cortex*, **33**, 219–250.
- Hitachi Company (2004). “Optical Topography System.” Retrieved December 20, 2007 from <http://www.hitachimed.com/contentindex.asp?ID=221>.

- Hoshi Y and Tamura M (1993). "Detection of dynamic changes in cerebral oxygenation coupled to neural function during mental work in man." *Neurosci. Letters* **150**, 5-8.
- Kazui, H., Kitagaki, H. & Mori, E. (2000). "Cortical activation during retrieval of arithmetical facts and actual calculation: A functional magnetic resonance imaging study." *Psychiatry Clinical Neuroscience*, *54*, 479-485.
- Koizumi H, Yamamoto T, Maki A, Yamashita Y, Sato H, Kawaguchi H, Ichikawa N (2003). "Optical Topography: practical problems and new applications." *Appl. Opt.* **42**, 3045-3062
- Maki A, Yamashita Y, Ito Y, Watanabe E, Mayanagi Y, Koizumi H (1995). "Spatial and temporal analysis of human motor activity using non-invasive NIR topography." *Medical Physics* **22**, 1997-2005
- McCarthy, R.A., & Warrington, E. (1987). "Cognitive mechanism in normal and impaired number processing. In Deloche, G., and Seron, X. (Eds.), *Mathematical Disabilities: Cognitive Neuropsychological Perspective*." Hillsdale: Lawrence Erlbaum Associates, pp. 201-219.
- McCarthy, R.A., and Warrington, E. (1990). Calculation. In McCarthy, R.A., and Warrington, E., *Cognitive Neuropsychology: A Clinical Introduction*. New York: Academic Press, pp. 262-274.
- Piaget, J. (1997). *The child's cognition of number*. New York: Routledge (175-202).
- Schmithorst, Vincent J., Holland, Scott K. & Elena Plante (2006). "Cognitive modules utilized for narrative comprehension in children: a functional magnetic resonance imaging study." *NeuroImage* **29** (1), 254-266.
- Strangman G, Boas DA, Sutton JP (2002). "Non-invasive neuroimaging using near-infrared light." *Biol. Psychiatry* **52**, 679-893.
- Temple, C. (1991). "Procedural dyscalculia and number fact dyscalculia." *Cognitive Neuropsychology*, *8*, 355-376.
- van Haskamp, N.J., & Cipolotti, L. (2001). "Selective impairments for addition, subtraction and multiplication. Implications for the organization of arithmetical facts. *Cortex*, **37**, 363-388.
- Villringer A, Planck J, Hock C, Schleinkofer L, Dirnagle U (1993). "Near infrared spectroscopy (NIRS): a new tool to study haemodynamic changes during activation of brain function in human adults." *Neurosci. Lett.* **154**, 101-104.
- Watanabe E, Yamashita Y, Maki A, Ito Y, Koizumi H (1996). "Non-invasive functional mapping with multi-channel near-infrared spectroscopic topography in humans." *Neuroscience Letters* **256**, 49-52.
- Yun-ting, Z., Quan, Z., Jing, Z., Wei, L., 2005. Laterality of brain areas associated with arithmetic calculations revealed by functional magnetic resonance imaging. *Chin. Med. J.* *118*, 633-38.

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

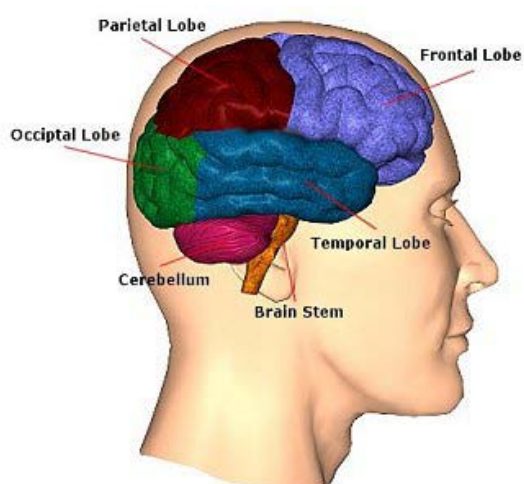


Figure 4. Near-infrared light penetrates the cerebral cortex through an emitting optical fiber and the detector fiber guides the reflected near-infrared light to a photomultiplier

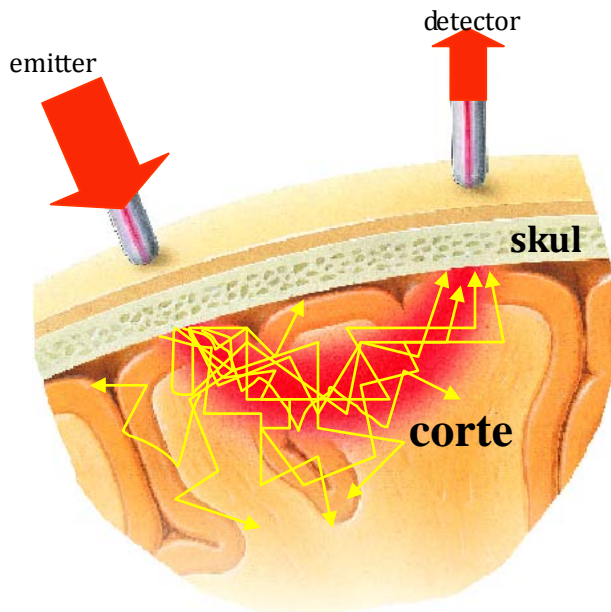
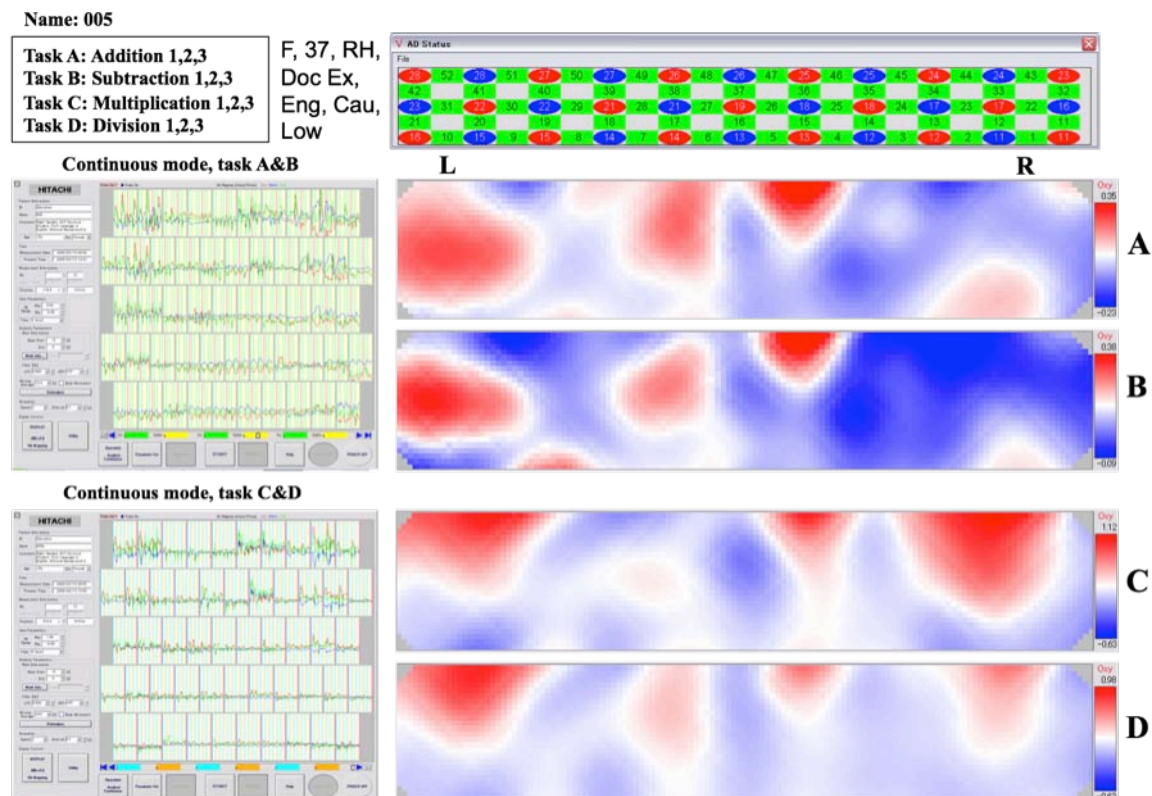
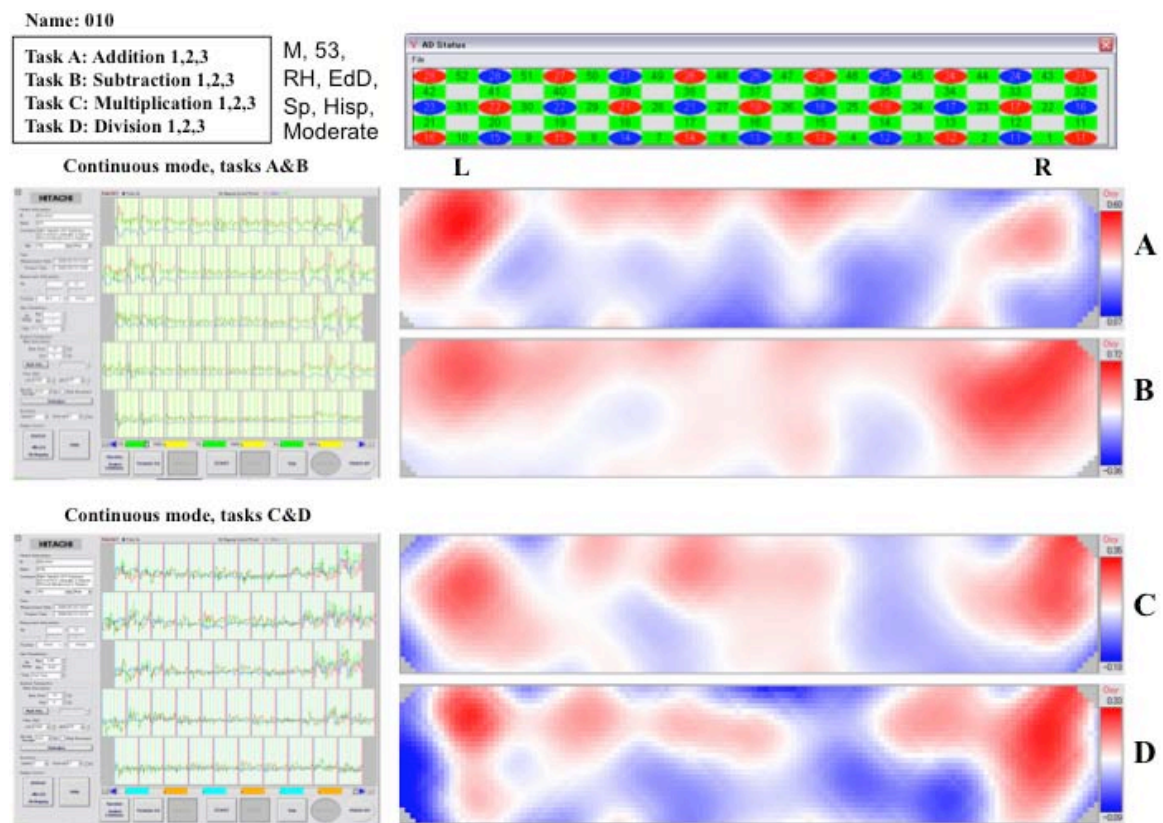


Figure 5. Continuous mode mapping from Participant 005



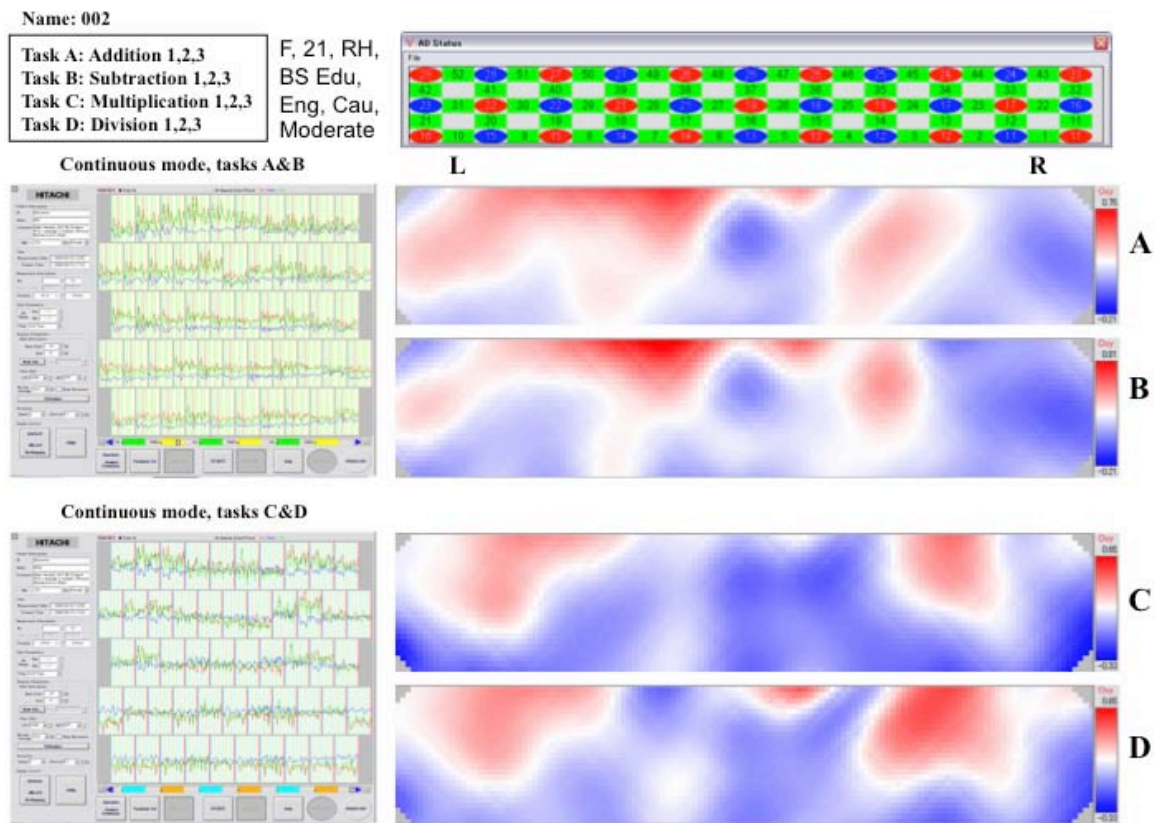
Note: Female, 37 years of age, right handed, doctoral student, English first language, Caucasian, low levels of oxygenated-Hb

Figure 6. Continuous mode mapping from Participant 010



Note: Male, 53 years of age, right handed, doctoral student, Spanish first language, Hispanic, moderate levels of oxygenated-Hb

Figure 7. Continuous mode mapping from Participant 002



Note: Female, 21 years of age, right handed, bachelor's degree student, English first language, Caucasian, moderate levels of oxygenated-Hb

Figure 8. Continuous mode mapping from Participant 011

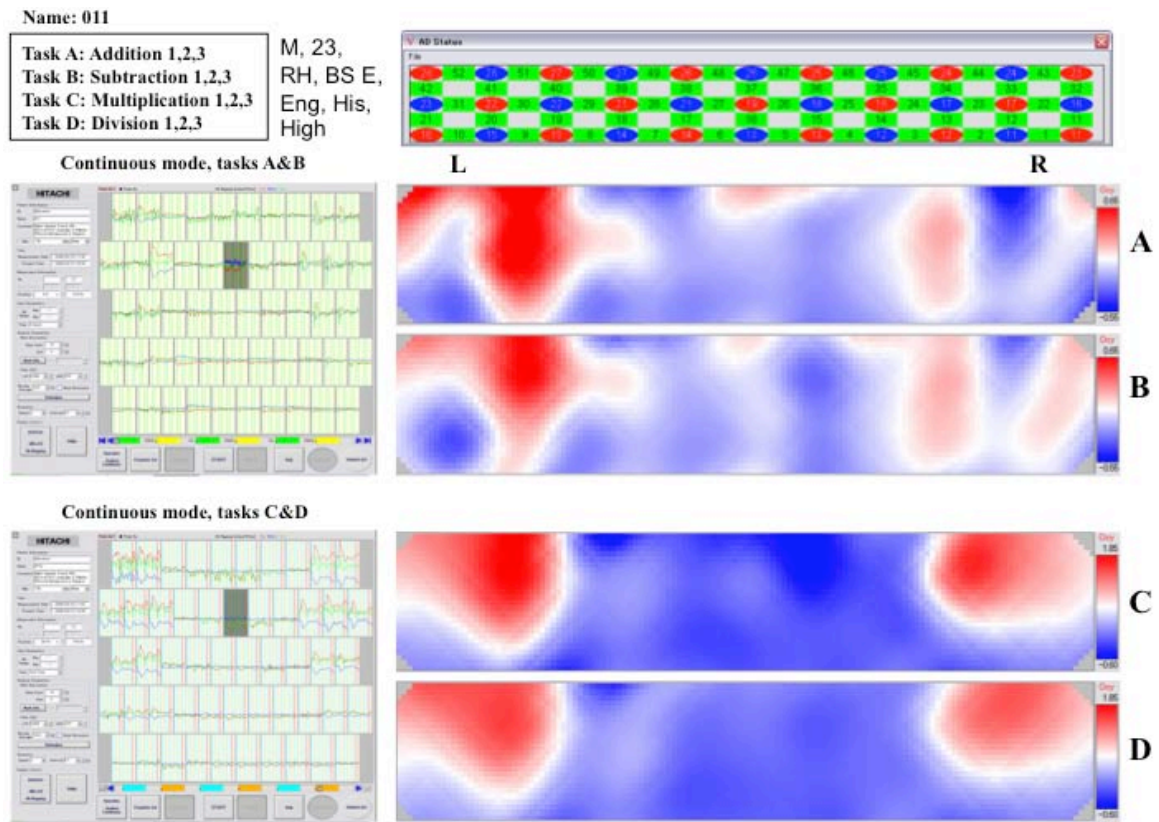


Figure 9. 2D-mapped and integrated hemodynamic changes during the performance of the mental tasks A – D for Participants 1 – 6

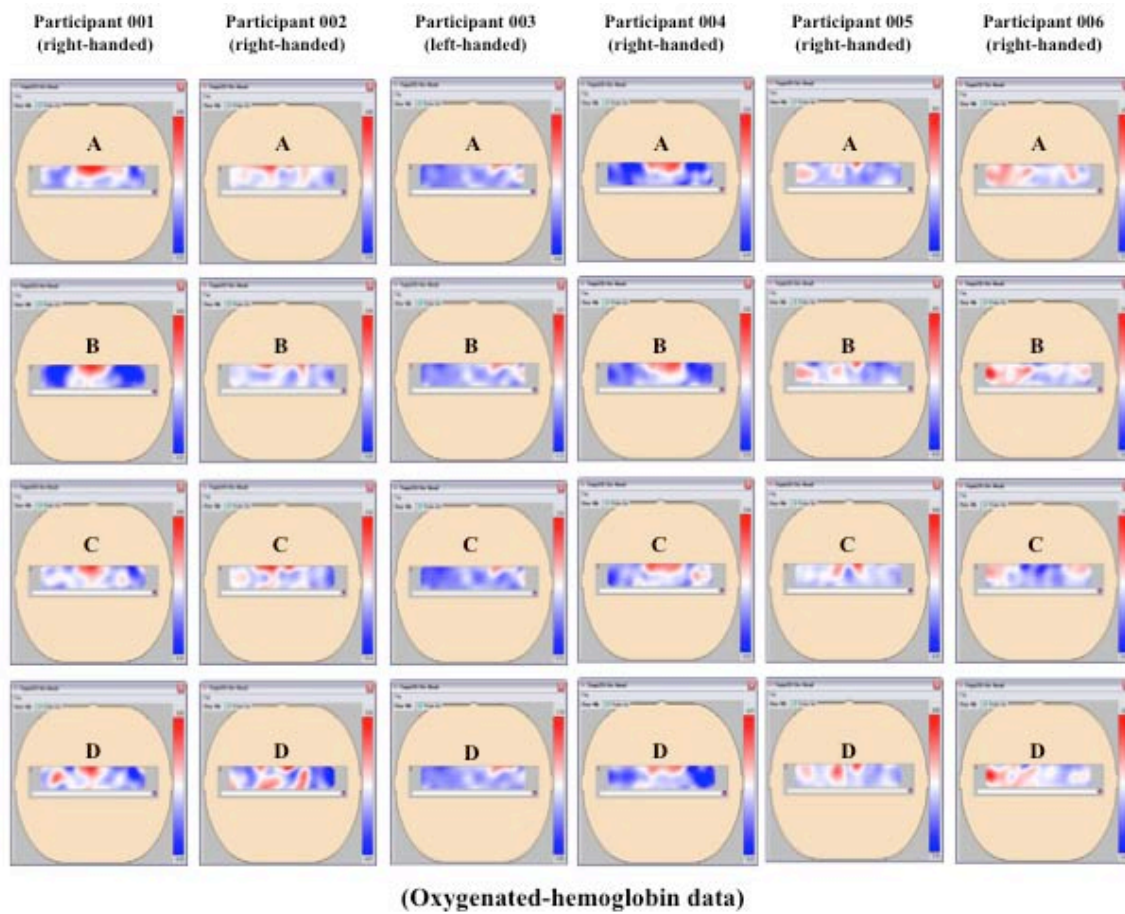


Figure 10. 2D-mapped and integrated hemodynamic changes during the performance of the mental tasks A – D for Participants 7, and 9 – 12

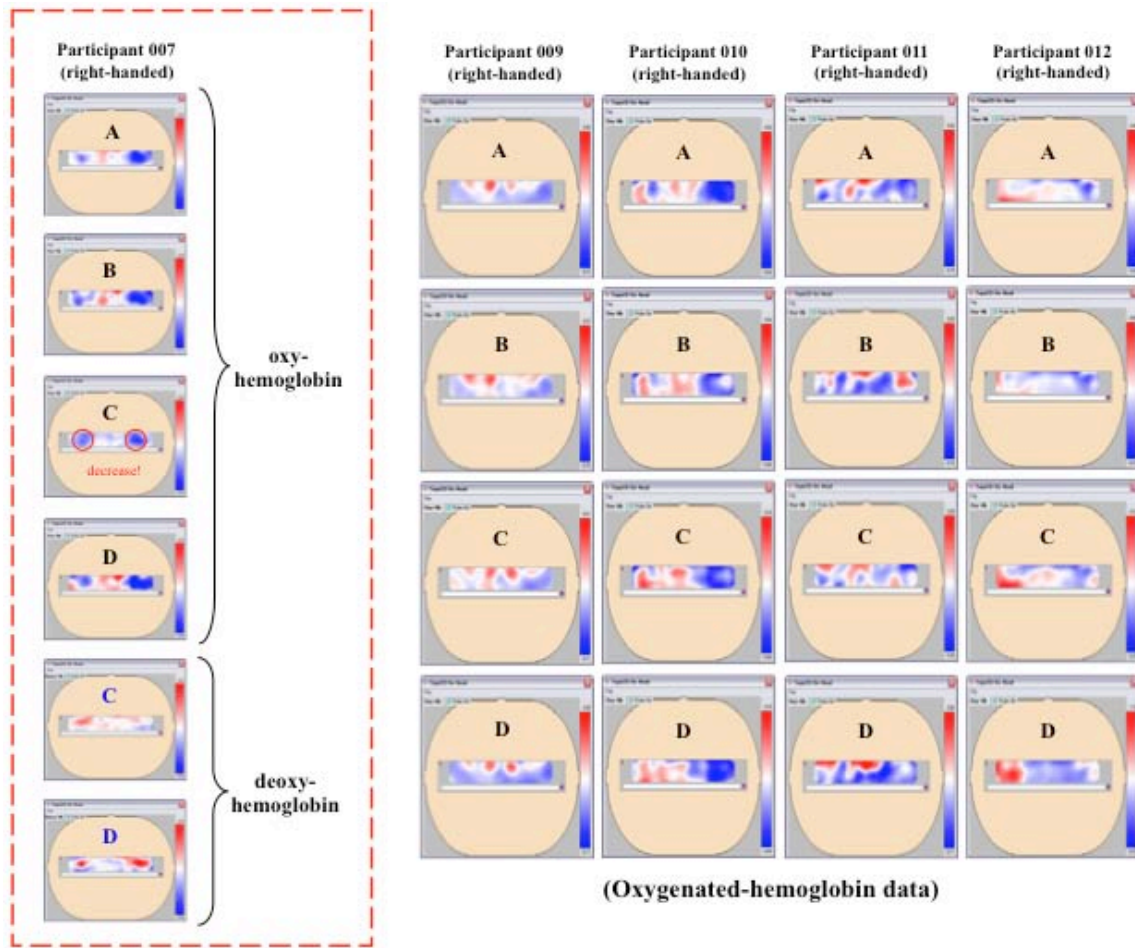


Figure 11. Changes in oxygenate-and deoxygenated-Hb in the left temporal/parietal cortex of participant 001, 004, 007 and 010

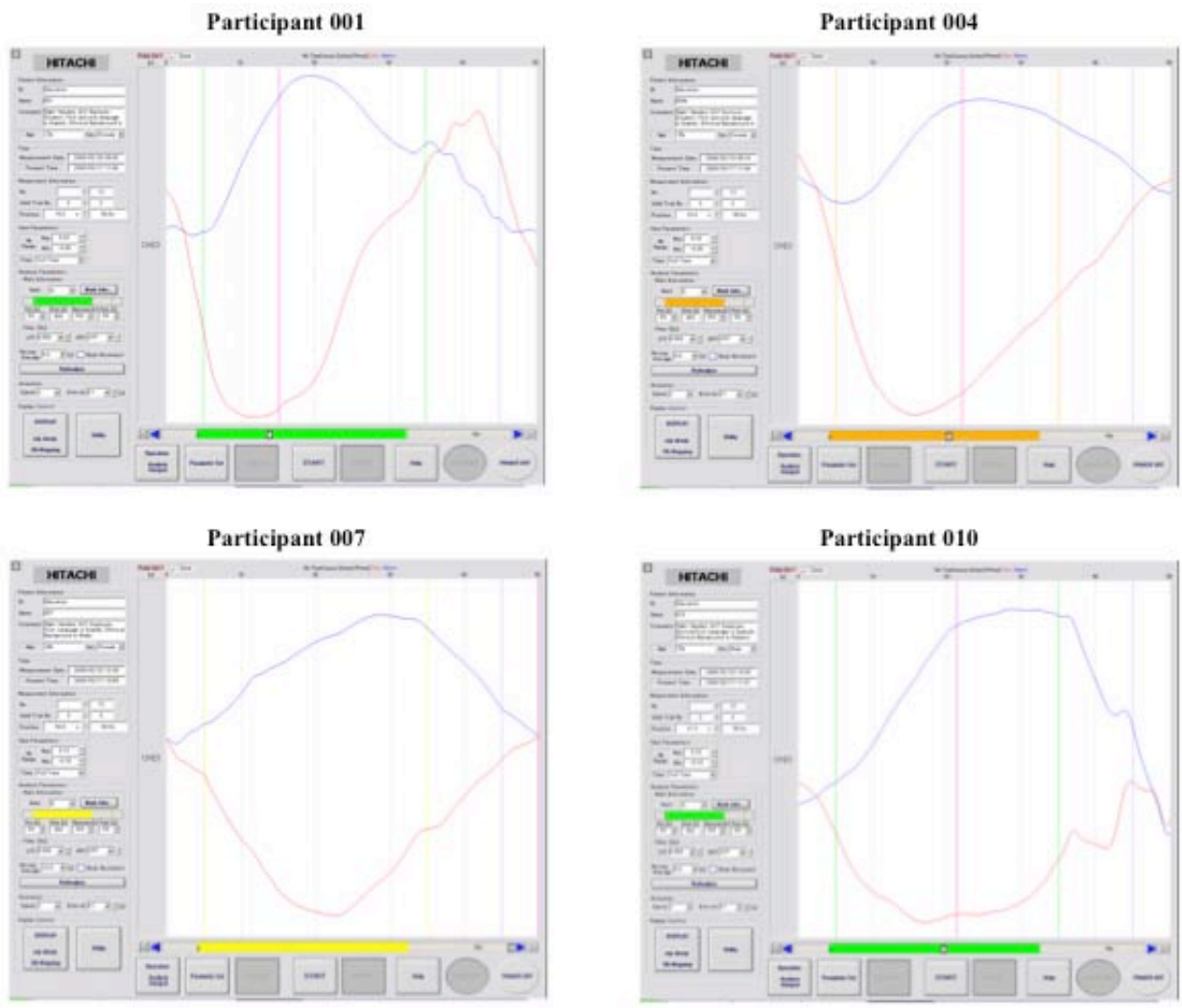


Figure 12. Integrated “Hb-mapping” data for Participant 003

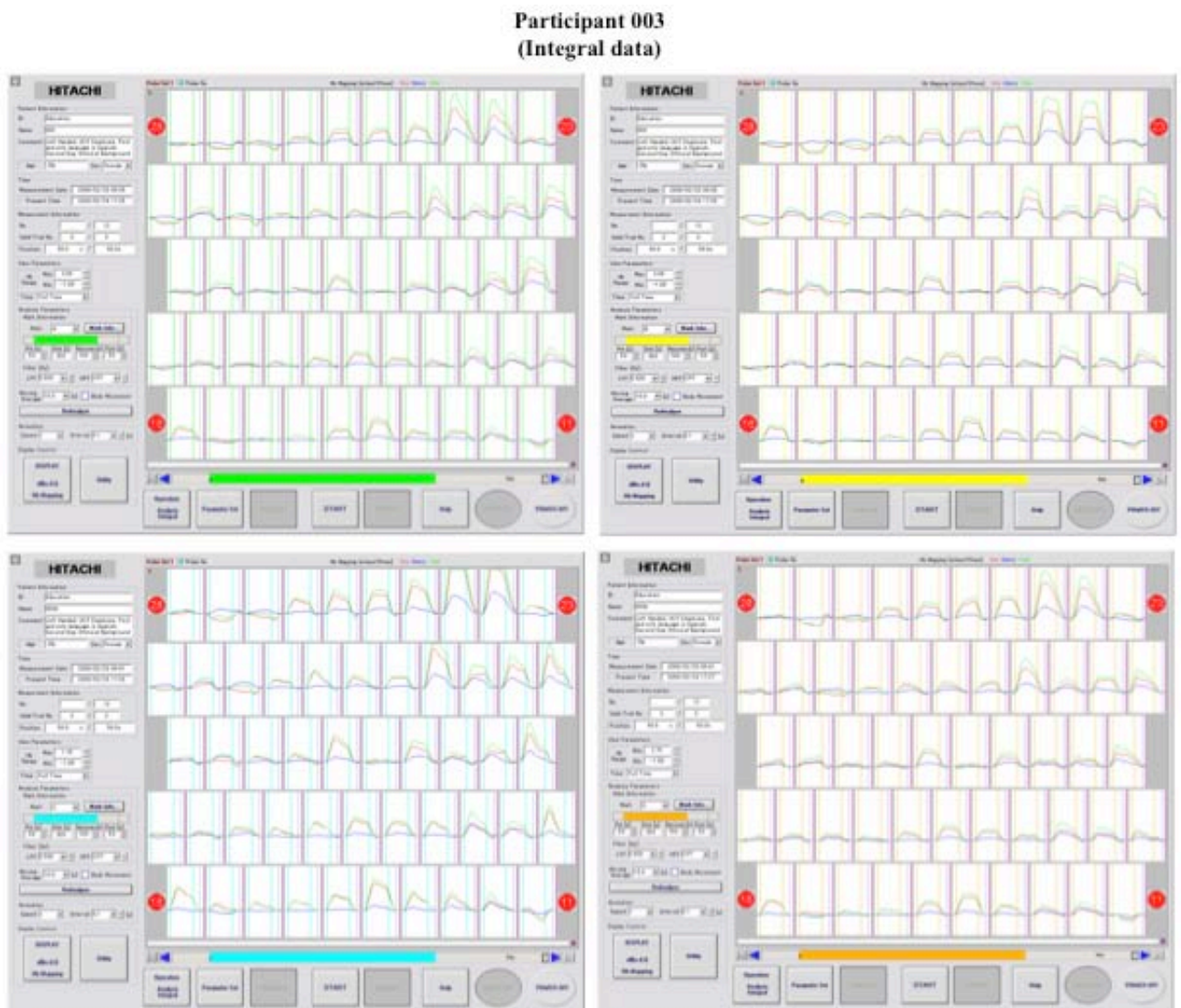


Figure 12B: Increasing concentration in oxygenated- (red) and total hemoglobin (green) and simultaneous decrease in deoxygenated hemoglobin (blue)

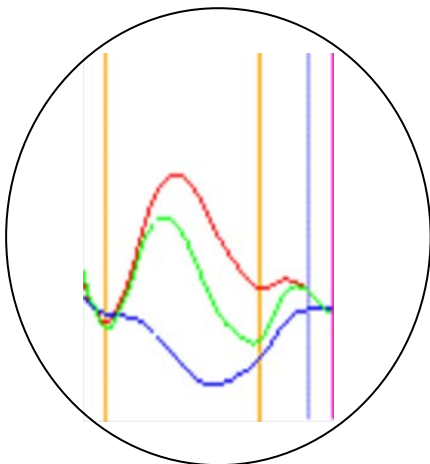


Figure 13. Integrated “Hb-mapping” data for Participant 004

**Participant 004
(Integral data)**



Figure 14. Integrated “Hb-mapping” data for Participant 012

**Participant 012
(Integral data)**



Figure 15. Integrated “Hb-mapping” data for Participant 005

Participant 005
(Integral data)

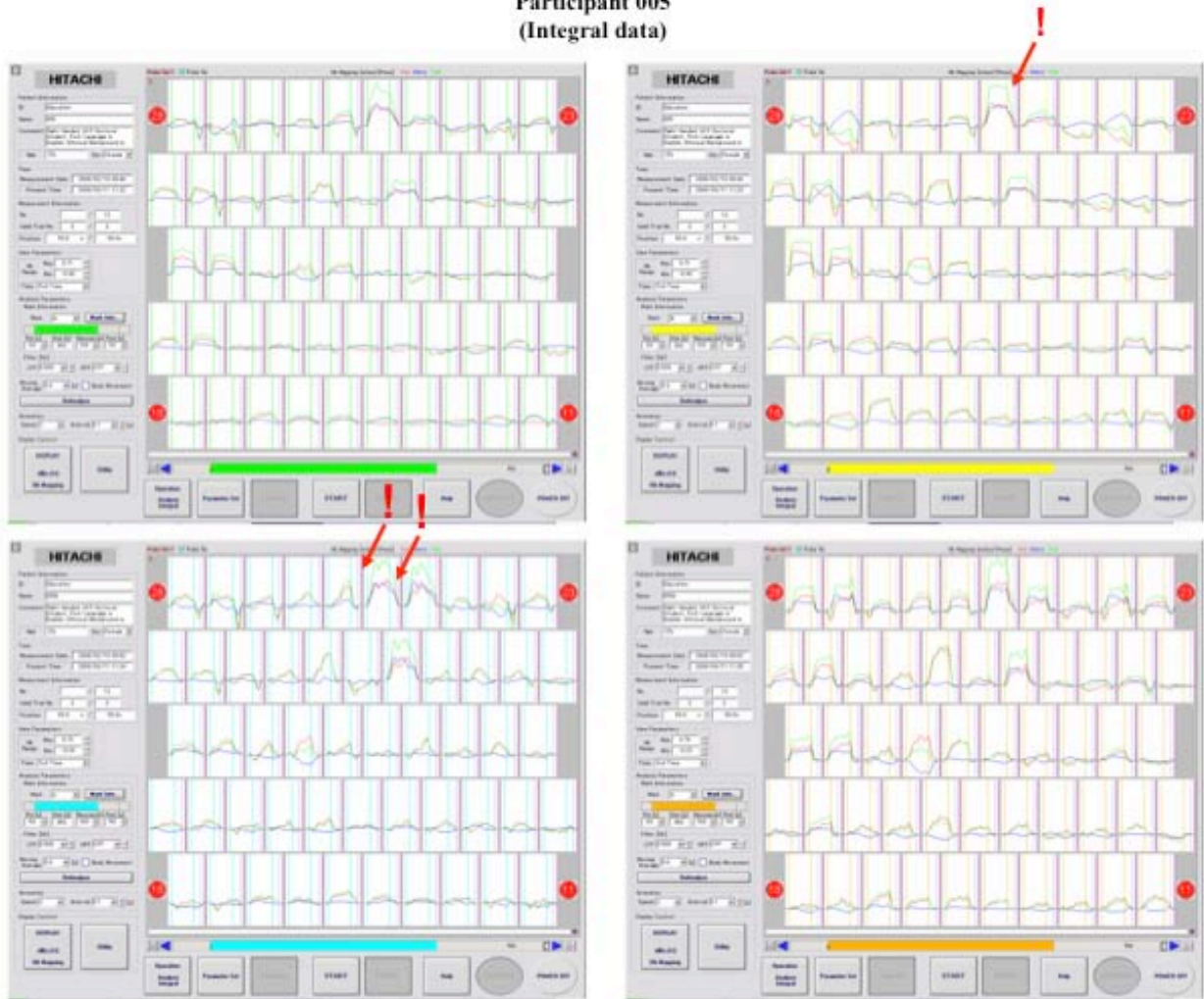


Figure 16. Integrated “Hb-mapping” data for Participant 009

Participant 009
(Integral data)



Figure 17. Deoxygenated-hemoglobin data for Participants 1 – 6

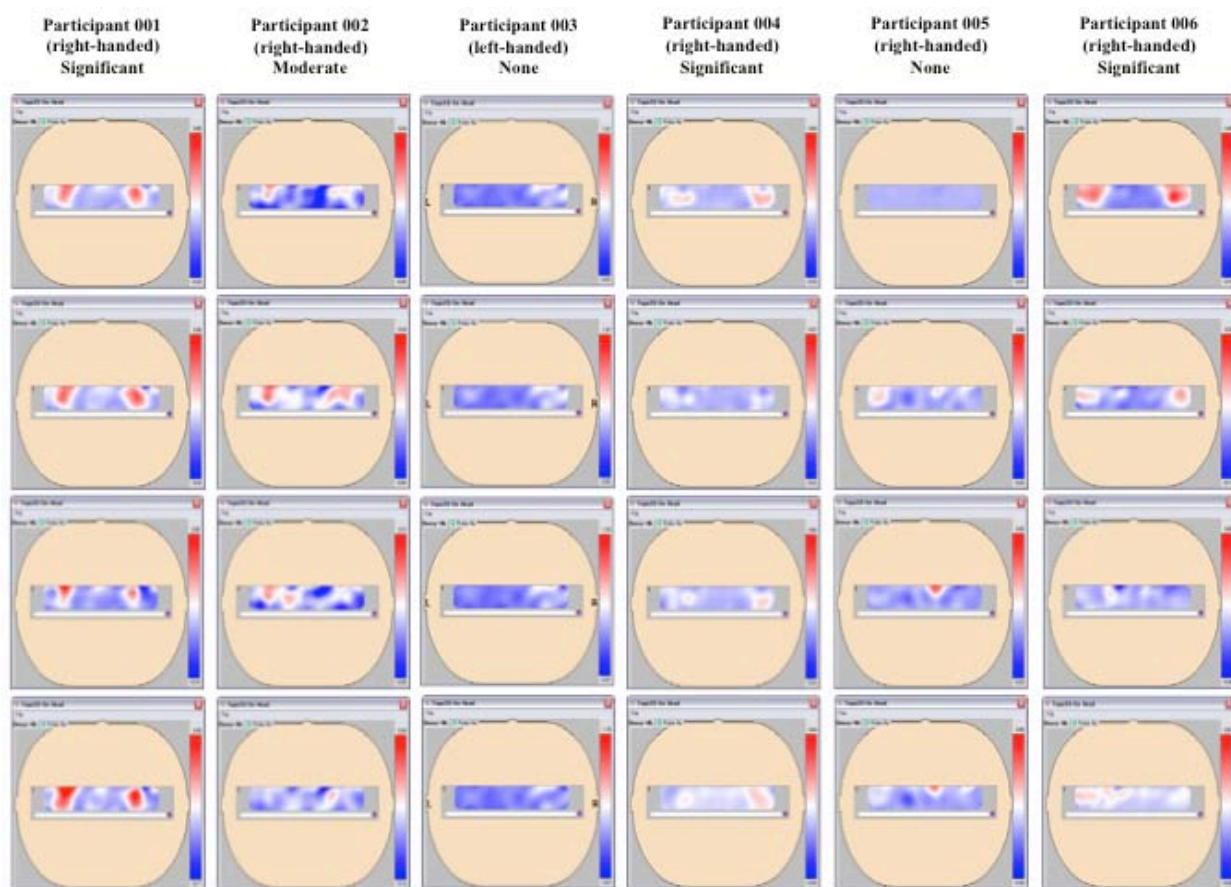


Figure 18. Deoxygenated-hemoglobin data for Participants 7, and 9 – 12

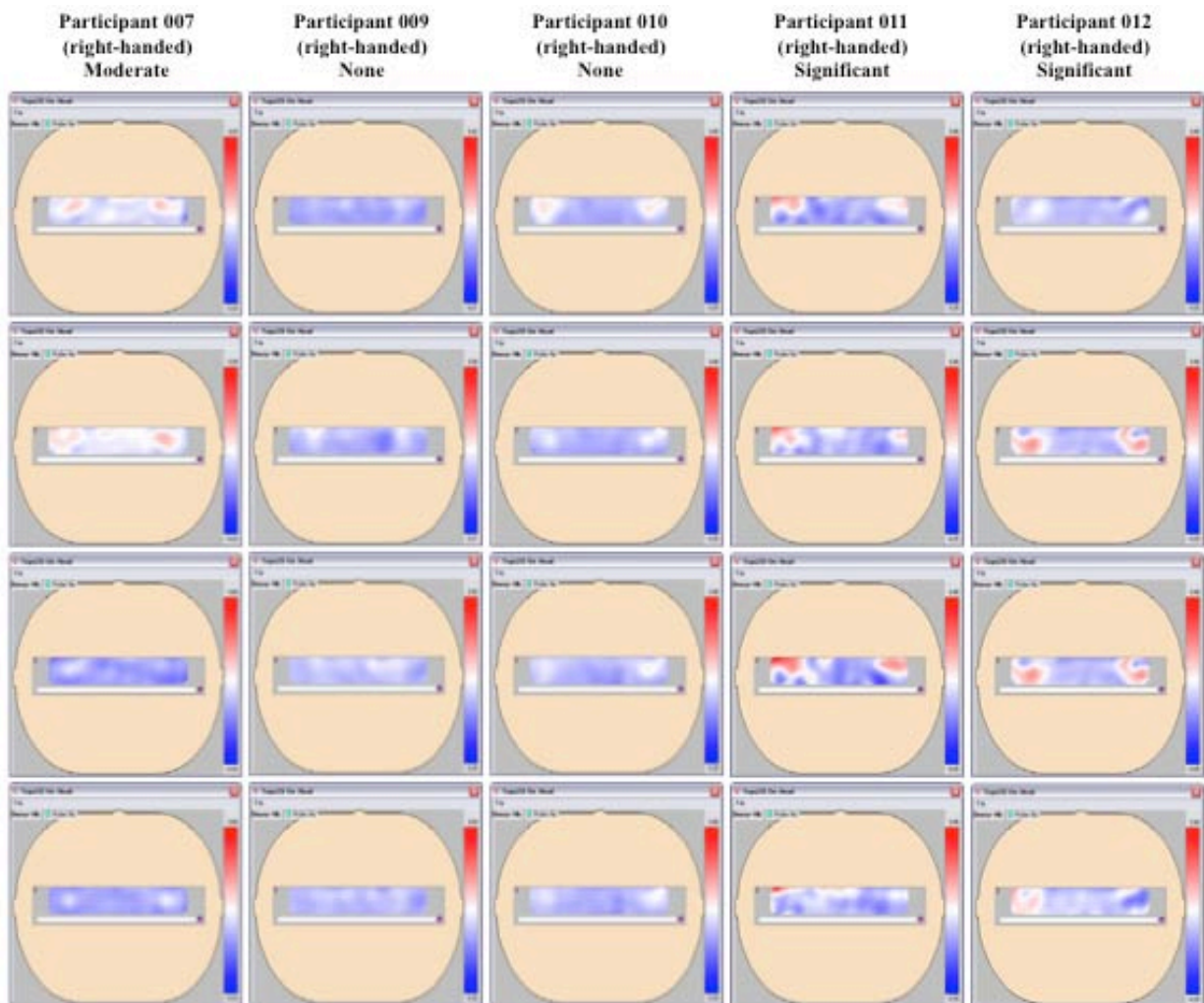
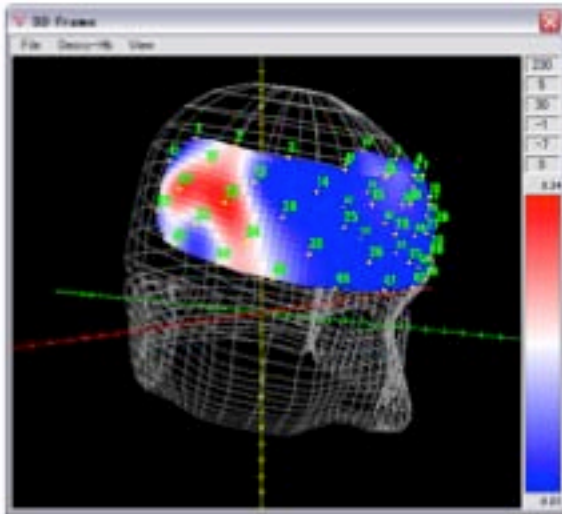
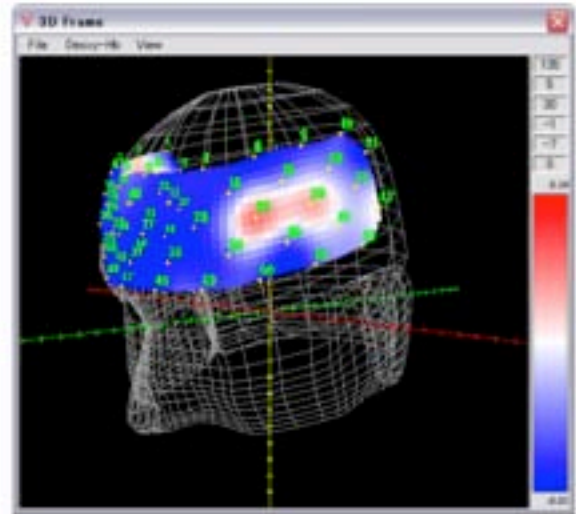


Figure 19. 3D display of changes in the concentration of deoxygenated-hemoglobin during four tasks for Participants 004 and 012

Participant 004

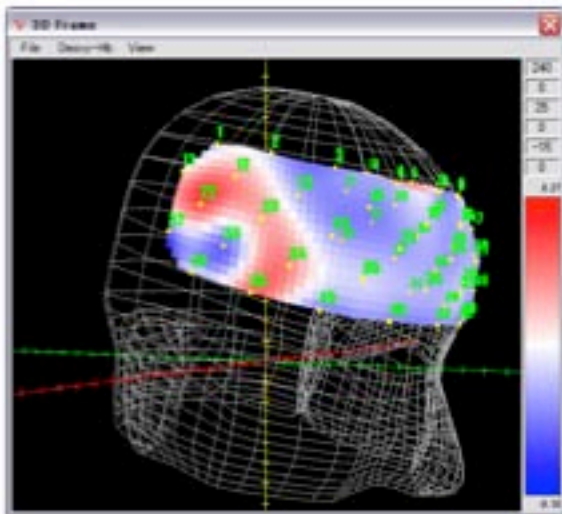


Channels: 12, 22, 23, 33, 34, 44, 45

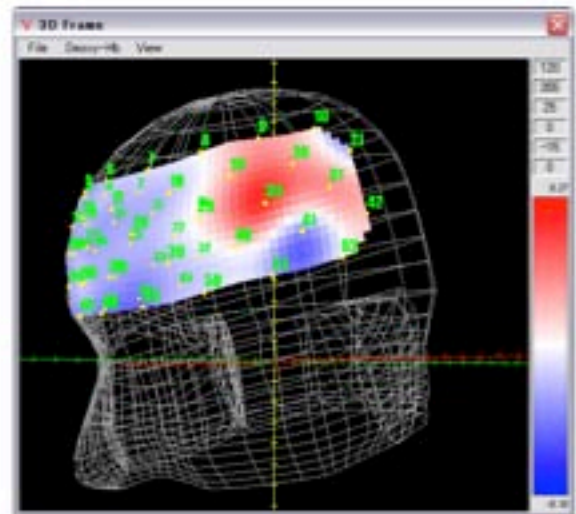


Channels: 29, 30

Participant 012



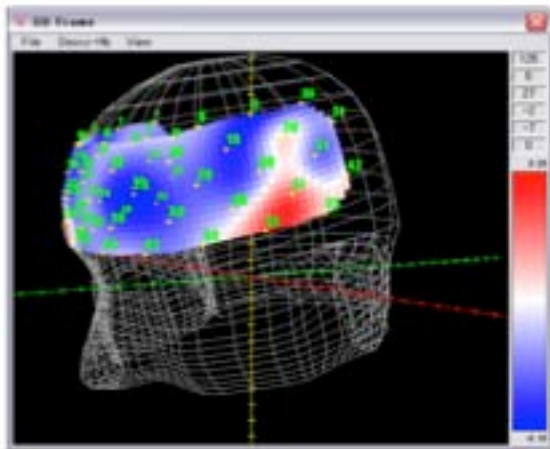
Channels: 12, 22, 23, 34, 44



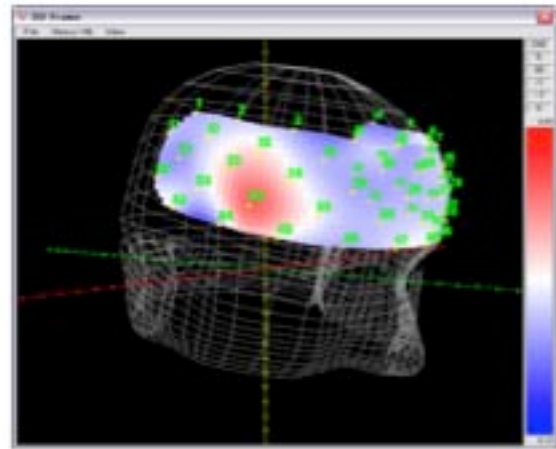
Channels: 20, 30, 31

Figure 20. 3D display of changes in the concentration of deoxygenated-hemoglobin during four tasks for Participants 001 and 005

Participant 005

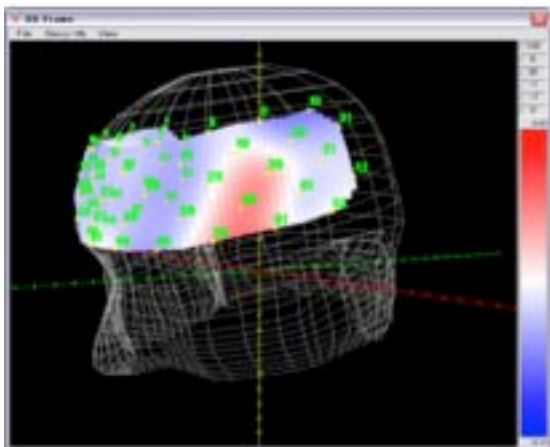


Channels 51, 41,

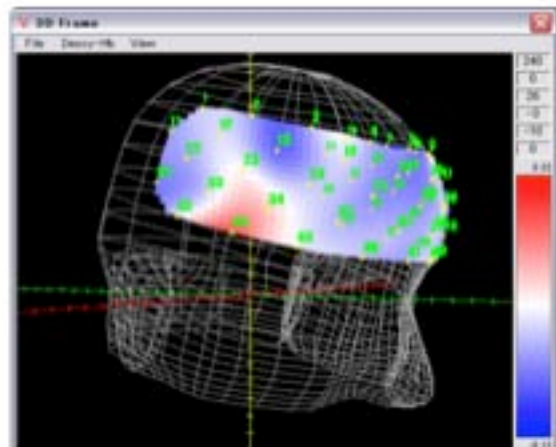


Channels 44, 34

Participant 001



Channels 30, 40, 50, 51



Channels 23, 24, 34

Figure 21. 3D display illustrating increases in deoxygenated hemoglobin for Participant 002 and 006

