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BASIC NEUROSCIENCES, GENETICS AND IMMUNOLOGY - ORIGINAL ARTICLE

Changes in cortical blood oxygenation during arithmetical tasks measured by near-infrared spectroscopy

Melany M. Richter · Kathrin C. Zierhut · Thomas Dresler · Michael M. Plichta · Ann-Christine Ehlis · Kristina Reiss · Reinhard Pekrun · Andreas J. Fallgatter

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Abstract Solving arithmetical problems is a core skill which is learned starting early in childhood and has been shown to involve a temporo-parietal network. In this study, we investigated hemodynamic concentration changes in oxygenated (O_2Hb) and deoxygenated hemoglobin (HHb) within cortical brain regions by means of near-infrared spectroscopy (NIRS). Ten healthy subjects had to calculate or just read two-digit addition tasks that were either presented as numeric formulas or embedded in text. We found higher increases for O_2Hb in parietal brain regions of both hemispheres for the calculation compared to the reading-only condition. Furthermore, these increases were more pronounced during text-embedded tasks than during numeric tasks. Corresponding decreases of HHb could also be detected. These first NIRS findings on that topic confirm that parietal regions are involved in the processing of arithmetic tasks while the amount of activation seems to depend on task modalities like difficulty or complexity.

Keywords Parietal cortex · Mental arithmetic · Neuroimaging · NIRS · Hemoglobin concentration

M. M. Richter and K. C. Zierhut contributed equally to the work underlying this manuscript.

M. M. Richter · T. Dresler · M. M. Plichta · A.-C. Ehlis · A. J. Fallgatter
Psychophysiology and Functional Imaging,
Department of Psychiatry, Psychosomatics and Psychotherapy,
University of Wuerzburg, Wuerzburg, Germany

M. M. Richter (✉)
Institute of Neuropsychology and Clinical Psychology,
Central Institute of Mental Health, University of Heidelberg,
J5, 68159 Mannheim, Germany
e-mail: melany.richter@zi-mannheim.de

K. C. Zierhut
Hospital of Psychiatry, Psychotherapy and Psychosomatic
Medicine, University of Magdeburg, Magdeburg, Germany

K. Reiss
Mathematical Institute, University of Munich, Munich, Germany

R. Pekrun
Department of Psychology, University of Munich,
Munich, Germany

Introduction

Simple arithmetic is a central component of numerical cognition and often used in daily life. Addition is one of the core basic operations in this context. Over the last decade, more and more studies, mainly using functional magnetic resonance imaging (fMRI), helped to unveil the neural foundations of basic arithmetic operations. Intraparietal brain areas were identified as a key region within the network of number processing (Kong et al. 2005; Piazza et al. 2007) with hints for a greater role of left hemispheric areas (Gruber et al. 2001; Rivera et al. 2005). Involvement of parietal areas was seen in adults as well as in children (Kawashima et al. 2004), in different cultures (Tang et al. 2006), and was observed not only in symbolic arithmetic (using, e.g. Arabic numbers) but also in non-symbolic representations of quantities (Venkatraman et al. 2005).

It has to be kept in mind that for retrieving simple and overlearned arithmetic facts (e.g. $2 + 3$) declarative knowledge is used and no computational effort has to be made (Ischebeck et al. 2006) which leads to different brain activation that does not reflect arithmetic skills (Zago et al. 2001). Non-trivial two-digit addition tasks guarantee that computational efforts have to be made for solving arithmetic problems (Kong et al. 2005) and should rule out guessing or retrieving results from declarative memory (for detailed information on procedural and declarative knowledge see Solso 2001).

Within the last few years, the non-invasive method of near-infrared spectroscopy (NIRS) has increasingly been used as an imaging method to assess brain activation. Being easily applicable and less restrictive for the persons measured compared to fMRI or PET (Fallgatter et al. 2004; Obrig et al. 2000; Strangman et al. 2002), NIRS is more and more used in neurophysiological research. NIRS enables to measure changes in cerebral hemoglobin concentration continuously, so BOLD-like responses in certain brain areas during the performance of neuropsychological tests can be detected. Compared to EEG, NIRS can assess the source of brain activation quite precisely and thus provide specific activation patterns for different cortical areas (Plichta et al. 2006b). Furthermore, NIRS has been shown to be a reliable measurement tool (Plichta et al. 2006a, 2007).

It could be shown that during the active phase in performing cognitive tasks, the concentration of oxygenated hemoglobin increased while deoxygenated hemoglobin decreased (Fallgatter and Strik 1998; Schroeter et al. 2002; Villringer et al. 1993). A milestone PET-study (Fox and Raichle 1986) could show that such a pattern of increasing oxygenated and decreasing deoxygenated hemoglobin is considered to reflect brain activation.

To our knowledge, only one recent study dealt with mental arithmetic measured by multichannel NIRS (Tanida et al. 2004). In that study, NIRS measurement was performed over prefrontal areas, thus exploring brain activity needed for more general problem solving in contrast to the specific activity associated with arithmetic problem solving. Earlier NIRS studies using mental arithmetic as a task to activate prefrontal brain areas have been performed only with single-channel NIRS equipment (Hoshi et al. 1994; Hoshi and Tamura 1993), and thus have not investigated parietal regions.

It is important to keep in mind that the way of presenting a mathematical problem influences its processing. For example, there are different types of word problems (in our context defined as arithmetical problems embedded in text) asking for different competencies with respect to their solution (Reusser 1997). Moreover, there is empirical evidence that word problems can be clearly distinguished from problems presented as a formula regarding the underlying problem-solving behavior (Stern 1997). It has, for example, been shown that object relations within the word problem text can be used as semantic cues during the mathematical modeling of the problem (Martin and Bassok 2005). A recent study could show that the processing of problems presented as a formula require mainly attentional and memory processes, whereas word problems additionally require problem solving and concept formation skills (Fuchs et al. 2006). It seems likely that word and numeric problems initiate different brain activation as these two types of representation differ in the amount of cognitive effort required and the neurophysiological networks that are activated. To our knowledge, this hypothesis has not been tested yet.

The aim of our study was to detect brain activation in parietal regions reflected by oxygenation changes measured by NIRS during a basal mathematical process (addition) in non-overlearned conditions (two-digit numbers). By this, we wanted to show that NIRS is able to detect cortical activation as assumed by current imaging studies, but with advantages of lower costs and easier application. This is a very important aspect, for if the comparability can be shown, larger NIRS studies on mathematical processing can be planned involving measurements of children, which can hardly be measured by fMRI or PET. The present study thus functions as a proof of principle preparing for further NIRS studies in children.

Furthermore, differences in brain activation between tasks presented numerically and tasks embedded in text were investigated. This aspect is very important regarding studies in children aiming at learning processes, because in school, word problems have always been a major part of mathematical education (Bernardo 2002).

We expected the oxygenation changes to be higher in calculation tasks compared to control tasks where the arithmetic problem only had to be read, but not to be solved. Additionally, we hypothesized that oxygenation changes during calculation tasks would be higher in word problems compared to numerical tasks because of more information that has to be processed.

Materials and methods

We acquired data of the cerebral tissue oxygenation in all subjects by multi-channel NIRS equipment (ETG-4000 Optical Topography System, Hitachi Medical Corp., Japan). Two arrays of 3 $\times$ 5 light detector and emitter optodes (resulting in 22 channels for each array) were used and placed over the electrode positions P3 (left hemisphere) and P4 (right hemisphere) according to the international 10-20-EEG-system. The use of different near-infrared wavelengths and a frequency modulation prevents crosstalk within this NIRS system. Reflected light is received by the detector optodes, and by using a modified version of the Beer-Lambert equation, the concentration changes of O_2Hb and HHb can be estimated. It has to be kept in mind that the ETG-4000 system is not able to measure the optical path length, so no absolute concentrations can be measured, but only concentration changes (scale unit: mmol × mm). A detailed description of the functioning of NIRS can be found elsewhere (Plichta et al. 2006a).

Ten healthy adults (3 male, 1 left-handed; mean age: 24.2 ± 2.4 years) have been included in our experiment which is in accordance with the Helsinki Declaration and has been approved by the local ethics board. None of the participants suffered from any mild or severe somatic or psychiatric disorder. After written informed consent was obtained, the NIRS arrays were placed on the participant's head. During NIRS measurement, participants had to perform arithmetic tasks in two different modalities (types): two-digit addition tasks presented numerically using Arabic numbers (e.g. 26 + 17) and similar tasks embedded in text (e.g. "Lisa has got 37 Euros in her piggy bank, her mother adds 25 Euros. How many Euros are in Lisa's piggy bank?"). Both types were presented in two conditions: a calculation condition where the correct result had to be chosen out of three suggestions and a reading condition where only the correct result was given.

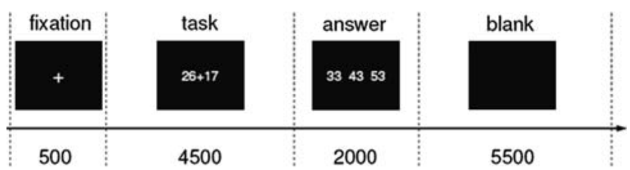

Fig. 1 Scheme of a trial: This picture illustrates the chronological course of a trial, starting with a fixation cross-followed by the task and response screen. In the inter-trial interval, a blank screen was shown. Durations are given in milliseconds

The whole experiment consisted of 140 trials (35 for each type and condition) presented on a computer screen. Each trial started with a fixation cross shown for 500 ms and was followed by the arithmetic task for 4,500 ms. After that, multiple-choice answers were presented for 2,000 ms. In the reading-only condition, only the correct result was displayed. Subjects had to press a button referring to the result he or she chose, or to the exclusively given (correct) result, respectively. This procedure assured that motor activity did not differ between conditions. Between the trials, a blank screen was shown for 5,500 ms. The sequence of a trial is shown in Fig. 1.

The tasks were presented in two blocks: one block consisted of the calculating condition only and one of the reading condition only. The order of these two blocks was randomized across participants. Before executing the reading condition block, participants were explicitly instructed not to calculate when looking at the presented numeric or word problems. Within each block, numeric and word problems were presented in a computer-randomized fashion. The performance in the calculating condition was registered: wrong answers as well as misses (i.e. no button press was recorded within 2 s, and the next trial started automatically) were recorded.

For data analysis, we defined a region of interest (ROI) for each hemisphere, which included the parietal regions described to be related to arithmetic problems (see "Introduction"). Thus, channels 6, 10, 11, and 15 were included for the left hemisphere and channels 8, 12, 13, and 17 for the right hemisphere. The location of the ROI projected on a standard brain can be seen in Fig. 2.

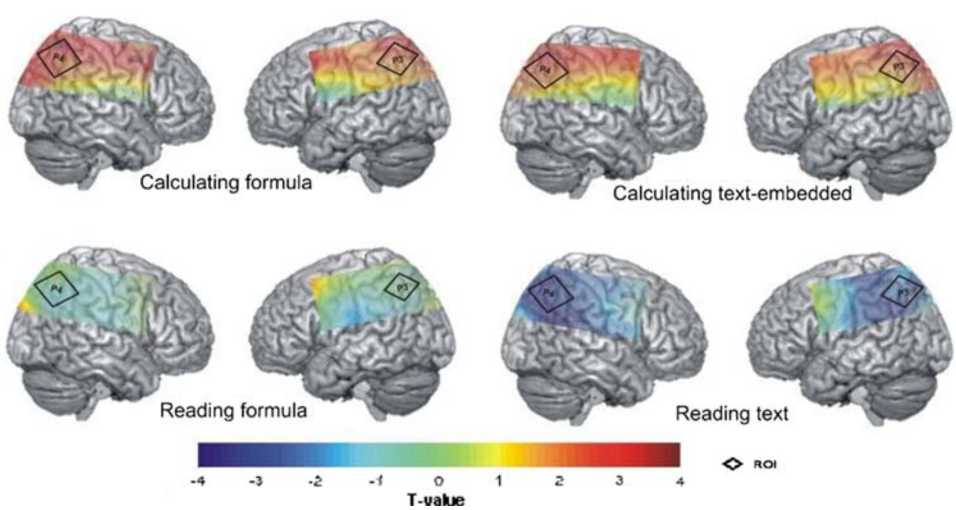

Fig. 2 Changes in O_2Hb concentration during the numeric task ("calculating formula") and the corresponding reading-only task ("reading formula") are presented on the *left side* of the figure. The word problem ("calculating text-embedded") and the corresponding reading-only task ("reading text") are displayed on the *right side*. Maps of t values for the comparison between active and baseline phase in all channels are superimposed on a standard brain to visualize the location of activation. T values are color-coded according to the legend at the *bottom* of the figure. The *rhombuses* mark the location of the ROI

The NIRS data were analyzed in a block design, averaged data of HHb- and O_2Hb-concentration were obtained. Concentration changes between a 2-s-interval directly preceding stimulus presentation (baseline phase) and another 2-s interval 6 to 8-s after stimulus onset (active phase, expected peak of the haemodynamic response function), respectively, were averaged over the 35 trials of each task condition. HHb- and O_2Hb-concentration changes were compared in a 2 × 2 × 2 × 2 ANOVA with the within-factors "type" (numeric vs. word), "condition" (calculation vs. reading-only condition), "phase" (active vs. baseline phase), and "side" (left vs. right hemisphere). Whenever necessary, post hoc *t* tests for matched samples were conducted to explore interaction effects. Statistical analyses were performed using SPSS 14.0 software.

To ensure that the effects found in the ROI are in fact ROI-specific, we subtracted the activation of four non-ROI channels located in fronto-temporal regions (left: 8, 12, 13, 17; right: 6, 10, 11, 15) from the ROI-activation. With these data corrected for non-ROI activation, we performed the same ANOVAs as described above and compared the results with the ROI-ANOVAs.

Results

Performance

Overall performance was significantly worse for the word problems (mean number of errors and misses: $M_{\text{w-em}} = 8.2 \pm 7.2$) compared to numeric problems ($M_{\text{n-em}} = 1.8 \pm 1.7$; $T_9 = 3.03$; $P = 0.014$). This was based on significantly more misses for word problems ($M_{\text{w-m}} = 6.6 \pm 7.1$) than for numeric problems ($M_{\text{n-m}} = 1.2 \pm 1.5$; $T_9 = 2.52$; $P = 0.033$), whereas the number of errors was not significantly different ($M_{\text{w-e}} = 1.6 \pm 1.5$; $M_{\text{n-e}} = 0.6 \pm 0.8$; $T_9 = 1.50$, n.s.). No significant correlations (Spearman's rho) between brain oxygenation data and number of errors and misses could be found.

NIRS

Regarding O_2Hb, we found main effects for the factors "type" ($F_{1,9} = 5.52$; $P = 0.043$) with significantly higher concentration changes for word problems compared to numeric tasks, and "condition" ($F_{1,9} = 8.22$; $P = 0.019$) with significantly higher concentration changes for the calculation task compared to the reading task. Furthermore, we found significant interaction effects for "type × condition" ($F_{1,9} = 8.92$; $P = 0.015$), "phase × condition" ($F_{1,9} = 9.76$; $P = 0.012$), and "side × phase × condition" ($F_{1,9} = 8.84$; $P = 0.016$) within the predefined ROI.

For "type × condition", O_2Hb values for word problems were higher in the calculation condition than in the reading-only condition ($T_9 = 3.25$; $P = 0.010$); furthermore, O_2Hb values in the calculation condition were higher for word problems compared to numeric tasks ($T_9 = 3.30$; $P = 0.009$) (see Fig. 3a). In- and decreases of oxygenation for "type × condition" are visualized in Fig. 2. For "phase × condition", post hoc tests revealed higher increases of O_2Hb in the active phase during calculation compared to only reading ($T_9 = 3.16$; $P = 0.012$) and significant differences between active and baseline phase for each condition (calculation: $T_9 = 2.73$; $P = 0.023$; reading: $T_9 = -2.49$; $P = 0.034$) (see Fig. 4a). Examination of the "side × phase × condition" interaction revealed stronger baseline-corrected (active-baseline phase) O_2Hb increase for calculation tasks compared to reading-only tasks in the left ($T_9 = 2.81$; $P = 0.020$) as well as in the right hemisphere ($T_9 = 3.43$; $P = 0.008$). There was no difference between hemispheres regarding task condition.

Changes in concentration of HHb were much less pronounced, leading to no significant main effects, but to interactions of "type × condition" ($F_{1,9} = 12.67$; $P = 0.006$) and "phase × condition" ($F_{1,9} = 12.90$; $P = 0.006$). Post hoc t-tests for "type × condition" revealed higher deoxygenation for calculating word problems compared to only reading them ($T_9 = -2.488$; $P = 0.035$), and stronger

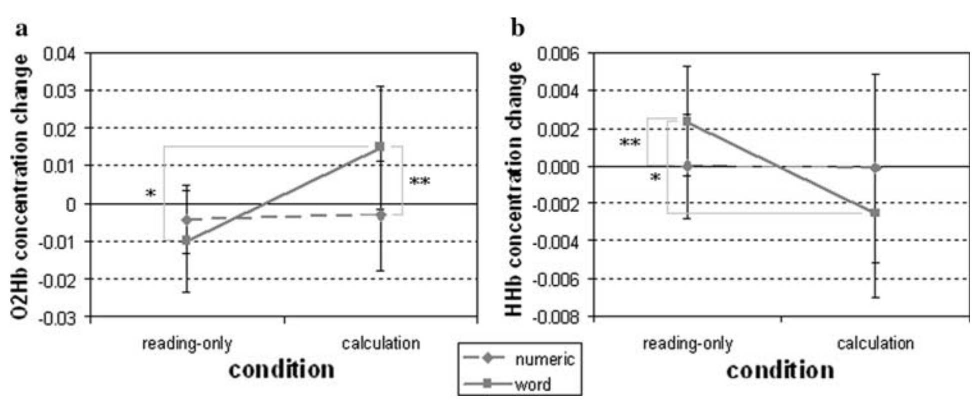

Fig. 3 Interaction of "type × condition" for O_2Hb (**a**) and HHb (**b**). Concentration changes for each type (numeric vs. word problem) in each condition (reading-only vs. calculation) are shown. Significant comparisons are marked by *asterisks* (* $P < 0.05$; ** $P < 0.01$). Unit of the concentration change is mmol × mm. *Bars* represent standard deviations

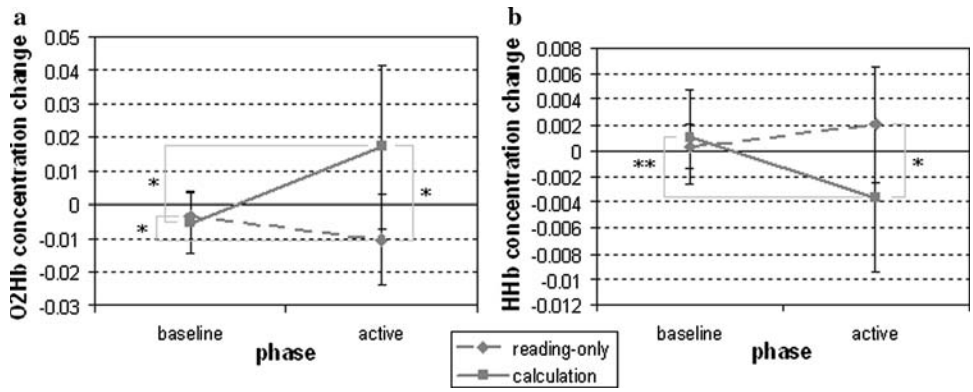

Fig. 4 Interaction of "phase × condition" for O_2Hb (**a**) and HHb (**b**). Concentration changes for each phase (baseline vs. active phase) in each condition (reading-only vs. calculation) are shown. Significant comparisons are marked by *asterisks* (* $P < 0.05$; ** $P < 0.01$). Unit of the concentration change is mmol × mm. *Bars* represent standard deviations

HHb decrease when reading numeric tasks compared to reading word problems ($T_9 = -4.90$; $P = 0.001$). Results of "type × condition" are shown in Fig. 3b. Further analyses of "phase × condition" showed that HHb values in the active phase decreased more during calculation than during reading-only tasks ($T_9 = -2.30$; $P = 0.047$). Additionally, a stronger decrease in HHb during active compared to baseline phase in the calculation condition ($T_9 = -3.63$; $P = 0.005$) was found. Results of "phase × condition" are shown in Fig. 4b.

Additionally, we performed ANOVAs corrected for non-ROI activation:

For O_2Hb, results comparable to those described above were found with a trend to significance for "type" ($F_{1,9} = 4.86$; $P = 0.055$) and "type × condition" ($F_{1,9} = 4.15$; $P = 0.072$) and significant results for "phase × condition" ($F_{1,9} = 6.89$; $P = 0.028$) and "side × phase × condition" ($F_{1,9} = 6.17$; $P = 0.035$). The main effect of "condition" was lost.

For HHb, analysis resulted in a significant interaction of "phase × type × condition" ($F_{1,9} = 11.67$; $P = 0.008$) with post-hoc analyses confirming the results found in the HHb-ANOVA described above: higher deoxygenation for solving word problems versus only reading them ($T_9 = -3.44$; $P = 0.007$); stronger HHb-decrease during calculation compared to reading-only in the active phase ("numeric" $T_9 = -2.44$, $P = 0.037$; "word" $T_9 = -2.96$, $P = 0.016$); more pronounced decrease of HHb-values during the active phase compared to baseline in the numeric calculation condition ($T_9 = -3.45$; $P = 0.007$).

Discussion

This is the first report on mathematical processing in parietal brain regions assessed by NIRS. It could be shown that O_2Hb concentration increases in superior and inferior parietal areas during arithmetic tasks whereas at the same time HHb concentration decreases (Figs. 3a, b, 4a, b). Based on the tight coupling of neural activity and oxygen delivery, this oxygenation pattern can be interpreted as an indicator for cortical activation (Fox and Raichle 1986). As hypothesized, more cortical activation for calculation compared to control tasks and for word problems compared to numeric problems was found.

To ensure that we measured specific activation in cortical areas related to mathematical processing, we performed analyses in which we subtracted activation found near our target region from activation within our ROI. The results of these "corrected" analyses confirmed the results obtained by our standard analyses. We decided to do this in addition to our basic analyses because of the known problems associated with difference measures (e.g. an underestimation of the real correlations between variables).

Interestingly, in the reading-only tasks, we found a decrease in oxygenation instead of an increase, which may be interpreted as a sign for deactivation in the measured area, possibly initiated by an activation in adjacent brain regions (e.g. in the Wernicke's area, the area for understanding words during a reading process) that we did not cover with our probe sets (Fallgatter et al. 1998).

The difference between calculation and reading-only conditions was not significant for numeric tasks. This may be explained by the design of the reading-only tasks: Looking at a formula for a time span of 4.5 s, it is difficult not to engage in mental calculation. However, when the mathematical problem is embedded in text, it is far easier not to calculate and to just stick to the story presented in the text. Therefore, in future studies, the presentation time of numeric tasks in reading-only control conditions should be shortened to avoid calculation.

A more pronounced activation pattern was found for word problems than for numeric tasks. This result could point to higher oxygen consumption demanded by word problems because of a more extensive network that has been activated by these problems (cf. Fuchs et al. 2006). In the present study, this result may be confounded with higher task difficulty evoked by higher time pressure: whereas most of the presentation time of the numeric task could be used to calculate, most of the time in the word problem was needed to read the text; in consequence, we found worse performance for word problems than for numeric problems. To address this problem, presentation times for word problems should be enlarged in future studies. Nevertheless, this higher oxygenation level could be associated with learning processes. Law and colleagues described a higher oxygenation level in a fronto-parietal network during an association-learning task whereas after completion of the learning process oxygenation decreased to baseline (Law et al. 2005). On this account, our data could be interpreted as a similar learning process dealing with solving unknown tasks presented as word problems under time pressure compared to basic calculation tasks presented as mere formula.

In summary, we found evidence that parts of the superior and inferior parietal gyrus of both hemispheres play a crucial role in the processing and solving of arithmetic problems for both word and numeric problems, which is in accordance to study results described in current literature, and that this activation can be measured by multi-channel NIRS. This result enables to plan for future studies measuring mathematical processing in children (who are difficult to measure using fMRI or PET). Additionally, this neuronal activation seems to be dependent on the task modality, i.e. the more difficult or complex the task is (e.g. reading and calculating under time pressure), the stronger is the resulting oxygenation. Future studies are needed to differentiate between difficulty and complexity.

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