Neural and behavioral correlates of arithmetic development and learning in children

Dissertation

zur Erlangung des Grades eines
Doktors der Naturwissenschaften

der Mathematisch-Naturwissenschaftlichen Fakultät
und
der Medizinischen Fakultät
der Eberhard-Karls-Universität Tübingen

vorgelegt
von

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April - 2017

Tag der mündlichen Prüfung:	07.11.2017
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ABSTRACT (ENGLISH)

Arithmetic learning improves mathematical competence, which is necessary for successful daily life. However, little is known about the neural underpinnings of arithmetic learning during childhood, the age when individuals learn most of the mathematical skills and the vast majority of our knowledge comes from adult studies.

In this dissertation project, four studies were conducted to investigate the neural and behavioral correlates of arithmetic development and learning in children. In Study 1 arithmetic development was evaluated longitudinally to see whether it is monotonous or there are intermediate phases in which certain domain-general processes become important but disappear later. In Study 2 arithmetic complexity was evaluated to see whether it relies on both magnitude and cognitive processes, such as in adults. In Study 3 it was asked whether the findings in adults are valid for children or are there intermediate stages. Furthermore, it was evaluated whether few training sessions are reflective of more long-term learning processes. In Study 4 the brain activation changes during the course of learning were measured to see whether they reveal similar changes as in after arithmetic learning.

The findings revealed that different domain-general cognitive processes are involved in different steps of arithmetic development and learning. Furthermore, arithmetic achievement occurs in two steps in children, first from slow effortful procedural processes to fast compacted procedural processes, and then to retrieval processes. These changes are distinguishable after one and several training sessions, and also during the course of learning. The findings are integrated in a theoretical model of arithmetic achievement in children, which contains two phases: (i) *the efficiency increase* (from slow effortful procedural processes to fast compacted procedural processes) and (ii) *the strategy change* (from fast compacted procedural processes to retrieval processes) phases. The model was developed based on two principles of brain function, optimum performance and energy consumption, and supported by several empirical studies.

Taken together, this dissertation project provides a comprehensive framework for arithmetic development and learning in children. The findings might be helpful to develop educational and therapeutic interventions and also a new measure of intervention outcomes, particularly in individuals with mathematical learning disabilities.

ABSTRACT (GERMAN)

Arithmetisches Lernen verbessert die mathematische Kompetenz, die für ein erfolgreiches Alltagsleben nötig ist. Allerdings weiß man noch wenig über die neuronale Basis von arithmetischem Lernen in der Kindheit, obwohl es das Alter ist, in dem Menschen die meisten ihrer mathematischen Fähigkeiten erwerben, und der überwiegende Großteil unseres Wissens stammt aus Studien mit Erwachsenen.

In diesem Dissertationsprojekt wurden vier Studien durchgeführt, um die neuronalen und behavioralen Korrelate arithmetischer Entwicklung und arithmetischen Lernens bei Kindern zu untersuchen. In Studie 1 wurde die arithmetische Entwicklung longitudinal evaluiert, um herauszufinden, ob diese monoton ist oder ob es Zwischenphasen gibt, in denen bestimmte domänenübergreifende Prozesse wichtig werden, später aber wieder verschwinden. In Studie 2 wurde die arithmetische Komplexität evaluiert, um herauszufinden, ob diese wie bei Erwachsenen sowohl auf der Verarbeitung von Größe als auch auf kognitiven Prozessen beruht. In Studie 3 war die Frage, ob die Ergebnisse von Erwachsenen auch für Kinder gelten oder ob es Zwischenphasen gibt. Darüber hinaus wurde untersucht, ob wenige Trainingseinheiten langfristigere Lernprozesse widerspiegeln. In Studie 4 wurden Veränderungen in der Gehirnaktivität während des Lernvorgangs gemessen, um herauszufinden, ob sich ähnliche Veränderungen wie nach arithmetischem Lernen feststellen lassen.

Den Ergebnissen zufolge sind unterschiedliche domänenübergreifende kognitive Prozesse an unterschiedlichen Schritten bei der arithmetischen Entwicklung und beim arithmetischen Lernen beteiligt. Außerdem erfolgt arithmetisches Lernen bei Kindern in zwei Schritten: zuerst von langsamen aufwändigen prozeduralen Prozessen zu schnellen komprimierten prozeduralen Prozessen und dann zu Abrufprozessen. Diese Veränderungen lassen sich nach einer und nach mehreren Trainingseinheiten sowie während des Lernvorgangs unterscheiden. Die Ergebnisse sind in ein theoretisches Modell zu arithmetischem Lernerfolg bei Kindern eingebunden, welches aus zwei Phasen besteht: (i) Phase der Effizienzsteigerung (von langsamen aufwändigen prozeduralen Prozessen zu schnellen komprimierten prozeduralen Prozessen) und (ii) Phase der Strategieänderung (von schnellen komprimierten prozeduralen Prozessen zu Abrufprozessen). Das Modell

wurde auf der Basis von zwei Prinzipien der Gehirnfunktion entwickelt – optimaler Leistung und Energieverbrauch – und wird von vielen empirischen Studien gestützt.

Insgesamt liefert dieses Dissertationsprojekt eine Theorie für arithmetische Entwicklung und arithmetisches Lernen bei Kindern. Die Ergebnisse können dazu dienen, pädagogische und therapeutische Interventionen sowie ein neues Maß für Interventionserfolg insbesondere für Personen mit einer mathematischen Lernstörung zu entwickeln.

GENERAL INTRODUCTION

Mathematical skills are a common demand of daily life in modern societies (Parsons & Bynner, 2005). Unlearned mathematical skills in childhood impact later academic and professional achievement (Duncan et al., 2007), socioeconomic well-being (Hanushek & Woessmann, 2010), and mental health outcomes (Parsons & Bynner, 2005), which lead to huge costs for societies, such as an annual cost of £2.4 billion in the UK (Gross, Hudson, & Price, 2009). Therefore, it seems very important for individuals to achieve these skills. However, investigating behavioral and neural correlates of arithmetic development and learning, and also the consequences of their dysfunction, has received considerably less funding and attention than other learning disabilities (Bishop, 2010). Moreover, mathematical disability has more consequences than other learning disabilities (Beddington et al., 2008; Parsons & Bynner, 2005). It has been shown that up to 20% of individuals suffer from mathematical disabilities (Menon, 2013; Williams, 2003), despite age-appropriate schooling and the absence of other cognitive deficits (Butterworth, Varma, & Laurillard, 2011). It is, therefore, essential to understand the underlying processes of mathematical development in typically developing children before turning toward the study of mathematically disabled children. Furthermore, investigating arithmetic development and learning is an ideal field to uncover the acquisition of cognitive skills during development on a larger scale. This is because the current status, content, progress, and goals can be easily specified in this field (Delazer et al., 2003). Such studies also help to fill in the gaps between education and neuroscience, which results in both disciplines obtaining new perspectives from each other (Ansari & Coch, 2006). This bridging is necessary for developing educational and therapeutic interventions, and also for assessing the outcomes of interventions for both typically developing children and children with mathematical disabilities (see also Zamarian, Ischebeck, & Delazer, 2009).

Mathematical knowledge contains different components (cf. Fig. 1), which need to be taken into account when mathematical achievement in children is investigated, as they are essential for an individual to become competent in mathematics (S. P. Miller & Hudson, 2007). Previous studies have shown that declarative, procedural, and conceptual knowledge are needed in arithmetic learning (e.g., Delazer, 2003; S. P. Miller & Hudson, 2007). Declarative knowledge or memory, i.e., semantic long-term memory, is mostly involved in storing and retrieving arithmetic facts, which is the fast way to find the solutions to very easy problems such as 4 × 1 (Ashcraft, 1992; see also Moeller, Klein, Fischer, Nuerk, & Willmes, 2011). Hence, in order to develop declarative knowledge, sufficient practice is needed to achieve mastery of specific problems. Procedural knowledge is the ability to solve math problems by following sequential steps (Goldman & Hasselbring, 1997). Therefore, procedural knowledge is required for more complex calculations, which require solving a problem step-by-step, according to the training methods that individuals have learned, for example to solve 13 × 82 (McCloskey, Caramazza, & Basili, 1985). Conceptual knowledge is the understanding of the principles and laws of mathematics, such as the idea that 4 × 17 is equal to 17 × 4 (Hittmair-Delazer, Semenza, & Denes, 1994), which provide the meaning of mathematics (S. P. Miller & Hudson, 2007). Therefore, conceptual knowledge is a network of information consisting of both discrete numerical facts and the relations between them (Goldman & Hasselbring, 1997). Understanding these relations is essential for generalizing and dealing with novel problems within new situations (Kameenui & Simmons, 1990). In sum, while learning some mathematical knowledge leads to mastery only in that particular skill or problem set, learning another type might generalize to new skills or sets. Moreover, the relations between the above-mentioned types of knowledge, particularly procedural and conceptual, have been under great debate and discussion during the last decades (Hiebert, 2013). While some researchers distinguish them from each other, some others subsume them in the same category (for a detailed discussion see Hiebert, 2013). Furthermore, learning of different knowledge types, namely declarative and procedural, leads to different brain activation networks (Delazer et al., 2005).

The application of these types of knowledge engages domain-specific and several domain-general cognitive processes (Delazer et al., 2003), which are necessary to consider when mathematical knowledge is investigated and taught. While domain-specific magnitude and quantity-based processes involve manipulating numbers, domain-general cognitive processes consist of working memory (WM), planning, and monitoring (Delazer et al., 2003). On the neural level, according to the triple-code model (Dehaene, Piazza, Pinel, & Cohen, 2003) three parietal circuits are involved in numerical and arithmetic processing. The core circuit, which is defined as the domain-specific area in number processing, is the horizontal part of the intraparietal sulcus (IPS), which reveals increased activation during quantity processing. The other two areas, which are assumed to be engaged in numerical processing as domain-general areas, are the left angular gyrus (AG) and bilateral posterior superior parietal area. While the left AG supports processing the numbers in verbal form, the bilateral posterior superior parietal area supports attentional and spatial demands of number and arithmetic processes (Dehaene et al., 2003). Additionally, Dehaene, Molko, Cohen, and Wilson (2004) suggested that prefrontal activation, which is mostly related to executive functions and WM, supports mental calculation. Klein et al. (2016) recently suggested an update to the triple-code model by adding some other related brain regions. They suggested that three frontal regions, namely the triangular part of the inferior frontal gyrus (IFGtri), BA 47, and the supplementary motor area (SMA), are involved in domain-specific magnitude process. With respect to verbally mediated arithmetic facts, they suggested the involvement of additional regions, namely the retrosplenial cortex (RC), ventro-medial prefrontal cortex, and the hippocampus (Klein et al., 2016). According to Poldrack (2000), learning is a shift from general purpose processes to more task-specific processes. Therefore, a shift from frontal regions to parietal regions within the above-mentioned network is expected due to arithmetic development and learning.

Given the significant impacts of mathematical skills in life, in the present dissertation project, the neural and behavioral correlates of arithmetic *development* and *learning* are investigated in typically developing children. Both arithmetic development and learning lead to improved performance. While development can be defined as a set of systematic changes over the life span, which are related to the maturation of the brain, learning is defined as the acquisition of new knowledge, which includes short-term changes after instruction that can occur either in the classroom or outside of school. As outlined above, this project can be considered the first step in a long trajectory to develop educational and therapeutic interventions for individuals suffering from poor mathematical competencies. Four studies were conducted in this project. In Study 1, arithmetic development was evaluated longitudinally to see whether it is monotonic, or there are intermediate phases in which certain domain-general processes become important but disappear later. In Study 2, arithmetic complexity was evaluated to see whether it relies on both magnitude and additional cognitive processes, such as in adults. In Study 3, it was asked whether the findings in adults are valid for children’s development, or if instead there are intermediate stages. Furthermore, it was evaluated whether too few training sessions are reflective of more long-term learning processes. In Study 4, the brain activation changes during the course of learning were measured to see whether they reveal similar changes after arithmetic learning. In addition to behavioral correlates, it seems to be important to investigate the neural correlates of arithmetic development and learning, because it has been shown that while behavioral findings may fail to predict future arithmetic performance, the neural findings predict it well (e.g., Supekar et al., 2013). Also, neural findings can help to interpret the behavioral findings (Szűcs & Goswami, 2007), such as different behavioral finding between adults and children in magnitude processing, which comes from undeveloped cognitive control in children and not the inability to process quantities (Temple & Posner, 1998). Moreover, reaching a more thorough understanding of mechanisms underlying arithmetic development and learning might help to develop neurobiological markers to diagnose mathematical learning disabilities at early stages and also assess the response to arithmetic training and interventions.

BEHAVIORAL CORRELATES OF ARITHMETIC DEVELOPMENT AND LEARNING

ARITHMETIC DEVELOPMENT AND LEARNING IN CHILDREN

Arithmetic development and learning lead to behavioral improvement in performance, which is measured by shorter response times (e.g., Ashcraft, 1982) or increased accuracy (J.-A. Jordan, Mulhern, & Wylie, 2009) in mental calculation. These behavioral achievements have been shown as an effect of both development and short-term learning in children. With respect to the developmental effect, a cross-sectional study of 2nd and 3rd graders indicated higher scores for mathematical reasoning and numerical operations in older children (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). In line with this finding, Huber, Fischer, Moeller, and Nuerk (2013) found that 6th graders outperformed 5th graders in solving multiplication and division problems with two levels of complexity. Another cross-sectional study in 4th through 7th grades reported that younger children solved simple division problems more slowly and less accurately than older children (Robinson et al., 2006). In agreement with developmental studies, learning studies reported similar behavioral improvements via different mathematical training methods such as one-to-one tutoring or computer technology (e.g., Fuchs et al., 2013; Li &

Ma, 2010). Rittle-Johnson and Koedinger (2009) showed that iterative lessons facilitate mathematical learning in 6th graders. In line with these findings, neuropsychological studies of patients with severe impairments even in performing simple calculations have shown significant improvements with arithmetic training (Girelli, Delazer, Semenza, & Denes, 1996; Whetstone, 1998). Therefore, it seems that there is a general consensus in the literature regarding these behaviorally robust findings.

These correlates of arithmetic development and learning have been behaviorally characterized as a shift from effortful procedural processes to more efficient and fast processes, such as an increased retrieval of information – in this case, the solutions of arithmetic problems – from semantic long-term memory (Siegler & Shrager, 1984; Siegler, 1988). While younger children utilize various strategies such as finger counting, counting from the larger operand, repeated additions, etc. (Siegler, 1988; Fuson, 2012), older children show less variety in arithmetic problem-solving and report higher reliance on automaticity and retrieval strategies (Ashcraft, 1992). However, according to different proposed models, arithmetic development might not be simply a linear change from more difficult procedural strategies to easier retrieval strategies. For instance, the overlapping-wave model (Siegler, 1996) suggests that while there is a constantly increasing use of retrieval strategies during development, several mixtures of different strategies might be used at different steps as well (see also Shrager & Siegler, 1998). In support of multi-stage arithmetic development and learning, Von Aster (2000) proposed a model of developmental dynamics of number processing and mental calculation. According to this model, three representational modules of the triple-code model (Dehaene et al., 2003), i.e., semantic, visual-Arabic, and verbal modules, are differentially important at different steps of development. Based on this model, these modules are semi-autonomous during development and depend on each other (for more details see Von Aster, 2000). Altogether, although behavioral studies of arithmetic development and learning converge to the same findings, different domain-general factors have been shown to influence arithmetic achievement in children.

DOMAIN-GENERAL COGNITIVE FACTORS INFLUENCE ARITHMETIC DEVELOPMENT AND LEARNING IN CHILDREN

Studies in children have suggested two groups of factors influencing arithmetic development: domain-specific and domain-general factors. Domain-specific factors include the core magnitude processes of numerals such as the approximate number system (N. C. Jordan, Glutting, & Ramineni, 2010; for a review see Dietrich, Huber, & Nuerk, 2015), non-symbolic arithmetic abilities (Gilmore, McCarthy, & Spelke, 2010), and spatial-numerical associations (Siegler & Opfer, 2003). Domain-general factors including cognitive (Bull, Espy, & Wiebe, 2008), educational, and social (Byrnes & Wasik, 2009) factors influence arithmetic development and learning in children (for a review see Cragg & Gilmore, 2014). With respect to domain-general cognitive factors, most of the studies in the field of experimental and developmental psychology have investigated different memory types and executive functions including WM, inhibition, and shifting (cf. Fig. 1) (Bull & Scerif, 2001; Bull & Lee, 2014; Clark, Pritchard, & Woodward, 2010; Fuhs, Hornburg, & McNeil, 2016; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014).

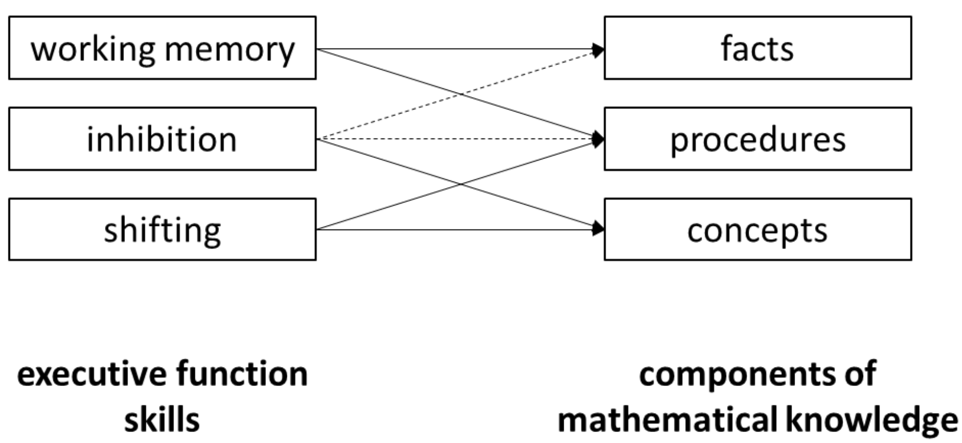

Fig. 1. A theoretical model suggesting the relation between domain-general executive functions and different components of mathematical knowledge. Dashed lines indicate changeable relationships over the course of development [from Cragg and Gilmore (2014)].

Different memory components including WM and short-term memory (STM) have already been reported to be involved in different mathematical competencies during development (Meyer et al., 2010) and at different ages (Menon, 2016). According to the model suggested by Miyake and colleagues (Shah & Miyake, 1996; Miyake & Shah, 1999), WM capacity contains two separate pools of domain-specific resources for verbal and visuospatial information, which keep and manipulate information independently (see also Friedman & Miyake, 2000; Jarvis & Gathercole, 2003; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Moreover, WM has been reported as a pure measure of a child's learning potential (Alloway & Alloway, 2010), which predicts a child's performance in mathematical learning (Alloway & Passolunghi, 2011). STM demonstrates temporal deterioration and capacity limits, whereas WM is a multi-component system that stores and manipulates information in STM, uses attention to manage STM, and applies STM to cognitive tasks (N. Cowan, 1988, 2008; Baddeley & Hitch, 1974; Baddeley, 1992). Recent studies have shown that the relative contributions of different memory components to general mathematic learning change during development. At first, preschool children rely more on visuospatial memory than verbal memory (McKenzie, Bull, & Gray, 2003), which makes it one of the best predictors of arithmetic performance one year later (Simmons, Singleton, & Horne, 2008). Later, starting from school age, learning is more dependent on a verbal rehearsal to preserve information in memory, thus recruiting more the phonological loop (Rasmussen & Bisanz, 2005; Hitch, Halliday, Schaafstal, & Schraagen, 1988). This has been explained by the use of verbally mediated strategies, in which children transform symbols and numbers into verbal code (Geary, Bow-Thomas, Liu, & Siegler, 1996; Logie, Gilhooly, & Wynn, 1994). By the first grade, performance relies equivalently on nonverbal and verbal memory. Later, the visuospatial component again becomes the best predictor of mathematical knowledge. Meyer et al. (2010) showed that the verbal components of memory predict mathematical reasoning skill in 2nd grade, whereas the visuospatial component is the best predictor in 3rd grade. Therefore, different WM and STM components seem to be critical for mathematics learning in general (for a review see Menon, 2016). However, a recent study by Nemati et al. (2017) revealed that at least in adults, the role of WM may be overestimated, because other domain-general processes like planning or self-control overcome WM in complex calculation.

While the majority of studies have investigated the influence of memory components, few studies have taken into account the possible relation of other executive functions, particularly inhibition and shifting, to mathematical knowledge in children. Inhibition is the ability to suppress or ignore distracting and irrelevant information (Bull & Scerif, 2001), a skill that has been reported to be related to mathematical competence in children (St Clair-Thompson & Gathercole, 2006; K. Lee et al., 2012; Gilmore et al., 2013). Cragg and

Gilmore (2014) suggested that inhibition might be more important at younger ages in order to suppress less efficient strategies and to enable more efficient, faster strategies in mental calculation. It also may have a more important role in some operations like multiplication than in others like subtraction. For instance, to retrieve the solution of a problem from a multiplication table (e.g., 3 × 8 = 24), operand-related solutions (21 in this case, which is the correct solution of 3 × 7) need to be inhibited to avoid mistakes (for more see Butterworth, Marchesini, & Girelli, 2003). Furthermore, it is suggested that inhibition and shifting are necessary to acquire new mathematical concepts, to be able to suppress automatic procedural strategies, and to shift attention towards new rules (Cragg & Gilmore, 2014). Shifting is the ability to switch attention between different tasks or different parts of a task (Cragg & Gilmore, 2014). A meta-analysis demonstrated that shifting ability predicts mathematical performance during development (Yeniad, Malda, Mesman, van IJzendoorn, & Pieper, 2013). Shifting is especially needed to switch between procedural strategies, as in complex arithmetic problem-solving (Cragg & Gilmore, 2014). All of the above-mentioned studies point to the fact that mental calculation not only involves domain-specific processes, i.e., manipulating numerals, but also several domain-general cognitive processes (Moeller, Klein, & Nuerk, 2013), which are not specialized to mathematics and are essential for almost every high-level cognitive process. However, the question remains whether different domain-general factors are differentially important at different ages.

NEURAL CORRELATES OF ARITHMETIC PROCESSING

ARITHMETIC COMPLEXITY IN ADULTS

While behavioral studies have already defined arithmetic development as increasing speed and precision in solving problems and finding solutions, it is important to uncover the neurobiological markers underlying this development. This is because neural findings can be helpful in interpreting the behavioral findings and sometimes to avoid misinterpretations. For instance, Temple and Posner (1998) showed similar brain mechanisms in magnitude processing in 5-year-old children and adults, while behavioral findings revealed a huge difference between them. Based on this finding, the authors suggested undeveloped cognitive control, but the same type of magnitude representation in children as in adults. Therefore, it seems essential to study neural correlates of arithmetic development alongside behavioral studies. Furthermore, not all individuals demonstrate the same means of improvement, and they recruit different strategies. Understanding the underlying neurobiological markers might help us to find that what makes arithmetic complex and go one step further to map dysfunctions in individuals having arithmetic difficulties, and develop more appropriate interventions.

Neuroimaging studies in adults have investigated arithmetic complexity by using one-digit and multi-digit arithmetic problems. They showed that one-digit multiplication involves a mostly left frontoparietal network (Gruber, Indefrey, Steinmetz, & Kleinschmidt, 2001; Zago et al., 2001), whereas multi-digit multiplication additionally involves the IPS, inferior parietal lobule and inferior frontal gyrus (IFG) bilaterally (Zago et al., 2001; Delazer et al., 2003; Delazer et al., 2005; Grabner et al., 2007). Larger activation in parietal regions during complex multiplication was interpreted as a result of domain-specific magnitude and quantity-based processes (Delazer et al., 2003) and larger activation in frontal regions as the engagement of domain-general cognitive processes (Gruber et al., 2001; Ischebeck et al., 2006).

Although there is agreement that complex arithmetic calculations rely on additional magnitude and cognitive processes in adults (e.g., Klein et al., 2016), studies pointed to different brain areas. For instance, some studies reported only domain-general cognitive processes related to arithmetic complexity. Gruber et al. (2001) investigated the neural correlates of arithmetic complexity by means of functional magnetic resonance imaging (fMRI) in adults. The simple task consisted of one-digit multiplication and inverted division problems, and the complex task consisted of one-digit and two-digit multiplication and division problems. They found that an increased complexity in arithmetic leads to increased activation within the left IFG, which is known to be involved in WM, executive functions, and the encoding and rehearsal of information. Zago et al. (2001) investigated the neural correlates of simple and complex multiplication problems, which were assumed to be solved by fact retrieval and computational strategies, respectively. Simple calculation led to an activation of the left parieto-premotor network, which was interpreted as a developmental trace of the representation of finger counting. Complex calculation led to an activation of the left frontoparietal network, which was interpreted as reflecting cognitive demands on visuospatial WM, and bilateral activation of the inferior temporal gyri, which are involved in producing visual mental imagery of numerals. Zago et al. (2001) suggested that arithmetic complexity relies on different engagements of visuospatial representations in the calculation. M. Rosenberg-Lee, M. Lovett, and J. Anderson (2009) revealed that arithmetic complexity relies on greater activity in a posterior superior parietal lobule, which is demanded by attentional aspects of arithmetic processing, and in the posterior parietal cortex, which is involved in the mental representation of numerals. However, they did not find any additional activation in horizontal IPS (but see Klein, Moeller, Glauche, Weiller, & Willmes, 2013), the core of numeral magnitude processes (Dehaene et al., 2003), or in the inferior prefrontal cortex, the area engaged in semantic retrieval processes. In another study, Delazer et al. (2003) observed bilateral activation of the frontoparietal network in both one-digit and two-digit multiplication, which was more extended and greater in two-digit multiplication. Moreover, the activation in simple multiplication was extended to the left AG (Delazer et al., 2003). However, because of the fixed number of presented trials in a block design, they avoid direct comparison of simple and complex conditions. This might be a critical problem in neuroimaging studies because the complex calculation usually takes a longer time. Therefore, a part of the activation may be due to the task complexity and not specifically numerical processes.

The left AG is one of the regions that has received contradictory interpretations in arithmetic processing. The left AG involvement, particularly in simple one-digit multiplication, is interpreted as a language-related process, in accordance with the evidence of rote retrieval from long-term semantic memory (Delazer et al., 2003; Grabner et al., 2007; Zhou et al., 2007; see also Klein, Moeller, Glauche, et al., 2013). In contrast, Menon, Rivera, White, Glover, and Reiss (2000) found bilateral activation in the AG to be associated with arithmetic complexity in adults. Moreover, Grabner et al. (2007) revealed that activation of the AG depends on math competencies during solving both one-digit and two-digit multiplication problems. They observed stronger activation of the AG, the middle temporal gyrus (MTG), the supplementary motor area, and the medial superior frontal gyrus (SFG) in the left hemisphere for individuals with high compared to low math competence. They suggested enhanced automatic, language-related processes of the AG during mental calculation in mathematically competent individuals (Grabner et al., 2007). However, Klein, Moeller, and Willmes (2013) suggested that taking into account fiber pathways of the brain sheds light on this seemingly contradictory evidence. In addition to the comparison between one-digit and multi-digit calculation, increased complexity of calculation within one-digit problems has been shown to increase engagement of the frontoparietal network in adults (Jost, Khader, Burke, Bien, & Rösler, 2009; Kiefer & Dehaene, 1997; Stanescu-Cosson et al., 2000). Klein, Moeller, Glauche, et al. (2013) suggested that increasing the complexity leads to a gradual shift from verbally mediated fact retrieval to magnitude related processing. In sum, the studies in adults conclude that increased complexity of arithmetic is associated with increased activation of frontal and parietal areas, showing the additional involvement of cognitive processes and greater engagement of domain-specific and visuospatial processes (see also Klein, Moeller, Glauche, et al., 2013).

Arithmetic complexity has been also documented in a few studies by means of oscillatory electroencephalography (EEG) in adults. It has been shown that mental calculations mostly lead to oscillatory changes in theta and alpha frequency bands (for review see Antonenko, Paas, Grabner, & van Gog, 2010; Hinault & Lemaire, 2016). Theta oscillation originates from hippocampocortical loops (Klimesch, 1999), the bilateral medial prefrontal cortex (Ishii et al., 1999), and the hippocampo-prefrontal feedback loop (Klimesch, 1999). Hence, theta activity has been interpreted as a function of different cognitive processes in mental calculation, such as sustained attention (Ishihara & Yoshii, 1972), executive functions, visual imagery of numerals (Mizuhara & Yamaguchi, 2007), and cognitive workload (Sammer et al., 2007). However, some studies have demonstrated an association between increased theta power and retrieval strategies during mental calculation in adults (Earle, Garcia-Dergay, Manniello, & Dowd, 1996; De Smedt, Grabner, & Studer, 2009; Grabner & De Smedt, 2011). Regarding the alpha frequency band, thalamocortical loops have been reported as the origin of oscillation, which is associated with search and retrieval in semantic long-term memory (Klimesch, 1999). Previous studies have reported an inverse correlation between alpha power and mental activity (Davidson, Jackson, & Larson, 2000), and between alpha power and procedural strategies in arithmetic processing (Micheloyannis, Sakkalis, Vourkas, Stam, & Simos, 2005; De Smedt et al., 2009; for a review see Hinault & Lemaire, 2016). In one of the few studies of arithmetic complexity in adults, Micheloyannis et al. (2005) investigated neurophysiological changes during one-digit and two-digit multiplication solving. They found increased theta power and decreased upper alpha power as a result of increased complexity of calculation. To sum up, arithmetic complexity in adults relies on greater engagement of both domain-general and domain-specific processes, which leads to greater activation in the frontoparietal network, increased theta power, and decreased alpha power.

ARITHMETIC COMPLEXITY IN CHILDREN

A further question is whether arithmetic complexity relies on both magnitude and additional cognitive processes in children, as it does in adults. Children rely on more diverse strategies for arithmetic problem solving compared to adults (Cooney, Swanson, & Ladd, 1988; Lemaire & Siegler, 1995; Sherin & Fuson, 2005; Siegler, 1988); therefore, arithmetic complexity might differ between these two groups. There is even a difference between younger and older children. According to the literature, identical problems are more complex for younger children than for older children. Therefore, the same arithmetic problems can be considered more complex for younger children than for older children. Understanding arithmetic complexity in children is important because children usually have problems with complex calculations rather than simple ones. It is also essential to investigate the neural correlates of this complexity, because it would be helpful for early diagnosis before schooling, and to distinguish the exact weakness of the frontoparietal network of arithmetic processing. This would be also beneficial for developing interventions based on findings in children rather planning based on the findings in adults. However, very little is known about the neurobiological correlates of arithmetic complexity, from directly comparing complex and simple calculations by the same group of children. Moreover, some neuroimaging studies of arithmetic development and learning indirectly give us some insight into the neural correlates of arithmetic complexity in children.

Rosenberg-Lee, Barth, and Menon (2011) found that increased complexity in one-digit addition is associated with both domain-general cognitive processes – increased activation within the right inferior frontal sulcus and anterior insula – and domain-specific magnitude processes – increased activation within the left IPS and superior parietal lobule (SPL) regions – in 2nd and 3rd graders, as in adults (see also Kawashima et al., 2004). However, a developmental frontoparietal shift has been shown in children, which makes it more difficult to draw conclusions about complexity-related brain activation in children than in adults. Rivera, Reiss, Eckert, and Menon (2005) demonstrated an activation increase in the left parietal cortex, supramarginal gyrus, adjoining anterior IPS, and lateral occipitotemporal cortex, while finding decreased activation in the dorsolateral and ventrolateral prefrontal cortex during development. This finding was supported by a cross-sectional study of children from 2nd to 7th grades, which reported an age-related decrease in activation within the IFG and age-related increase in the left MTG during one-digit simple multiplication (Prado, Mutreja, & Booth, 2014). A recent study in 9 to 12-year-old children revealed bilateral activation of the AG and the supramarginal gyri during one-digit subtraction relative to non-symbolic calculation (Peters, Polspoel, de Beeck, & De Smedt, 2016). This difference was a result of greater retrieval strategy use in one-digit subtraction compared to non-symbolic processing, which was more complex and needed more magnitude-based procedural strategies (see also Polspoel, Peters, & De Smedt, 2016). These findings point to an increased functional specialization of the left posterior parietal cortex and decreased dependencies on domain-general processes in frontal regions (for a review see Menon, 2010). Moreover, they reveal that more reliance on the retrieval of information from long-term memory indicates a simpler calculation, whereas procedural algorithm-based strategies are mostly used in solving more complex problems.

Additionally, some studies have suggested a transitional role of the hippocampus system and its connectivity to the prefrontal cortex in the strategy shift from complex to simple calculation (Cho et al., 2012). In a longitudinal study of 7- to 9-year-old children, Qin et al. (2014) showed the pivotal role of the hippocampal system in the transition from procedural to retrieval memory-based strategies (for training see Supekar et al., 2013). They reported that more complex calculations, which rely mostly on counting strategies in younger and less-trained children, engage a prefrontal-parietal network, whereas older and more mathematically trained children show increased hippocampo-neocortical functional connectivity, which is related to more retrieval strategies (Qin et al., 2014; Supekar et al., 2013; but see Rivera et al., 2005). This finding is corroborated by the hypothetical model by Klein et al. (2016) suggesting that the hippocampal network is more used when more arithmetic facts are learned, and also that its connectivity to the AG strengthens during verbally mediated fact retrieval in problem solving (see also Klein, Moeller, Glauche, et al., 2013). Altogether, studies in children suggest that more frontal engagement is associated with arithmetic complexity, which is altered by the improvement of arithmetic performance during development, meaning that problems become less complex for older children. However, it needs to be tested directly in children to see whether arithmetic complexity in children relies on both domain-general and domain-specific regions, as in adults, or if it only relies on domain-general regions, as shown by cross-sectional and learning studies in children.

NEURAL CORRELATES OF ARITHMETIC DEVELOPMENT AND LEARNING

ARITHMETIC LEARNING IN ADULTS

As outlined above, investigating the neural correlates of arithmetic calculation alongside the behavioral correlates of arithmetic learning might have several advantages. For instance, these could include better interpretation of behavioral findings, the development of new diagnostic and intervention techniques, preschool early screening for mathematical difficulties, and also planning the optimal learning methods for patients with different brain lesions. Therefore, it seems to be essential to uncover the neural correlates of arithmetic learning in healthy adults.

The majority of our knowledge about the neural correlates of arithmetic learning in adults comes from multiplication studies. These findings might not necessarily apply to mathematic achievement in general; however, it is easy to indicate the strategy use in this operation. According to these studies, arithmetic learning is characterized by a strategy shift from more effortful and algorithm-based to more retrieval processes, which results in brain activation changes (for a review see Zamarian et al., 2009). On the cognitive level, arithmetic learning has been defined as a decreased engagement of verbal and visuospatial WM, attentional control, planning, self-monitoring, mathematical rules and algorithms in the calculation (Delazer et al., 2003). On the neural level, this learning has been frequently demonstrated to be accompanied by reduced frontoparietal network activation and increased activation of the left AG in adults (Delazer et al., 2003; Delazer et al., 2005; Ischebeck et al., 2006; Ischebeck, Zamarian, Schocke, & Delazer, 2009; Grabner, Ischebeck, et al., 2009; Pauli et al., 1994; see also Klein et al., 2016). The frontoparietal network consists of both domain-general and domain-specific processing areas engaged in mental calculation. Inferior, middle and superior frontal gyri are associated with additional cognitive processes such as WM and planning in mental calculation. The IPS, SPL, and inferior parietal lobule (IPL) are associated with magnitude processing of numerals (for a review see Arsalidou & Taylor, 2011). The left AG is involved with retrieving information from long-term memory (Dehaene & Cohen, 1997; Dehaene et al., 2003). Klein et al. (2016) suggested the pivotal role of the hippocampal cortex and RC in arithmetic fact retrieval, in addition to the left AG (see also Bloechle et al., 2016). Altogether, following the definition of learning by Poldrack (2000), arithmetic learning in adults entails a shift from general purpose processes in frontal regions to more task-specific processes, in this case magnitude and number processes.

The fronto-parietal shift during arithmetic learning has been shown several times. In the first neurophysiological training study by means of event-related potentials (ERP), Pauli et al. (1994) revealed diminished positivity in frontocentral sites and enhanced stable positivity in centroparietal sites due to simple multiplication training. They interpreted this shift as a result of the increase of automatized processes (Pauli et al., 1994). In line with this finding, Delazer et al. (2003) reported activation of the IPS, the IPL, and IFG in the contrast between untrained and trained problems, and less deactivation of the left AG in the inverse contrast (see also Delazer et al., 2005; Ischebeck et al., 2006). Delazer et al. (2003) suggested that this learning in adults is mostly supported by the left hemisphere. This frontoparietal shift was already reported after only eight repetitions of complex multiplication problems in adults (Ischebeck, Zamarian, Egger, Schocke, & Delazer, 2007). They observed gradually decreasing activation of the frontoparietal areas, and at the same time, increasing activation of tempo-parietal regions including the left AG. Moreover, this increase in activation of the left AG has been also shown in untrained but related problems in other basic operations. A successful transfer is important for efficient arithmetic performance because it enables people to solve new problems. Ischebeck et al. (2009) observed stronger activation of the AG in the contrast between related and unrelated division problems, after multiplication training. Therefore, it seems that this shift from frontal to parietal cortex, and then to the left AG, due to arithmetic learning is a robust finding in adults.

Several studies have suggested that the above-mentioned shift depends on several factors. Delazer et al. (2005) showed that while two different learning methods led to a shift from slow procedural strategies to fast automated procedures and retrieval strategies, they were associated to different brain regions. One arithmetic learning method was a “drilling” approach, which emphasizes the rote memorization of calculation procedures (R. Cowan, 2003). In this method, an understanding of the whole procedure is not necessary, and the learning is based on the association between the operands and solution (Baroody, 2003), as in memorizing a multiplication table. The other method enforces an understanding of the procedural strategies based on the mathematical principles and the relation between the operational steps. This method focuses on the application of sequential algorithms until the individuals gradually build up a set of memorized facts (Zamarian et al., 2009). Delazer et al. (2005) demonstrated that training by way of procedural strategies leads to the activation of the precuneus, whereas training by rote leads to the activation of the medial parietal areas extending to the left AG. The authors interpreted successful retrieval strategies, as the dominant process after training, might be associated with different brain regions and not necessarily the left AG (see also Bloechle et al., 2016; Klein et al., 2016). In line with these findings, Grabner, Ischebeck, et al. (2009) examined the specificity of the AG activation for arithmetic fact retrieval. Surprisingly, similar brain activation changes, i.e., decreased activation of the frontoparietal network and less deactivation in bilateral AG, were observed in both arithmetic and figural-spatial problems (Grabner, Ischebeck, et al., 2009). The authors concluded that the AG is not specific to arithmetic learning.

Furthermore, the activation of the left AG depends on mathematical competence (Grabner et al., 2007) and the experimental design (Bloechle et al., 2016). Contradictory to most of the neurocognitive studies on arithmetic training, which have looked only at the contrast of trained and untrained sets in the post-training measurements, Bloechle et al. (2016) conducted both pre- and post-training fMRI measurement. They found that the contrast of trained versus untrained complex multiplication problems in the post-training fMRI illustrated higher activation in the AG, while surprisingly, the contrast of trained problems in a post-training session versus pre-training displayed no significant change in the AG. Ischebeck et al. (2006) suggested that learning-related brain changes depend also on the arithmetic operation. They observed higher activation of the left AG for multiplication, but not for subtraction training. Ischebeck et al. (2006) suggested that while training leads to faster and more efficient strategies in trained subtraction, it leads to a shift from magnitude processes to retrieval strategies only in trained multiplication. Altogether, these studies point to the fact that arithmetic learning in adults might not be a simple shift from frontal areas to parietal areas, and then within parietal areas from more superior regions to the inferior regions, particularly the left AG.

In addition to the fMRI studies, a few oscillatory EEG studies have provided information about neural circuits of arithmetic learning in adults. Grabner and De Smedt (2012) observed an increased power in theta and lower alpha frequency bands over parietal and occipitoparietal sites in trained sets versus untrained matched sets, which was more dominant in a figural-spatial task relative to the arithmetic task. They interpreted these training-related power changes as a result of increased retrieval of the solutions from long-term memory. Similar oscillatory changes were observed in adults who demonstrated a significant training effect in division problem-solving after 10 minutes, in the range of theta, alpha, and beta frequency bands (Skrandies & Klein, 2015). In sum, it seems that arithmetic learning in adults can be defined as a strategy shift. Although several studies have shown the non-specificity of some regions, particularly regarding the involvement of the AG, there is a general agreement about a shift from frontal to parietal areas in arithmetic learning in adults (Zamarian et al., 2009).

ARITHMETIC DEVELOPMENT AND LEARNING IN CHILDREN

The findings in adults are not easily transferable to children (Kaufmann, Wood, Rubinsten, & Henik, 2011). However, neuroimaging studies of arithmetic learning are scarce in children, and most of our knowledge is drawn from studies in adults. The next question to consider is whether the procedural to retrieval shift found in adults is valid for children's development, or are there intermediate stages? Below we discuss why the story of this shift may not capture the learning in children. Moreover, the cross-sectional, longitudinal, and math tutoring studies will be discussed because they can provide useful information about the neural correlates of arithmetic development and learning in children.

Arithmetic development has been defined as a shift from more domain-general processes to more domain-specific processes, and is indicated by a reduced activation of frontal regions and an increased activation of parietal regions. In a cross-sectional study of 8 to 19 years old, Rivera et al. (2005) found that older participants rely more on left parietal areas, supramarginal gyrus, adjoining anterior IPS and the left lateral occipitotemporal cortex during one-digit calculation. In the absence of any alteration in gray matter density, Rivera et al. (2005) interpreted this finding as evidence of enhanced functional maturation. On the other hand, younger participants relied more on bilateral MFG and SFG, and the left IFG, supplementary motor area and anterior cingulate, suggesting more demands on WM and executive function to achieve the same results as older participants. Furthermore, stronger activation of the left hippocampus and bilateral dorsal basal ganglia was observed in younger children, which was interpreted as showing higher demands on both declarative and procedural memory systems (Rivera et al., 2005). The authors concluded that a developmental shift occurs from frontal areas to the left IPL in mental calculation. Kucian, von Aster, Loenneker, Dietrich, and Martin (2008) reported greater activation in the left IPS in adults (age of 22-32 years) compared to 3rd graders and 6th graders, but weaker activation in the anterior cingulate gyrus, which is assumed to be related to attentional and WM load of calculation. Kucian et al. (2008) proposed an increase of automated processes in arithmetic problem-solving with age, which is reflected by the enhanced activation of domain-specific areas and decreased activation of the supporting domain-general areas. These findings were replicated with various symbolic and non-symbolic magnitude comparison tasks comparing the brain activation patterns between children and adults (e.g., Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Ansari & Dhital, 2006; Cantlon et al., 2009). The findings were accompanied by a strategy shift from procedural strategies to retrieval, which is a faster and more efficient way of calculation.

In contrast to the above findings, Rosenberg-Lee et al. (2011) reported increased activation of the frontoparietal network after one year of schooling. They found greater activity in dorsal stream parietal areas, including right SPL, IPS, and AG, as well as ventral visual stream areas, including bilateral lingual gyrus, right lateral occipital cortex, and right parahippocampal gyrus in 3rd graders as opposed to 2nd graders (Rosenberg-Lee et al., 2011). Furthermore, 3rd graders demonstrated stronger activation of the left dorsolateral prefrontal cortex, and greater deactivation of the ventral medial prefrontal cortex, along with greater functional connectivity between the left dorsolateral prefrontal cortex and parietal regions. Increased activation of the IPS was interpreted as reflecting an amodal, language-independent semantic representation of numerical quantity during arithmetic development and learning (see also Ansari, 2008). Regarding the IPS as the core of numerical processing, it has been suggested that the right IPS has a stable role in numerical processing, whereas the functions of the left IPS change during development (Emerson & Cantlon, 2015). However, Kawashima et al. (2004) showed that an activation change occurs in the right IPS as well. They observed greater activation of the right IPS during one-digit calculation in adults (ages 40-49 years) compared to children (ages 9-14 years).

More recent studies have suggested that additional brain regions, particularly the hippocampal system, are involved in arithmetic development and learning. In a one-to-one math tutoring study, 3rd graders revealed a similar strategy shift from procedural to retrieval after eight weeks of training (Supekar et al., 2013). Interestingly, Supekar et al. (2013) found the pre-training hippocampal volume, the functional connectivity of the hippocampus with dorsolateral and ventrolateral prefrontal cortices, and the basal ganglia to predict arithmetic improvement. They suggested that the neural networks underlying arithmetic learning are not necessarily the typical regions such as IPS and the AG involved in arithmetic processing in adults, but are associated with changes in the morphometry of the hippocampus and its connectivity with frontal regions (Supekar et al., 2013). Surprisingly no behavioral measures, consisting of IQ, WM, and general math abilities, predicted arithmetic achievement. Based on these findings, one might conclude that neural measures are helpful for an early preschool diagnosis of future math difficulties, while behavioral measures might fail. A longitudinal study in children aged from 7 to 9 years supported the role of the hippocampus in math learning in children (Qin et al., 2014). The authors suggested a critical transient role of the medial temporal lobe, including the hippocampus, in arithmetic learning in children. Moreover, they showed that the hippocampal system is pivotal in the strategy shift from procedural to retrieval, which was shown by the increased involvement of the hippocampus and decreased involvement of the frontoparietal network during mental calculation (Qin et al., 2014). Note that a new hypothetical model by Klein et al. (2016) suggests hippocampal engagement during arithmetic development and learning in adults as well, which has been supported by training studies in adults (e.g., Bloechle et al., 2016).

It has been also suggested that neural correlates of different operations are not necessarily identical during development. In a cross-sectional study from 2nd through 7th grades, Prado et al. (2014) found similar behavioral correlates in both one-digit subtraction and multiplication problems, but dissociated neural correlates. A grade-related activation increase of the left temporal areas, which are involved in language processes, was observed in multiplication but not in subtraction. With respect to subtraction, a grade-related increase of the right parietal cortex, which is involved in quantity and magnitude processing, was observed. Furthermore, an age-related decrease in activation within the IFG was observed, which shows a developmental frontoparietal shift in arithmetic problem-solving (Prado et al., 2014). The authors concluded that fluency in arithmetic problem-solving is achieved by both increased retrieval and increased use of efficient procedural strategies, depending on the arithmetic operation.

Altogether, a remaining question is whether arithmetic development and learning in children is a simple shift from domain-general processes to more task-related domain-specific processes, as arithmetic learning studies demonstrate in adults, or if there is any shift within domain-general factors. As discussed above, different domain-general factors might influence arithmetic performance during development. Moreover, because of the lack of knowledge about neural correlates of arithmetic learning in children, it is unclear whether these shifts are monotonic or if there are intermediate phases in which certain domain-general processes become important but disappear again in adulthood. Furthermore, it might be interesting to see whether the training studies with children are reliable if there are minimal training sessions, and whether this learning reflects more long-term learning processes.

NEUROIMAGING TOOLS IN CHILDREN

Several different neuroimaging tools have already been used to measure brain activation changes during different cognitive and motoric tasks in children. Each tool has some benefits, but also some limitations that make it less applicable in special populations such as children. For instance, fMRI has a high spatial resolution and records both cortical and subcortical activations, but it is very expensive, highly sensitive to motion artifacts, inappropriate for motoric responses, low in temporal resolution, and requires an artificial body position, which costs extra time and effort in testing children.

FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS)

fNIRS has been developing since the 1990s, and has already been used in about 1000 studies (cf. Fig. 2) to investigate brain activation in healthy and disordered individuals (Ehlis, Schneider, Dresler, & Fallgatter, 2014).

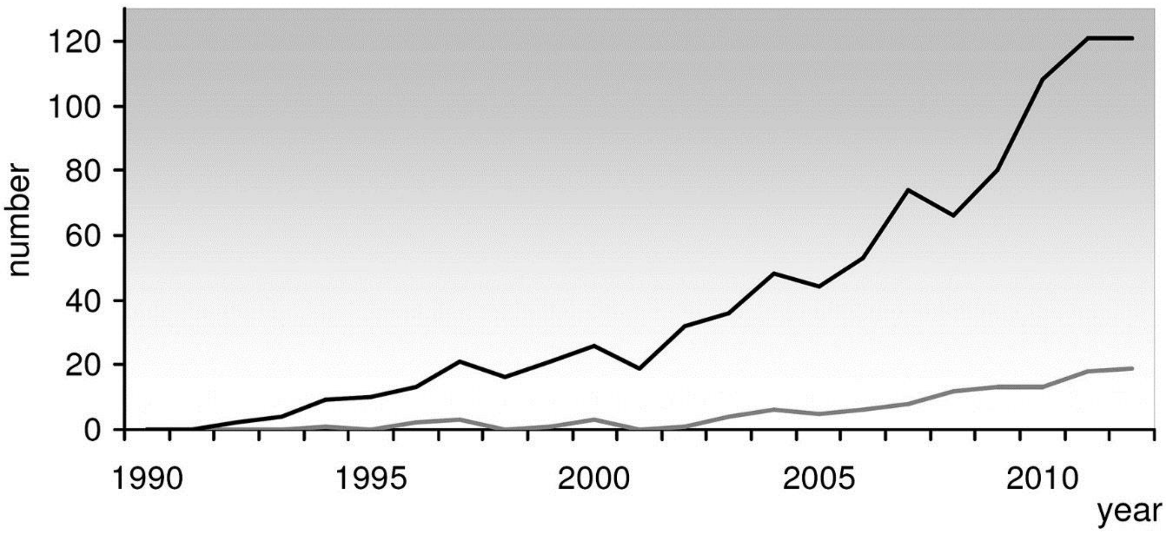

Fig. 2. Graphical time course of published original research articles on fNIRS used to investigate human cortical functions in general (dark gray line) and in psychiatric research in particular (light gray line). Annual publications are depicted [from Ehlis et al. (2014)].

According to fNIRS, neural activation results in increased cerebral blood flow due to neurovascular coupling and increased oxygen consumption (Scholkmann et al., 2014), which lead to changes in oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb) (Wolf et al., 2002). Non-invasively, fNIRS records these changes as an indirect measure of brain activation. Usually, two wavelengths are used in continuous wave fNIRS, which is the most common fNIRS tool in neuroscience. The near-infrared spectral range is about 650-950 nm, the range of light that can propagate into biological tissue, and these wavelengths are only weakly absorbed by water, hemoglobin, collagen, and proteins (Scholkmann et al., 2014). Below 650 nm, light is highly absorbed by hemoglobin, and above 950 nm it is highly absorbed by water (cf. Fig. 3). The two optimal wavelengths are 692 and 830 nm, which provide the highest signal-to-noise ratio (Sato, Kiguchi, Kawaguchi, & Maki, 2004). In this range, O_2Hb and HHb have higher absorption compared to the other substances, because of their low concentrations (for a discussion see review by Scholkmann et al., 2014). Increased O_2Hb or decreased HHb represent brain activation in fNIRS measurement.

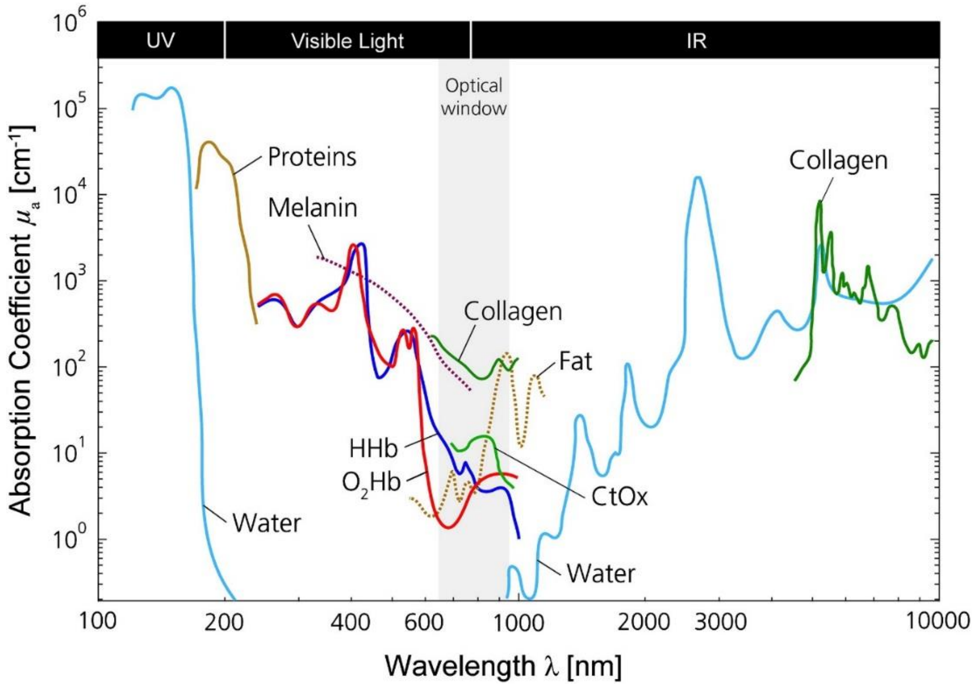

Fig. 3. Natural logarithmic absorption spectra (nM) for different chromophores in human tissue. Shown are the spectra for O_2Hb, HHb, proteins, water, collagen, fat, and cytochrome oxidase (CtOx) in the region from 100 nm to 10,000 nm [from Scholkmann et al. (2014)].

The utilization of fNIRS has several advantages, including the possibility of combining fNIRS with other brain imaging methods such as fMRI (Heinzel et al., 2013), EEG (Schneider et al., 2014), Positron Emission Tomography (Rostrup, Law, Pott, Ide, & Knudsen, 2002), and Single-Photon Emission Computed Tomography (Schytz et al., 2009). Moreover, it is possible to measure brain activation during ecologically valid situations as in school settings (Baker, Martin, Aghababyan, Armaghanyan, & Gillam, 2015; Dresler et al., 2009; Obersteiner et al., 2010) or during whole-body movement (Piper et al., 2014; see also Bahnmueller, Dresler, Ehlis, Cress, & Nuerk, 2014), and there is a relatively low propensity for retaining movement artefacts. Therefore, it is suitable for measuring brain activation in children in upright body postures, like sitting behind a desk and in front of a computer. The other important advantage of fNIRS is in measuring children, patients confined to bed, patients with psychiatric disorders, and those with syndromes involving motor restlessness such as attention deficit/hyperactivity disorder, all of which are situations where many brain imaging methods may fail (Ehlis et al., 2014). fNIRS is also a rather cheap method compared to methods such as fMRI; it is easily applicable, and highly versatile, which altogether allows for frequent measurement repetitions. These advantages made it suitable not only for diagnosis but also recently for use as a treatment method such as fNIRS-neurofeedback (e.g., Marx et al., 2014).

However, fNIRS has also some limitations including restricted depth and lateral spatial resolution (Wabnitz et al., 2010), the confounding influence of extracranial signals (Haeussinger et al., 2014), and variation in anatomical parameters such as scalp-to-cortex distance (Haeussinger et al., 2011) as well as in peripheral hemodynamic parameters such as skin perfusion (Takahashi et al., 2011). Therefore, by means of fNIRS only cortical activation can be detected, and not activation of deep brain structures. Further, fNIRS has been shown to be a reliable tool for the investigation of groups of subjects, although it is not sufficiently reliable for the single-subject measure (for a review see Scholkmann et al., 2014).

While fNIRS seems to be a promising tool in cognitive neuroscience, few studies have already applied fNIRS in the field of numerical cognition (e.g., Dresler et al., 2009; Verner, Herrmann, Troche, Roebers, & Rammsayer, 2013). Altogether, fNIRS seems to be a very suitable tool to measure brain activation in children in an ecologically valid setting, similar to the school setting (Obersteiner et al., 2010). Moreover, children are allowed to move a little – they are not so restricted as with fMRI – and fNIRS easily allows for combined measurement with other tools such as EEG, while requiring fewer noise corrections than other common brain imaging tools like fMRI.

ELECTROENCEPHALOGRAPHY (EEG)

The EEG is a non-invasive measure of the electrical activity of neurons, showing brain activation. Different types of analyses can be done on the EEG signal, which provide different kinds of information. For instance, ERP provides a measure of the brain's electric potentials in response to an external stimulus, which are therefore phase- and time-locked to the stimulus. It offers very high temporal resolution in comparison to other techniques (Luck, 2014). On the other hand, frequency analysis of the EEG signal provides information about brain activity related to functional neural networks (Hinault & Lemaire, 2016). In this method, brain waves are divided into different frequency bands such as delta, theta, alpha, beta, and gamma, and the power changes within each frequency band can reveal different brain functions.

Similar to the other tools, EEG has also advantages and disadvantages. It has a very high temporal, but low spatial resolution, and is relatively sensitive to motion. Moreover, it is much cheaper than many brain imaging tools, and because it is small and portable, it is easily applicable in very different situations such as in schools. However, in order to reduce environmental noise, the best place to record is in an electrically shielded room. The other big advantage of EEG is that brain waves can be recorded and analyzed in different ways. For instance, cognitive and motor processes lead to an event-related potential (ERP) and also to a change in continuous EEG in form of event-related synchronization and desynchronization (ERS/ERD) (Pfurtscheller, 2001). While ERS is a power increase due to the synchronized oscillation of EEG signals, ERD is a short-lasting localized decrease in power (cf. Fig. 4). The percentage values of ERS/ERD are calculated by this expression: ERS/ERD% = (PSD of activation duration – PSD of rest duration) / PSD of rest duration × 100 (Pfurtscheller & Da Silva, 1999). Compared to ERP, which is the summation of post-synaptic potentials and is both time- and phase-locked to the event, ERS/ERD is time-locked but non-phase locked to the event, is highly frequency-band specific (Pfurtscheller, 2001; Pfurtscheller & Da Silva, 1999), and reflects quantificational measures of brain dynamics (Pfurtscheller & Aranibar, 1977).

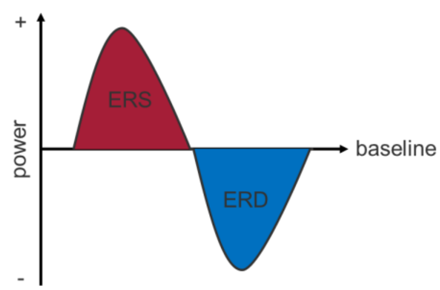

Fig. 4. Increased ERS (red) is identical to increased power density, while increased ERD (blue) means reduced power density. The baseline is defined as the time of no specific process in the brain, such as experimental rest time.

The EEG signal is a combination of different brain waves (cf. Fig. 5). Previous studies indicate that theta and alpha frequency bands are sensitive to cognitive tasks such as arithmetic processing and behave in opposite ways (e.g., Dolce & Waldeier, 1974). For instance, task complexity, attentional and cognitive demands, and memory load lead to theta ERS (increase in theta power) but cause alpha ERD (decrease in alpha power) (Antonenko et al., 2010; Gevins, Smith, McEvoy, & Yu, 1997; Klimesch, 1999; Pfurtscheller, Stancak, & Neuper, 1996; Pfurtscheller & Da Silva, 1999). Furthermore, some cognitive functions are more closely related to one of these frequency bands. In particular, it has been reported that theta band oscillations reflect the encoding of new information, whereas alpha band oscillations reflect searching for and retrieving information from long-term semantic memory storage (Antonenko et al., 2010; O. Jensen & Tesche, 2002; Klimesch, 1999; Sammer et al., 2007; Sauseng & Klimesch, 2008).

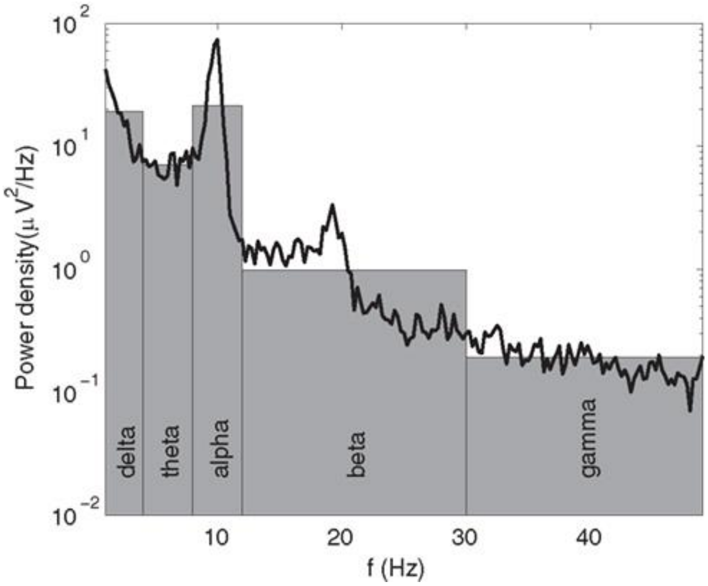

Fig. 5. An EEG frequency band spectrum (black line). The band powers are displayed by the areas of the gray bars, which are analyzed in ERS/ERD method [from Van Albada and Robinson (2013)].

In numerical cognition, there is ambiguity regarding the function of different EEG frequency bands in arithmetic processing. On the one hand, some studies interpret the theta frequency band as being associated with cognitive demands of arithmetic processing such as sustained attention and WM, and the alpha frequency band as an indicator of fact retrieval processes from long-term memory in different arithmetic tasks (Harmony et al., 1999; Klados et al., 2013; Micheloyannis et al., 2005; Mizuhara & Yamaguchi, 2007; Moeller, Wood, Doppelmayr, & Nuerk, 2010). However, other studies interpret the theta band as a function of arithmetic fact retrieval processes and the alpha band as a function of procedural processes (De Smedt et al., 2009; Grabner & De Smedt, 2011, 2012). Therefore, it seems to be essential to conduct studies in this field by means of oscillatory EEG, particularly in children, to shed light on these contradictory interpretations in the field of numerical cognition. Furthermore, these findings would be of interest not only to researchers, but also clinicians, for instance to develop new therapies using EEG neurofeedback.

AIM OF THE STUDIES

The aim of the dissertation project is to uncover the behavioral and neural correlates of arithmetic development and learning in children. This includes monitoring arithmetic achievement during development, both longitudinally and by direct learning. Moreover, this project investigates the relation between domain-general and domain-specific processes, which are essential in the development and learning of arithmetic in children. As outlined previously, this dissertation project contains four studies. In these studies, multiplication performance, as one of the most investigated arithmetic operations in adults (Zamarian et al., 2009), is explored on the behavioral and neural levels in typically developing children. In Study 1 the behavioral correlates of arithmetic learning, along with domain-general cognitive factors influencing this achievement, were investigated longitudinally. The question was whether domain-general factors are differentially important at different ages. In Study 2 the behavioral and neural correlates of arithmetic complexity were investigated. Few neuroimaging studies have investigated this issue in children, so that most of our knowledge comes from adults, yet children rely on more varied strategies for arithmetic problem solving compared to adults. This means that problems defined as complex for children might not be the same for adults. Therefore, the question was whether arithmetic complexity relies on both magnitude and additional cognitive processes in children, as in adults. Study 3 was conducted in typically developing children in order to find the behavioral and neural correlates of short-term arithmetic learning in children. The question was whether the procedural to retrieval shift found in adults is valid for children's development, or if there are intermediate stages. In Study 4 the behavioral and neural changes during arithmetic learning in typically developing children were investigated in order to monitor the brain activation changes gradually. While Ischebeck et al. (2007) observed a frontoparietal shift during arithmetic learning in adults, the question was whether similar changes can be observed in children during learning. This dissertation project can be considered the first step on a long path to develop educational and therapeutic interventions for children with mathematical difficulties.

STUDY 1

Children usually improve in arithmetic problem-solving with age and experience. For instance, strategies used in processing multiplication change from procedure- and strategy-based calculation to retrieval during children's development (Cooney et al., 1988; Lemaire & Siegler, 1995). It has been reported that there is a transition to the retrieval strategy for solving single-digit multiplication problems in 4th grade (Cooney et al., 1988). However, this retrieval process is not constant during the following years of development (Campbell & Graham, 1985). Longitudinal development of the automatic associations within the fact retrieval network has not been sufficiently understood. It is important to investigate the development of multiplication ability from 3rd to 4th grades, because at this stage, basic arithmetic skills begin to improve indirectly, outside of direct training, and are mostly applied in higher-level mathematics at school. Therefore, in Study 1, the behavioral correlates of multiplication development were longitudinally monitored from 3rd to 4th grade.

Furthermore, in Study 1, the contributions of different memory components including verbal and visuospatial short-term memory (STM) and WM were longitudinally investigated in the multiplication performance of 3rd and 4th graders. A meta-analysis of WM and mathematics demonstrated that among several domain-general cognitive factors, WM has a pivotal role in many aspects of development and learning in mathematics (Peng, Namkung, Barnes, & Sun, 2015), which changes dynamically over development (for a review see Menon, 2016). For instance, Meyer et al. (2010) reported that mathematical reasoning was predicted by the phonological component in 2nd graders, while it was predicted by the visuospatial component in 3rd graders. Therefore, the question addressed by this study was whether the shift from the verbal to the visuospatial component of WM is evident in multiplication problem-solving between 3rd and 4th grades. We hypothesized that because children in grade 4 are not receiving direct multiplication training, but rather indirectly apply it, they might not necessarily show improvement in one-digit multiplication. Also that because of this indirect non-verbal training, verbal memories do not make up the essence of this learning anymore.

STUDY 2

Following Study 1, the behavioral and neural correlates of arithmetic complexity were investigated. It has been reported that even older children in 5th and 6th grades make mistakes in arithmetic problem-solving, especially in complex problems (e.g., Huber et al., 2013). However, the origin of arithmetic complexity is not clear in children, because all studies in children have investigated only either simple or complex arithmetic calculation. A few studies in adults have revealed the activation of bilateral brain regions, especially left frontal cortex and IPS, during complex as opposed to simple multiplication problems. In Study 2, multiplication complexity was simultaneously investigated by means of fNIRS and EEG with 5th graders. Simultaneous fNIRS-EEG is helpful to measure, directly and indirectly, neural activity underlying complexity processing in multiplication and to examine cross-measurement validity. There are very few studies in children, and most of our knowledge about arithmetic complexity comes from adults, whereas children rely on more diverse strategies for arithmetic problem-solving than adults. The question here was whether the findings in adults generalize to neurocognitive processing in children. Following the literature showing neurocognitive differences between adults and children, and considering the developmental frontoparietal shift in brain activation underlying arithmetic learning, we hypothesized that greater frontal activation related to complexity would be engaged in domain-general cognitive processes. Moreover, while most of the studies in this field have used a fixed-paced paradigm, in Studies 2 and 3 a self-paced paradigm was used. Whereas the former might lead to a confound between more complex problems and longer activation time, the latter does not. Therefore, another question in these studies was whether the findings of previous studies are replicated by means of a self-paced paradigm (for more details see Shallice, 2003).

STUDY 3

Several fMRI studies of complex multiplication learning in adults have suggested decreasing brain activation in the frontoparietal network along with increasing activation of specific cortical and subcortical areas, especially the left AG. This activation shift has been assumed to be associated with a shift from procedural to retrieval processes in multiplication problem-solving (for a review see Zamarian et al., 2009). On the other hand, longitudinal and training studies of other arithmetic operations in children have revealed a decreased involvement of the frontoparietal network and increased involvement of the hippocampus (Qin et al., 2014; Supekar et al., 2013), but not the AG. Therefore, the question in this study was whether the procedural to retrieval shift found in adults is valid in children's development, or whether there are additional intermediate stages. In Study 3, neural correlates of simple and complex multiplication learning were measured simultaneously by fNIRS-EEG in typically developing children. This was the first systematic brain imaging study of multiplication learning in children using a pre- and post-measurement design. Based on studies in adults, we hypothesized activation reduction in frontal areas related to domain-general processes and an activation increase in a parietal area related to domain-specific processes. Because of the lack of knowledge about neural correlates of arithmetic learning in children, it is unclear whether these shifts are monotonic or if there are intermediate phases in which certain domain-general processes become important but disappear again in adulthood. Furthermore, it might be interesting to see whether the training studies with children are reliable if there are very few training sessions, and whether this learning is reflective of more long-term learning processes.

STUDY 4

Neurophysiological studies in adults revealed oscillatory EEG changes after short-term arithmetic learning, which were indicated by power increases in theta and lower alpha bands (Skrandies & Klein, 2015). Early brain activation changes have been also reported after eight repetitions of complex multiplication problems in adults (Ischebeck et al., 2007). However, early neurophysiological changes during arithmetic learning are still unclear in children. In Study 4, brain oscillatory changes were monitored during six repetitions of multiplication problems by means of ongoing EEG in typically developing children in 5th grade. The question was whether the same oscillatory changes are observable in children during learning. Similar to studies in adults, we hypothesized a power increase in both theta and lower alpha bands in children. Another question was whether the brain activation changes after arithmetic learning are the same as the changes during the course of learning. Post-training changes might be what persists after memory consolidation. Therefore, these two kinds of findings might essentially differ.

LIST OF AUTHOR CONTRIBUTIONS

STUDY 1

Soltanlou, M., Pixner, S., & Nuerk, H. C. (2015). Contribution of working memory in multi-plication fact network in children may shift from verbal to visuospatial: a longitudinal investigation. *Frontiers in psychology*, 6: 1062, doi: 10.3389/fpsyg.2015.01062.

- Study conception and design: SP and HCN
- Experiment and material preparation: SP and HCN
- Acquisition of data: SP
- Analysis and interpretation of data: MS and HCN
- Drafting the manuscript: MS
- Revising the manuscript critically for important intellectual content: MS and HCN

STUDY 2

Soltanlou, M., Artemenko, C., Dresler, T., Haeussinger, F.B., Fallgatter, A.J., Ehlis, A.-C., Nuerk, H.-C. (in press). Increased arithmetic complexity is associated with domain-general but not domain-specific magnitude processing in children: A simultaneous fNIRS-EEG study. *Cognitive, Affective, & Behavioral Neuroscience*.

- Study conception and design: MS, CA, TD, AJF, ACE and HCN
- Experiment and material preparation: MS, CA, TD and HCN
- Acquisition of data: MS and CA
- Analysis and interpretation of data: MS, CA, TD, FBH, ACE and HCN
- Drafting the manuscript: MS
- Revising the manuscript critically for important intellectual content: MS, CA, TD, FBH, AJF, ACE and HCN

STUDY 3

Soltanlou, M., Artemenko, C., Ehlis, A.-C., Huber, S., Fallgatter, A.J., Dresler, T., Nuerk, H.-C. (revision submitted). No support of angular gyrus engagement in arithme-tic learning in children: Evidence from a simultaneous fNIRS-EEG study. *Scientific Reports.*

- Study conception and design: MS, CA, TD, AJF, ACE and HCN
- Experiment and material preparation: MS, CA, TD and HCN
- Acquisition of data: MS, CA and SH
- Analysis and interpretation of data: MS, CA, TD, SH, ACE and HCN
- Drafting the manuscript: MS
- Revising the manuscript critically for important intellectual content: MS, CA, TD, SH, AJF, ACE and HCN

STUDY 4

Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A.J., Nuerk, H.-C., Ehlis, A.-C. (under review). Early oscillatory EEG changes underlying interactive arithmetic learning in chil-dren. *BMC Neuroscience.*

- Study conception and design: MS, CA, TD, AJF, ACE and HCN
- Experiment and material preparation: MS, CA, TD and HCN
- Acquisition of data: MS and CA
- Analysis and interpretation of data: MS, CA, TD, ACE and HCN
- Drafting the manuscript: MS
- Revising the manuscript critically for important intellectual content: MS, CA, TD, AJF, ACE and HCN

STUDY 1: CONTRIBUTION OF WORKING MEMORY IN MULTIPLICATION FACT NETWORK IN CHILDREN MAY SHIFT FROM VERBAL TO VISUOSPATIAL: A LONGITUDINAL INVESTIGATION

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Soltanlou, M., Pixner, S., & Nuerk, H. C. (2015). Contribution of working memory in multiplication fact network in children may shift from verbal to visuospatial: a longitudinal investigation. *Frontiers in psychology*, 6: 1062, doi: 10.3389/fpsyg.2015.01062.

ABSTRACT

Number facts are commonly assumed to be verbally stored in an associative multiplication fact retrieval network. Prominent evidence for this assumption comes from so-called operand-related errors (e.g., $4 \times 6 = 28$). However, little is known about the development of this network in children and its relation to verbal and non-verbal memories. In a longitudinal design, we explored elementary school children from grades 3 and 4 in a multiplication verification task with the operand-related and -unrelated distractors. We examined the contribution of multiplicative fact retrieval by verbal and visuospatial short-term and working memory (WM).

Children in grade 4 showed smaller response times in all conditions. However, there was no significant difference in errors between grades. The contribution of verbal and visuospatial WM also changed with the grade. Multiplication correlated with verbal WM and performance in grade 3 but with visuospatial WM and performance in grade 4.

We suggest that the relation to verbal WM in grade 3 indicates primary linguistic learning of and access to multiplication in grade 3 which is probably based on verbal repetition of the multiplication table heavily practiced in grades 2 and 3. However, the relation to visuospatial semantic WM in grade 4 suggests that there is a shift from verbal to visual and semantic learning in grade 4. This shifting may be induced because later in elementary school, multiplication problems are rather carried out via more written, i.e., visual tasks, which also involve executive functions. More generally, the current data indicates that mathematical development is not generally characterized by a steady progress in performance; rather verbal and non-verbal memory contributions of performance shift over time, probably due to different learning contents.

Keywords: multiplication, arithmetic, fact retrieval, operand errors, verbal working memory, visuospatial working memory

INTRODUCTION

Children usually get better in arithmetic problem-solving with age and experience. For instance, the processing strategy of multiplication in children changes from the procedure- and strategy-based calculation to retrieval during developmental ages (Cooney et al., 1988; Lemaire & Siegler, 1995). It has been reported that there is a transition to retrieval process for solving single-digit multiplication problems in grade 4 (Cooney et al., 1988). However, this retrieval process is not constant during the following years of development (Campbell & Graham, 1985). Nonetheless, longitudinal studies for verification of this claim are scarce. In particular, the development of the automatic associations within the fact retrieval network has not been sufficiently understood.

Of major importance in multiplication verification performance is operand-relatedness. Operand-relatedness is whether the presented or responded answer belongs to the table of one of the operands or not. For instance, in a production task, an operand-related error is when a participant responds with 24 when presented with the problem 7 × 4 because 24 is part of the same multiplication table of one of the operands (here the 4). An operand-unrelated error would be the solution 30 because this number belongs neither to the multiplication table of 4 nor of 7. In a verification task for the problem 4 × 6 = 24, an operand-related verification distractor would be 4 × 6 = 28 and the operand-unrelated distractor would be 4 × 6 = 29.

It has been reported that the operand-related distractor errors make up about 87.5% of all errors in adults (Domahs, Delazer, & Nuerk, 2006; Campbell, 1997) and about 75.7% of all errors in children (Butterworth et al., 2003). The large frequency of operand-related errors has been explained in terms of a developing memory representation in an interrelated network of facts (Ashcraft, 1987). This representation means that during retrieval of a multiplication answer from an interconnected multiplication network, the operand-related distractors will activate the retrieval processing more than the operand-unrelated distractors and lead to a slower response with more errors. These assumptions have been implemented in the network interference model which explains that arithmetic facts are stored as nodes in an associative network in long-term memory and are retrieved via a spreading activation (Campbell, 1995). The presented multiplication generates activation in the corresponding nodes and this activation spreads along the connecting pathways to associated nodes. For example, the presentation of 7 × 3 activates node 7 along with its related nodes (14, 21, 28, etc.) and node 3 with its related nodes (6, 9, 12, etc.). In other terms, the activation of associates which are the operand-related distractors (e.g., 28 instead of 21 in the example above), increases the accessibility of these associates. Consequently, it is more plausible to verify it erroneously as a correct answer. However, in the operand-unrelated distractors (e.g., 25 instead of 21 in the example above), there is minimum activation of the associates, hereby decreasing the accessibility of them as a correct answer. Hence, activation of multiple associates interferes with the solutions because it renders these associates more accessible.

To our knowledge, there are very few longitudinal studies in regard to multiplication development in children considering operand-relatedness. For instance, in a study by Lemaire and Siegler (1995) it was shown that in three sessions of multiplication production assessment in grade 2, the proportion of both operand-related and -unrelated errors increased. The other study which used multiplication verification in children did not report error analyses because it was stable at about 6% in grades 3 and 4 (De Brauwer & Fias, 2009). Therefore, it is still unclear if error patterns and their relation to operand-relatedness change longitudinally in children and consequently what can be inferred with regard to the longitudinal change in the multiplication fact retrieval network.

From the structure of the network interference model, two hypotheses could be brought forward for our longitudinal developmental study on multiplication facts. (i) Because the strength of the association network could increase with age and experience, the operand-relatedness error effect should be larger in older children. (ii) The alternative hypothesis would be that the network becomes more refined in reciprocal inhibition so that the single entries can be better separated with age and experience. Then, the operand-relatedness error effect should be smaller in older children. In our opinion, both views are possible. The current study set out to discern these two hypotheses.

Another main issue of this study is that to our knowledge the possible varying influence of other cognitive processes on the multiplication performance has not been studied longitudinally in children. One natural candidate for such a cognitive process is a memory, containing working memory (WM) and short-term memory (STM). One account of WM capacity is defined by Miyake and colleagues (Shah & Miyake, 1996; Miyake & Shah, 1999). In this model, WM capacity contains two separate pools of domain-specific resources for verbal and visuospatial information. Each domain keeps and manipulates information independently from the other. This distinction between verbal and visuospatial domains has been supported by the previous findings (e.g., Friedman & Miyake, 2000; Jarvis & Gathercole, 2003; Miyake et al., 2001). WM has been reported as a pure measure of a child's learning potential (Alloway & Alloway, 2010). Thus, it has been assumed to predict a child's performance in mathematic learning based on the WM skills (Alloway & Passolunghi, 2011). While WM is defined as an ability of storage and manipulation of information, STM is considered as only storage of information for a temporary period of time (for more see Alloway, Gathercole, & Pickering, 2006). In other words, WM is a memory system containing separable interacting components, while STM is almost a single store (Alloway et al., 2006). In sum, STM demonstrates temporal deterioration and capacity limits, whereas WM is a multi-component system that stores and manipulates information in STM and uses attention to managing STM and applies STM to cognitive tasks (N. Cowan, 1988, 2008; Baddeley & Hitch, 1974; Baddeley, 1992). Therefore, STM involves a minimal load of processing, while WM contains an additional process for manipulation of information that leads to higher loading of the process. Different components of STM and WM have already been reported to be involved in different mathematical tests during developing stages (see also Meyer et al., 2010) but the possibility of their different role in development of multiplication has not been longitudinally considered – therefore, the differential roles of STM and WM will also be considered in the current study.

Recent studies have shown that the relative contributions of memory components to general mathematic learning changes during development ages. At first, preschool children rely more on visuospatial memory than verbal memory for learning and remembering arithmetic; therefore, the best predictor of the arithmetic performance at this age is visuospatial sketchpad capacity (McKenzie et al., 2003; Simmons et al., 2008). Later, starting from school age, learning is more dependent on a verbal rehearsal to preserve information in memory, thus recruiting more the phonological loop (Rasmussen & Bisanz, 2005; Hitch et al., 1988). This has been explained by verbally mediated strategies, in which children transform symbols and numbers into verbal code (Geary et al., 1996; Logie et al., 1994). By the first grade, performance relies equivalently on nonverbal and verbal memory. Meyer et al. (2010) showed that the verbal components of memory predict mathematical reasoning skill in grade 2, whereas the visuospatial component is the predictor in grade 3. Therefore, different WM and STM components seem to be critical for mathematics learning in general. However, currently, we have only little data on how the different verbal and visuospatial components of WM and STM contribute to multiplication performance in different ages in elementary school and how the importance of such components changes over time. For our study, we hypothesized a shift between memory components, from verbal to visuospatial, in children during development in multiplication similarly to those reported by Meyer et al. (2010) for mathematical reasoning. In the current study as we collected longitudinal data, the first aim was to evaluate in which way children process multiplication in grade 3 and 4. According to the previous findings, we expected children in grade 4 to be faster and possibly less error-prone than in grade 3. The second aim was to investigate whether their memory processing is differentially influenced by operand-relatedness with age and experience, especially with regard to the error data. Finally, the third and main aim of this study was to investigate the contributions of verbal-linguistic and visuospatial non-verbal representations on arithmetic skill, namely the influence of verbal and visuospatial STM and WM on multiplication skill.

MATERIALS AND METHODS

The current study was part of a large longitudinal project evaluating numerical development from grade 1 to grade 4. In this study, we focused on the development of multiplication performance which was measured only from grade 3 to grade 4.

PARTICIPANTS

In total, 77 native German-speaking Austrian children (39 girls and 38 boys) were assessed in multiplication both at the end of grade 3 and grade 4. The children were between 8 years 6 months and 10 years 5 months (M = 9 years 4 months, SD = 7 months) in grade 3 and one year older in grade 4. All children had a normal or corrected-to-normal vision and IQ scores in the normal range. No child received special education services or had documented brain injury or behavioral problems. This study was carried out in accordance with the recommendations of the Landesschulrat, the regional school administration, which was responsible for approval of school-related studies in Austria at that time. Parents of all subjects gave written informed consent in accordance with the Declaration of Helsinki.

Multiplication stimuli

Children were tested on a computerized multiplication verification task. The experiment started with 8 practice trials. Multiplication problems (range of operands: 3–8; problem size: 13–54) along with the answer probe were presented at the same time on the screen in white against a black background (font: Arial; size: 48-point). Problems were presented in the form x × x = xx at the x/y coordinates (512/300) on a screen with the resolution set to 1024 x 768. In total there were 80 multiplication trials. Half of the trials were true (i.e., the solutions were displayed) and half of them were false (i.e., distractors which had to be rejected were displayed). The distractors consisted of operand-related and operand-unrelated trials. In the operand-related trials the operand split was ± 1 from the solutions on the multiplication table (e.g., 6 × 3 = 21). In the operand-unrelated trials, the displayed answers were not from the multiplication table. In the operand-unrelated trials the displayed answer differed from the solution by ± 2 to ± 9, with the average split matched at 0.4 (e.g., 6 × 3 = 13). The task was a verification paradigm where the displayed answer needed to be verified as correct or incorrect. Problem size was held approximately constant between item categories. Problems and answer probes were presented until a response was given or the response time of 15000 ms finished. The response was made by pressing the ‘‘Alt’’ or ‘‘Alt Gr’’ button of a QWERTZ keyboard to verify whether the displayed answer was the solution or distractor, respectively. It is essential to note that the solutions and distractors refer to the stimuli presented in the verification task, not the children’s responses. The children’s responses were correct or incorrect. The fixation cross was presented at the beginning of each trial for 500 ms. The inter-stimulus interval was set to 1500 ms. No feedback was given.

Memory tasks

Four memory components including verbal and visuospatial STM and verbal and visuospatial WM (Alloway et al., 2006; Alloway & Passolunghi, 2011) were assessed in the present study. For verbal STM, children were asked to immediately recall spoken sequences of letters (presentation rate: one letter per second). Starting with two-item sequences, sequence length was increased by one letter when at least two of three given sequences were recalled correctly; otherwise, testing was stopped. The verbal STM score was the maximum sequence length at which at least two sequences were repeated correctly. For visuospatial STM, in a block tapping task (Corsi, 1973), children needed to repeat pointing to cubes in the same order as the experimenter. Again, children started with two-item sequences. The procedure and scoring were identical to those in letter repetition. In general, forward span tests were defined as STM and backward span tests were defined as WM (N. Cowan, 1988; see also N. Cowan, 2008).

For verbal and visuospatial WM, children were asked to recall sequences of letters and blocks in reverse order. The procedure and scoring were identical to those in the STM tasks. It is noteworthy that the current study included forward recall as a measure of verbal and visuospatial STM and backward recall as a measure of verbal and visuospatial WM. In forwarding recall tasks, the processing load is minimal as children immediately recall the sequences (Alloway et al., 2006). In contrast, in the backward recall tasks, there is an additional requirement to recall the reverse sequence that imposes a substantial processing load on the child. This higher processing load has been illustrated by the finding that forward spans scores are higher than backward spans (Isaacs & Vargha-Khadem, 1989; Vandierendonck, Kemps, Fastame, & Szmalec, 2004).

PROCEDURE

All children were assessed individually in one-on-one sessions in a separate room. In both grades, multiplication performance and WM and STM were assessed.

ANALYSIS

Response times (RTs) were measured by key-press. Only RTs for correct responses were entered into the analyses. Furthermore, response latencies shorter than 200 ms or longer than 15000 ms were not considered; however, there was no response out of this range. In a second step, responses outside the interval of ± 3 SD around the individual mean were excluded. Thus, about 3% of the responses in grade 3 and about 4.5% of the responses in grade 4 were not considered for further analyses. First, we ran two repeated-measures analyses of variance (ANOVAs), first for the solution and distractor (operand-related and -unrelated together) trials for both grades and second for the operand-related and operand-unrelated distractors for both grades. Second, the correlation of the WM components was analyzed using stepwise multiple linear regression analysis on mean RTs and error rates. For the error analysis, an arcsine square-root transformation was applied to approximate normal distribution (e.g., Winer, Brown, & Michels, 1971).

Because of controversies regarding confirmation of null hypothesis using traditional statistical inference, the Bayesian method was used in the current study. The method described in detail by Masson (2011) enables calculating graded evidence for null hypothesis (i.e., no difference between groups) and the alternative hypothesis (i.e., the difference between groups). In the analysis, the sum of squares and number of observations from an ordinal analysis of variance (ANOVA) were used to calculate Bayesian factors which then can be used to calculate posterior probabilities (see also Raftery, 1995). In fact, we employed the Bayesian method in order to estimate the likelihood of correctness of the null and alternative hypotheses.

RESULTS

Trials with RTs 3 standard deviations above or below a child's average RT were excluded. Children with a trial exclusion or an error rate of more than 33% were not considered (6 children [mean age = 9 years 4 months, 2 girls and 4 boys]). Thus, the data of 71 children was considered in the analyses. Children had on average significantly higher WM scores in grade 4 than in grade 3 (see Table 1). A previous study suggested that the window between 2nd and 3rd grades is too short a time frame for major changes in WM capacity (Meyer et al., 2010) but interestingly we found that this difference is statistically significant between grade 3 and 4.

Table 1. Means and standard deviations of memory components.

	Grade 3		**Grade 4**			
Variable	***M***	***SD***	***M***	***SD***	t^a	p^b
Verbal STM	4.55	0.73	4.92	0.73	-4.68	<.001
Verbal WM	2.89	0.60	3.30	0.55	-4.72	<.001
Visuo-spatial STM	5.06	0.70	5.56	0.67	-4.88	<.001
Visuo-spatial WM	4.18	1.10	4.69	0.86	-3.82	<.001

[a] Paired sample *t*-test
[b] Two-tailed significance level of .01

SOLUTION VS DISTRACTOR

First, we investigated the effect of grade on the solution and distractor (both operand-related and -unrelated together) trials for RTs and accuracy.

RESPONSE TIMES

Raw RT of correct responses was analyzed by repeated-measures ANOVA with grade (3 or 4) and condition (solution or distractor) as within-participant factors. Children took on average 3118 ms (SD = 1243 ms) to choose the correct answer in grade 3 and 2320 ms (SD = 916 ms) in grade 4. Children in grade 4 were on average 798 ms faster than in grade 3, $F(1,70) = 58.46$, $p < .001$, $\eta_p^2 = 0.46$. RTs for the solution condition was 531 ms faster than for the distractor condition which indicated a significant difference between the two conditions, $F(1,70) = 162.07$, $p < .001$, $\eta_p^2 = 0.70$. Interaction of grade × condition showed that the effect of grade is greater for the distractor than for the solution, $F(1,70) = 9.14$, $p = .003$, $\eta_p^2 = 0.12$ (Fig. 1a and Table 2). Bayesian analysis revealed that the posterior probability of null hypothesis for grade and condition was about zero (the same probability of alternative hypothesis was complementary, i.e., about 1). The posterior probability of null hypothesis for interaction was .10 (the same probability of alternative hypothesis was .90).

Table 2. Mean (M) and standard deviation (SD) of the RTs and error rates for multiplication trials.

		Grade 3		**Grade 4**	
		M	***SD***	***M***	***SD***
RT (ms)	Solution	2799	1091	2108	847
	Operand-related distractor	3468	1466	2523	948
	Operand-unrelated distractor	3406	1371	2544	1045
Errors (%)	Solution	6.30	6.24	5.77	6.04
	Operand-related distractor	7.68	9.41	8.94	10.52
	Operand-unrelated distractor	4.15	7.37	5.56	8.17

ERROR RATES

Error rates were analyzed by repeated-measures ANOVAs with grade (3 or 4) and condition (solution or distractor) as within-participant factors. Overall, children responded incorrectly to 6.11% of all trials in grade 3 and on 6.51% in grade 4. Error rates did not differ significantly neither between the grades, $F(1,70) = 0.11$, $p = .74$, $\eta_p^2 = 0.002$, between the conditions, $F(1,70) = 0.095$, $p = .76$, $\eta_p^2 = 0.001$, nor in their interaction, $F(1,70) = 3.04$, $p = .09$, $\eta_p^2 = 0.042$. Thus, the RT differences could not be explained by speed-accuracy trade-offs. Bayesian analysis revealed that the posterior probability of null hypothesis for grade and condition was .89 (the same probability of alternative hypothesis was .11). The posterior probability of null hypothesis for interaction was .65 (the same probability of alternative hypothesis was .35). This is rated as positive evidence for the null hypothesis applying the criteria suggested by Masson (2011).

OPERAND-RELATED VS OPERAND-UNRELATED

Second, we investigated the effect of grade on the operand-related and operand-unrelated distractor trials for RTs and accuracy. Note that this analysis was done for the distractors only.

RESPONSE TIMES

Raw RT of correct responses was analyzed by repeated-measures ANOVA with grade (3 or 4) and condition (operand-related or operand-unrelated) as within-participant factors. Children in grade 4 were on average 903 ms faster than in grade 3, $F(1,70) = 53.74$, $p < .001$, $\eta_p^2 = 0.43$. Raw RT neither differed significantly between conditions, $F(1,70) = 0.28$, $p = .60$, $\eta_p^2 = 0.004$, nor did interaction between conditions and grade, $F(1,70) = 1.57$, $p = .22$, $\eta_p^2 = 0.022$, (Table 2 and Fig. 1b). Bayesian analysis revealed that the posterior probability of null hypothesis for grade was about zero (the same probability of alternative hypothesis was about 1). However, the posterior probability of null hypothesis for condition was .88 (the same probability of alternative hypothesis was .12); and for interaction .79 (the same probability of alternative hypothesis was .21).

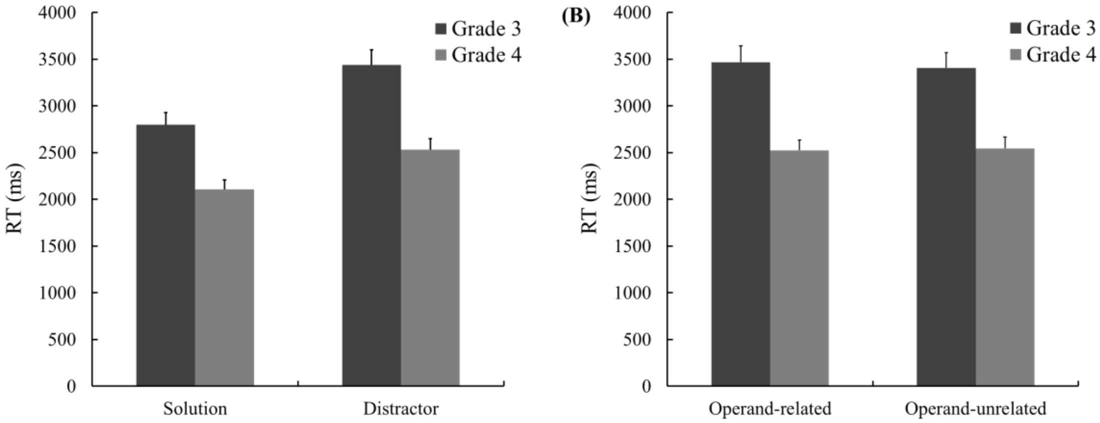

Figure 1. A) Mean RTs (in ms) for the solution and distractor. B) Mean RTs (in ms) for the operand-related and -unrelated distractors. Error bars reflect standard errors.

ERROR RATES

Error rates were analyzed by repeated-measures ANOVAs with grade (3 or 4) and condition (operand-related or operand-unrelated) as within-participant factors. The operand-related distractor trials were significantly more error-prone than the operand-unrelated distractor, $F(1,70) = 22.82$, $p < .001$, $\eta_p^2 = 0.25$. Error rates neither differed significantly between the grades, $F(1,70) = 1.43$, $p = .24$, $\eta_p^2 = 0.02$, nor did interaction between conditions and grade, $F(1,70) = 0.06$, $p = .81$, $\eta_p^2 = 0.001$. Bayesian analysis revealed that the posterior probability of null hypothesis for grade was .80 (the same probability of alternative hypothesis was .20). However, the posterior probability of null hypothesis for condition was about zero (the same probability of alternative hypothesis was about 1); and for interaction .89 (the same probability of alternative hypothesis was .11).

RELATION BETWEEN MULTIPLICATION PERFORMANCE AND MEMORY COMPONENTS

REGRESSION ANALYSIS[1]

[1] We know from many previous numerical and arithmetic experiments that RT data in children are very noisy. Hence, employing z-transformed RT to reduce inter-individual differences in intra-individual variance (cf. Nuerk, Kaufmann, Zoppoth, & Willmes, 2004, and many following papers since), we reanalyzed linear regressions. In general, none of the memory components predicted z-transformed RTs in grade 3. In grade 4 the verbal WM component predicted solution z-transformed RT, distractor z-transformed RT, and operand-related distractor z-transformed RT. However, this suggests that intra-individual noise in the RT data may at least partially account for the null effects observed in RTs.

In order to investigate which memory component predicted multiplication performance in grade 3 and 4, a series of stepwise regression analyses were conducted. For each grade, one regression predicted each of the 10 verification dependent variables (total RT, solution RT, distractor RT, operand-related distractor RT, operand-unrelated distractor RT, total error, solution error, distractor error, operand-related distractor error, and operand-unrelated distractor error) from the four memory components measured concurrently. All four memory scores were entered simultaneously with a stepwise function. This approach allowed us to identify the best predictors for different dependent variables in both grades. The model of total errors in grade 3 comprised only the predictor verbal WM, $R^2 = .057$, adjusted $R^2 = .044$, $F(1, 69) = 4.193$, $p = .044$, while the other memory components failed to explain significant amounts of additional variance. Inspection of the individual beta weights indicated a significant influence of verbal WM (Table 3). The model of the operand-unrelated distractor errors in grade 3 comprised only the predictors verbal WM and verbal STM, $R^2 = .178$, adjusted $R^2 = .153$, $F(2, 68) = 7.340$, $p = .001$, while the other memory components failed to explain significant amounts of additional variance. Inspection of the individual beta weights indicated a significant influence of verbal WM and verbal STM (Table 3). The model of total errors in grade 4 comprised only the predictor visuospatial WM, $R^2 = .072$, adjusted $R^2 = .058$, $F(1, 69) = 5.325$, $p = .024$, while the other memory components failed to explain significant amounts of additional variance. Inspection of the individual beta weights indicated a significant influence of visuospatial WM (Table 3). All other predictors and criterion variables were not significant in regression analyses. Bayesian analysis revealed that the posterior probability of null hypothesis for total error in grade 3 was .51 (the same probability of alternative hypothesis was .49). However, the posterior probability of null hypothesis for the operand-related distractor error was about zero (the same probability of alternative hypothesis was about 1); and for total error in grade 4 was .38 (the same probability of alternative hypothesis was .62).

Table 3. Results for significant predictors entered in the stepwise multiple regression analysis.

Grade	Variable	Predictor	*B*	Standardized beta	*t*	*p*[a]
3	Total error	Verbal WM	-0.049	-0.239	-2.048	.044
	Operand-unrelated distractor error	Verbal STM	0.095	0.408	3.603	.001
		Verbal WM	-0.069	-0.242	-2.132	.037
4	Total error	Visuo-spatial WM	-0.041	-0.268	-2.308	.024

DISCUSSION

In the current study, we collected longitudinal data from children in grade 3 and 4. The first aim of the study was to evaluate how children process multiplication in different grades. The second aim was to investigate the development of the multiplication fact retrieval network, i.e., whether their memory of multiplication facts is influenced by operand-relatedness. Furthermore, the third and main aim of this study was to investigate the contributions of verbal and visuospatial STM and WM to multiplication skill.

MULTIPLICATION FACT FLUENCY INCREASES LONGITUDINALLY WITH AGE AND EXPERIENCE

As we expected, children in grade 4 were faster than in grade 3 which is in line with previous findings that children become faster during development (Koshmider & Ashcraft, 1991; De Brauwer & Fias, 2009; Butterworth et al., 2003; Lemaire, Abdi, & Fayol, 1996). Although children in both grades depended heavily on memory retrieval to solve the simple one-digit problems, this retrieval processing was more dominant in grade 4 (Verguts & Fias, 2005). Thus, because of the faster processing, verification of the solution and rejection of the distractor was faster.

As regards RTs, children in both grades verified the solutions faster than the distractors (Koshmider & Ashcraft, 1991; De Brauwer & Fias, 2009). Koshmider and Ashcraft (1991) explained this result by saying that the solutions facilitate verification of the correct answer in children when the solutions are used as a prime, probably because the solutions make the strongest activation in the related nodes which in turn accelerates memory retrieval process.

As regards errors, the difference of error rate between the solutions and distractors was not statistically significant in the current study: The error rates remained stable, about 6% of grade 3 and 4. Again, this non-significant change in error rates is in line with previous results (Koshmider & Ashcraft, 1991; De Brauwer & Fias, 2009).

In brief, children in grade 4 were faster in both conditions than in grade 3 but their performance in regard to error did not differ significantly. This can be explained by more efficient and faster solving strategies with age which are, however, not yet more accurate than the slower strategies of younger children.

NO CHANGES IN THE OPERAND-RELATEDNESS EFFECT WITH AGE AND EXPERIENCE

In line with our main hypothesis, the operand-related distractors were erroneously responded to significantly more frequently than the operand-unrelated distractors. The finding is in line with the previous studies in children (Butterworth et al., 2003; Koshmider & Ashcraft, 1991; Lemaire & Siegler, 1995) which reported operand-related errors as the most frequent errors. It implies that multiplication facts are stored in the associative network already one year after the first multiplication facts are learned. The suggestion of the interacting neighbors model even holds for those young children in grades 3 and 4. The model assumes that the operand-related distractors lead to stronger confounding with the solutions than the operand-unrelated distractors.

However, as regards the operand-relatedness effect, we found no difference between grades 3 and 4. In fact, there was an operand-relatedness effect in both grades but it was neither stronger nor weaker than in the other grade. This result was again in line with the only longitudinal study of multiplication in a verification paradigm in children (De Brauwer & Fias, 2009). The finding of the present study is consistent with the idea that multiple changes may occur in the associative network. First, the strength of the association network increases with age and experience (which leads to faster retrieval in older children). Second, the network may become more refined in reciprocal inhibition. More association strength with age would lead to a higher operand relatedness effect because related entries are activated more. However, better reciprocal inhibition would lead to the better differentiation between entries and therefore to a lower operand relatedness effect because related entries could be more easily inhibited. If both processes increase similarly with age and experience, the operand-relatedness effect may stay unchanged. This is what we found in the present study.

AN AGE-RELATED SHIFT FROM VERBAL TO VISUOSPATIAL WORKING MEMORY PREDICTING MULTIPLICATION PERFORMANCE

Interestingly, we found that verbal WM predicts multiplication problem-solving in grade 3, while in grade 4 visuospatial WM is the predictor. This finding for multiplication performance extends and refines current accounts of the role of different WM components during different developing stages. A developmental change of the influence of verbal and visuospatial components was reported several years ago for more general math capabilities: It was shown that there is a strong link between verbal and mathematical skills when young children are learning new information which becomes weaker with older children as the result of practice (A. R. Jensen, 1980). In accordance with this finding, several studies have shown the weak conjunction between the phonological loop and mathematical performance in adults (Heathcote, 1994; Logie & Baddeley, 1987; Logie et al., 1994). The present study did not find any significant correlation between verbal WM and multiplication performance in grade 4 which can be related to a gradual shift from strongly verbal representations of multiplication to the build-up of a more abstract semantic retrieval of mathematical facts from long-term memory which is visually based, at least when the stimuli are presented visually as in our study.

One possible suggestion is that one may expect to see more predictability of verbal WM in grade 4. However, this was not the case. Three reasons may explain this finding. First, learning and task context of multiplication problems encountered in (Austrian) schools may contribute to their explanation. While in the initial learning phase in grades 2 and 3, multiplication problems may be more auditorily and verbally trained, they may be more often encountered visually as part of more complex arithmetic problems in grade 4. Second, the shift towards more visuospatial processing is consistent with previous studies on arithmetic development showing that in children, arithmetic tasks require superior demand of visuospatial processing during the development (Alloway & Passolunghi, 2011). In fact in adults, Fürst and Hitch (2000) showed that the phonological loop is not crucially caught up in retrieving factual mathematical knowledge which is also consistent with our data that verbal WM plays a lesser role in older children. Finally, the same verbal to visuospatial WM shift has been observed in other arithmetic domains. Meyer et al. (2010) found such a shift from grade 2 to grade 3 in some basic arithmetic and mathematical reasoning. For these reasons, we believe that our finding of a developmental shift from verbal to visuospatial WM with age and experience does not come as a surprise but is actually consistent with the literature in other fields of arithmetic development. In sum, the data shows an important developmental shift from verbal to visuospatial WM in the prediction of simple multiplication problem performance (as indexed by overall errors) from grade 3 to grade 4.

Furthermore, neuroimaging studies revealed a neural dissociation of verbal and visuospatial WM (Smith, Jonides, & Koeppe, 1996; Thürling et al., 2012), which were modified differently due to arithmetic training. The brain activation pattern of development and training of calculation shows a shift of activation from the frontal to the parietal regions (for a review see Zamarian et al., 2009). This modification shows a shift from the verbally representation of the calculation to more visually representation. While the frontal area is involved in verbal WM, the parietal area is mostly involved in visuospatial WM (Dumontheil & Klingberg, 2012; for a review see Cabeza & Nyberg, 2000).

Interestingly, for the operand-unrelated distractor errors in grade 3, verbal STM reached significance as the only STM predictor in our whole study. However, this makes sense because during the second and third years of elementary school children are commonly highly trained with the direct verbal learning of multiplication facts. Therefore, verbal STM is still significant for multiplication in grade 3. In the fourth grade, however, children have to use the learned skills, such as multiplication, indirectly in more advanced mathematic problems such as mathematical text questions which do not involve any aspect of STM massively in this grade. Verbal STM may only affect the operand-unrelated distractor errors because the operand-relatedness may lead to interference specifically in the STM where no information is manipulated. Vice versa, the solutions share at least one element with possible operand-related distractors. It seems plausible that in such clear cases which require no manipulation and selection of information, verbal STM processing is most predictive. Again, our finding that verbal STM influences multiplication performance in earlier grades is consistent with previous findings from other more general arithmetic measures. For instance, Alloway and Passolunghi (2011) showed that verbal and visuospatial STM were involved in the arithmetic performance at age 7 but only visuospatial STM was involved at age 8. Although the prediction of operand-unrelated distractor error by verbal STM in grade 3 was reasonable, the positive correlation between verbal STM and operand-unrelated distractor error was unexpected. One possible explanation would the interference of other simultaneous processes, which occupy STM. We know that the results of simple multiplication problems are retrieved from long-term memory (for a review of neuroimaging studies see Zamarian et al., 2009). Indeed, the results of the one-digit time one-digit multiplication problems, which belong to the multiplication table are stored in long-term memory and retrieved via WM. Therefore, it may conclude that to answer these problems, we do not rely so much on STM (Butterworth, Cipolotti, & Warrington, 1996). Hence, any involvement of STM in other simultaneous processes can interfere with this fact retrieval procedure. But this is not the case of WM. We know that WM is involved in almost every cognitive process. Since WM has a crucial role in the retrieving of multiplication result, higher WM capacity can lead to a better manipulation on different processing including multiplication performance. Butterworth et al. (1996) showed that in a patient with impaired STM, the mental calculations such as one-digit multiplication are intact. However, we believe that this is only a possible interpretation, which needs to be tested directly.

None of the memory components were able to predict RTs in both grades. We believe that this is due to high (inter-individual and intra-individual) variability in the RT measures for the children, which may be overcome in comparisons of means but may be critical for inter-individual comparisons and correlations. Variability in RTs can be explained by several sources. First, children use different strategies for multiplication problem-solving (Cooney et al., 1988; Sherin & Fuson, 2005) which mostly lead to equal (correct) responses but to different RTs. Second, individual differences in mathematical competence modulate RTs during mental arithmetic. For instance, Grabner et al. (2007) suggested that the recruitment of retrieval strategies during arithmetic problem-solving may be caused by individual differences in mathematical ability. Therefore, different children rely on different memory processes. This may lead to highly variable RTs, not only intra-individually but also inter-individually, even though both ways may lead to the solution of the multiplication problem. For these reasons, RT may be more sensitive to intra- and inter-individual variability than errors. Future studies should probably combine investigations of the strategy used and different WM components to examine if specific WM components are associated with specific solving strategies.

CONCLUSIONS AND PERSPECTIVES

In line with the previous findings (Meyer et al., 2010; Swanson, 2006), the current study suggests that although verbal WM may facilitate early stages of arithmetic learning and performance, visuospatial WM may support later arithmetic performance during the development – at least during elementary school. We would like to mention that while we found this shift in the prediction of multiplication problem-solving from grade 3 to 4, the others found it in different ages, however albeit for different mathematical contents. For instance, Meyer et al. (2010) found the shift in mathematical reasoning from grade 2 to 3. Meyer et al. (2010) were concerned with mathematical reasoning. Their mathematical reasoning subtest of the WIAT-II "is a verbal problem-solving test that measures the ability to count, identify geometric shapes and solve single- and multi-step word problems." In contrast, we were concerned with multiplication. Multiplication – as said above – is introduced in grade 2, verbally trained in grade 3 and then integrated into visual tasks in grade 4 – therefore the shift from verbal to visual makes sense for multiplication at exactly that age. Because the mathematical reasoning subtest of the WIAT-II is an aggregate score of many different tasks, it is hard to tell, why the shift was caused in Meyer et al. (2010) from grade 2 to 3. However, because the subtests contained some very basic tasks like counting or identifying geometric shapes, which are introduced earlier than multiplication, it is possible that the shift from verbal to visuospatial WM is also earlier in their study. In sum, it seems that this shift may be found in different developing ages for differing mathematical skills. This shift may serve as an essential step in mathematical development, however, its relation to age may vary according to mathematical content – in our view, this deserves further more detailed investigation in the future.

This changing role of verbal and visuospatial WM components for predicting arithmetic performance could be useful for diagnosis and intervention in children with mathematical learning difficulties. However, we recommend that future studies should also assess children's strategy use. By examining strategy-use together with the contribution of different memory components, researchers might be able to uncover cognitive demands of multiplication learning in developmental ages.

As regards the fact retrieval network itself, the current data suggest that retrieval is faster and more efficient from grade 3 to grade 4; however, the lack of change in the operand-relatedness effect with age may suggest that in children's fact retrieval network both the automatic association and reciprocal inhibition of concurrent responses may increase. More associations and at the same time better inhibition might lead to an unaltered operand-relatedness effect in this longitudinal study. This is only a speculative interpretation which needs to be examined in future studies with considering an inhibitory control, attentional processing, and self-regulation as well.

ACKNOWLEDGEMENT

We would like to thank all participating children and their parents as well as the involved school teachers and principals. This research was funded by a grant from the AKTION Österreich- Tschechien (45p13) to Silvia Pixner und Hans-Christoph Nuerk, as well as by a grant from the ScienceCampus Tübingen, project 8.4 to Hans-Christoph Nuerk supporting Mojtaba Soltanlou. Hans-Christoph Nuerk's research is further supported by the LEAD Graduate School [GSC1028], funded by the Excellence Initiative of the German federal and state governments. Finally, we thank Amanda Lillywhite and Jennifer Proehl for the proofreading of the manuscript.

STUDY 2: INCREASED ARITHMETIC COMPLEXITY IS ASSOCIATED WITH DOMAIN-GENERAL BUT NOT DOMAIN-SPECIFIC MAGNITUDE PROCESSING IN CHILDREN: A SIMULTANEOUS fNIRS-EEG STUDY

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Soltanlou, M., Artemenko, C., Dresler, T., Haeussinger, F. B., Fallgatter, A. J., Ehlis, A.-C., & Nuerk, H.-C. (in press). Increased arithmetic complexity is associated with domain-general but not domain-specific magnitude processing in children: A simultaneous fNIRS-EEG study. *Cognitive, Affective, & Behavioral Neuroscience.*

ABSTRACT

The investigation of the neural underpinnings of increased arithmetic complexity in children is essential for developing educational and therapeutic approaches, and might provide novel measures to assess the effects of interventions. Although a few studies in adults and children have revealed the activation of bilateral brain regions during more complex calculations, little is known about children.

We investigated 24 children undergoing one-digit and two-digit multiplication tasks while simultaneously recording functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG) data.

fNIRS data indicated that one-digit multiplication was associated with brain activity in the left superior parietal lobule (SPL) and intraparietal sulcus (IPS) extending to the left motor area, and two-digit multiplication was associated with activity in bilateral SPL, IPS, middle frontal gyrus (MFG), left inferior parietal lobule (IPL) and motor areas. Oscillatory EEG data indicated theta increase and alpha decrease in parieto-occipital sites for both one-digit and two-digit multiplication. The contrast of two-digit versus one-digit multiplication yielded greater activity in right MFG, and greater theta increase in fronto-central sites.

Activation in frontal areas and theta band data jointly indicate additional domain-general cognitive control and working memory demands for heightened arithmetic complexity in children. The similarity in parietal activation between conditions suggests that, children rely on domain-specific magnitude processing not only for two-digit, but – in contrast to adults – also for one-digit multiplication problem solving. We conclude that in children, increased arithmetic complexity tested in an ecologically valid setting is associated with domain-general processes, but not with alteration of domain-specific magnitude processing.

Keywords: arithmetic; multiplication; complexity; fNIRS; oscillatory EEG

INTRODUCTION

The investigation of the neural underpinnings of increased arithmetic complexity in children is essential for uncovering potential biomarkers to identify children at risk of mathematical learning disabilities, and to develop educational and therapeutic approaches. Neuroimaging studies have shown that brain activation patterns might provide new measures to assess the effects of interventions, because successful training leads to brain activation changes rather than only to behaviorally compensatory strategies (Iuculano et al., 2015). For instance, both magnitude training (Hyde, Khanum, & Spelke, 2014) and cognitive training (e.g., Witt, 2011) have been shown to improve proficiency in complex arithmetic in children. Therefore, it has been shown that neural findings are helpful for a better understanding of behavioral results (Szűcs & Goswami, 2007). However, neural correlates of problem-solving at different levels of arithmetic complexity have not yet been identified in children.

Arithmetic complexity is commonly studied by investigating the contrast between multi-digit and one-digit calculations. Neuroimaging studies in adults demonstrated that one-digit multiplication involves a mostly left fronto-parietal network (Gruber et al., 2001; Zago et al., 2001), whereas two-digit complex multiplication involves the intraparietal sulcus (IPS), inferior parietal lobule (IPL), angular gyrus (AG) and inferior frontal gyrus (IFG) bilaterally (Delazer et al., 2003; Delazer et al., 2005; Grabner et al., 2007; Zago et al., 2001; Menon et al., 2000). Greater activation in parietal regions was interpreted as demonstrating domain-specific magnitude and quantity-based processes, i.e., manipulating the numerals (e.g., Delazer et al., 2003), whereas activation in frontal regions was interpreted as signifying domain-general cognitive control and working memory processes in more complex calculations (Gruber et al., 2001; Ischebeck et al., 2006). Although there is general agreement about neural correlates of arithmetic complexity in adults, not all studies report the same findings. For instance, M. Rosenberg-Lee, M. C. Lovett, and J. R. Anderson (2009) suggested that arithmetic complexity, i.e., more complex strategy use in this case, relies on the posterior superior parietal lobule, required for attentional demands, and on the posterior parietal cortex, for mental representation of numerals, but not on the IPS and the inferior prefrontal cortex. The findings of these adult studies, however, are not easily transferable to children, due to shifts in activation from frontal to parietal areas during numerical processing tasks with increasing age and experience levels (Kaufmann et al., 2011; Prado et al., 2014; Menon, 2010).

A few studies have investigated arithmetic complexity in children. In 2nd and 3rd graders, increased complexity of addition was associated with both domain-general cognitive processes – increased activation within the right inferior frontal sulcus and anterior insula – and domain-specific magnitude processes – increased activation within the left IPS and superior parietal lobule (SPL) regions (Rosenberg-Lee et al., 2011). According to the developmental fronto-parietal shift, activation of the IFG, dorsolateral and ventrolateral prefrontal cortex decrease and activation of the left parietal cortex, supramarginal gyrus, adjoining anterior IPS, and lateral occipito-temporal cortex increase with age (e.g., Prado et al., 2014; Rivera et al., 2005). Therefore, arithmetic complexity engages more frontal regions for younger children, who rely mostly on counting strategies than for older children who are more mathematically trained (see also Peters et al., 2016; Polspoel et al., 2016). This shows a decrease of dependency on domain-general cognitive processes with age (for a review see Menon, 2010). Moreover, some studies have suggested a fundamental role for the hippocampal system and its connectivity to the prefrontal cortex in strategy shifts between complex and simple calculations (e.g., Cho et al., 2012), showing the pivotal role of the hippocampal system in the transition from procedural to retrieval memory-based strategies (Qin et al., 2014; Supekar et al., 2013). Altogether, studies in children suggest that more frontal engagement is associated with arithmetic complexity.

Reaching a more thorough understanding of mechanisms underlying increasing arithmetic complexity might help to develop neurobiological markers to assess responses to arithmetic trainings and interventions. For instance, Supekar et al. (2013) found that hippocampal volume and its intrinsic functional connectivity with dorsolateral and ventrolateral prefrontal cortices predicted arithmetic achievement in children, but surprisingly no behavioral measures were able to (for longitudinal finding see Evans et al., 2015). To date, studies in children have usually investigated either one-digit or two-digit multiplication calculation. Further, comparisons across studies are not unequivocal, because of differences in paradigms, procedures, analysis methods, languages, and so on (Kaufmann et al., 2011; Prado et al., 2014). Therefore, we used a within-participant design in the present study to investigate the neural correlates of one-digit and two-digit multiplication problem solving in children, allowing for a direct examination of brain activity associated with increased complexity in arithmetic problem-solving.

In order to address this issue in an ecologically valid setting (e.g., Obersteiner et al., 2010), a natural written production task was utilized in a self-paced paradigm. Two imaging techniques, functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG), were simultaneously applied in order to directly and indirectly measure neural activity underlying the processing of increased complexity in multiplication. Because of several characteristics of fNIRS, such as a reduced sensitivity to movement artifacts, which makes it particularly suitable for children and patients, this technique has been increasingly used in functional neuroimaging studies focusing on the cerebral cortex (for a review see Ehlis et al., 2014). For EEG, the continuous data signal can be analyzed using different methods such as event-related synchronization (ERS) and desynchronization (ERD), i.e., quantificational measures of brain dynamics (Pfurtscheller & Aranibar, 1977). Studies indicate that theta and alpha frequency bands behave in opposite ways in response to cognitive tasks such as arithmetic processing (e.g., Dolce & Waldeier, 1974). For instance, task complexity, attentional and cognitive demands, and memory load lead to theta ERS (increase in theta power) but also cause alpha ERD (decrease in alpha power) (Antonenko et al., 2010; Gevins et al., 1997; Klimesch, 1999; Pfurtscheller et al., 1996; Pfurtscheller & Da Silva, 1999). Furthermore, some cognitive functions are more closely linked to one of these frequency bands. In particular, it has been reported that the theta band reflects the encoding of new information, whereas the alpha band reflects searching for and retrieving information from long-term semantic memory storage (Antonenko et al., 2010; O. Jensen & Tesche, 2002; Klimesch, 1999; Sammer et al., 2007; Sauseng & Klimesch, 2008). In numerical cognition, some studies interpreted the theta frequency band as a sign of domain-general cognitive demands of arithmetic processing such as sustained attention and working memory, and the alpha frequency band as an indicator of fact retrieval from long-term memory in different arithmetic tasks (Harmony et al., 1999; Klados et al., 2013; Micheloyannis et al., 2005; Mizuhara & Yamaguchi, 2007; Moeller et al., 2010). However, other studies interpreted the theta band as a function of arithmetic fact retrieval processes and the alpha band as a function of procedural processes (De Smedt et al., 2009; Grabner & De Smedt, 2011, 2012). Therefore, using fNIRS simultaneously with EEG may help to more consistently interpret the findings of brain dynamic changes recorded by oscillatory EEG signals in arithmetic processing (see also Sammer et al., 2007).

Given previous findings, we hypothesize greater domain-specific magnitude processes for two-digit than one-digit multiplication, which should lead to extensive activation in parietal regions in fNIRS data, potentially more left-lateralized (Chochon, Cohen, Van De Moortele, & Dehaene, 1999; Kazui, Kitagaki, & Mori, 2000; Rickard et al., 2000). Moreover, additional domain-general cognitive demands for two-digit compared to one-digit multiplication are expected, which should result in activation in frontal regions in fNIRS data and greater theta ERS in EEG data (see also Micheloyannis et al., 2005). Note that in order to measure arithmetic complexity in an ecologically valid situation, the written production paradigm was used in the present study, which might lead to greater motor responses and irrelevant brain activation changes in the motoric areas compared to more common paradigms such as verification. Additionally, because of considerable inter-individual differences in children (Siegler, 1988; De Smedt, 2015), and the contribution of domain-general cognitive factors to these differences (Vanbinst, Ghesquiere, & De Smedt, 2014; Nemati et al., 2017), the role of memory components (for a review see Menon, 2016) and strategy use (e.g., Grabner & De Smedt, 2011) in multiplication performance was assessed (for a review see Vanbinst & De Smedt, 2016).

MATERIAL AND METHODS

PARTICIPANTS

26 typically developing 5th grade children participated in the study. No child had a history of neurological or mental disorders. Due to technical problems during EEG recording, two children were excluded: for one child, the connection failed between the recorder and computer presenting the task, and in the other child, no trigger was recorded by the EEG recorder. The remaining 24 children (9 girls; age 11.1 ± 0.5 years old) were right-handed with normal or corrected-to-normal vision. Informed consent was obtained from all children and parents included in the study. They received expense allowance for participation. The study was approved by the Ethics Commission of the University Hospital of Tuebingen.

MATERIAL

16 one-digit and 16 two-digit multiplication problems were used. The one-digit problems (e.g., 3 × 9) included two one-digit operands (range 2–9) with two-digit solutions (range 12–40). The two-digit problems (e.g., 18 × 4) included two-digit (range 12–19) times one-digit operands (range 3–8) with two-digit solutions (range 52–98). The order of small and large operands was counterbalanced in both conditions. Problems with ones (e.g., 8 × 1), commutative pairs (e.g., 18 × 4 and 4 × 18) or ties (4 × 4) were not used. The experiment was run using Presentation® software (version 16.3, Neurobehavioral Systems Inc., www.neurobs.com). Multiplication problems were presented on the screen in white font against a black background (see Fig 1a). Responses were recorded via written production, which children typically use to perform arithmetic tasks in school.

fNIRS

fNIRS data were collected with the ETG 4000 Optical Topography System (Hitachi Medical Co., Tokyo, Japan), which uses two wavelengths (695 and 830 nm) to calculate the absorption changes in oxygenated (O2Hb) and deoxygenated hemoglobin (HHb) concentration using a modified Beer-Lambert law. The sampling rate was 10 Hz and the inter-optode distance was 30 mm. 15 optodes (8 emitters, 7 detectors) in a 3 × 5 arrangement were attached to an elastic combined fNIRS-EEG cap (Brain Products GmbH., Herrsching, Germany) over both hemispheres resulting in 22 measurement channels per hemisphere (cf. Fig 1b). Channel 14 (left hemisphere) was placed over the P3 electrode site, and channel 18 (right hemisphere) was placed over P4 in accordance with the international 10/20 system (Jasper, 1958). The localization of the corresponding cortical areas (Tsuzuki et al., 2007; Singh, Okamoto, Dan, Jurcak, & Dan, 2005) is based on the AAL (automatic anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002) in SPM software (http://www.fil.ion.ucl.ac.uk/spm).

EEG

EEG was recorded from 21 scalp electrodes also embedded into the combined fNIRS-EEG cap (cf. Fig 1b). Given the fixed optode distances, EEG electrodes were placed according to the extended international 10/20 system (Jasper, 1958; Oostenveld &

Praamstra, 2001). To identify eye movement artifacts in the EEG signal, electrooculography (EOG) was recorded from an additional electrode below the right eye. The ground electrode was placed on AFz and the online reference electrode on FCz. Electrode impedance was kept below 20 kΩ. EEG data were recorded using a 32-channel DC-amplifier and the Brain Vision Recorder software (Brain Products GmbH., Herrsching, Germany). Data were digitized at a rate of 1000 Hz with an online band-pass filter of 0.1-100 Hz.

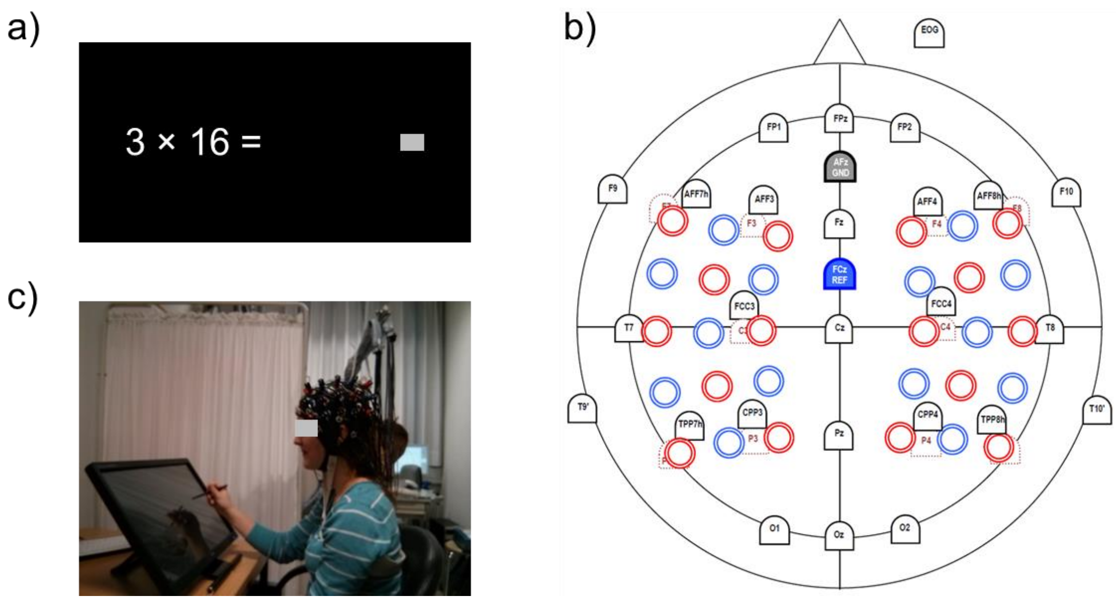

Fig1 a) Multiplication problems: in a production paradigm, the problems were presented on the left side of the screen until the participant pressed the gray box or the maximal response time was reached. b) Schematic positions of fNIRS optodes and EEG electrodes: the red circles indicate emitters and blue ones indicate detectors in the two arrays of 3 × 5. Small white shapes indicate positions of the EEG electrodes. Red dotted shapes indicate the original position of some EEG electrodes according to the international 10/20 system. c) Experimental setting: children wrote their responses on the touch screen.

NEUROPSYCHOLOGICAL TESTS

Intelligence was measured using the similarities and matrix reasoning subtests of the German Wechsler intelligence quotient (IQ) test (Hamburg-Wechsler-Intelligenztest für Kinder-IV: HAWIK-IV; Petermann, Petermann, & Wechsler, 2007). Due to time constraints, we only used these two subtests to control for general verbal and performance intelligence of the participants. Four memory components were assessed (Alloway et al., 2006). The letter span test was used to measure verbal short-term memory, and the block tapping task (Corsi, 1973) was used to assess visuospatial short-term memory. For these verbal and visuospatial working memory tasks, children were required to recall sequences of letters or cubes inversely. In general, forward span tests were defined as short-term memory and backward span tests were defined as working memory (N. Cowan, 2008; for more see Mojtaba Soltanlou, Pixner, & Nuerk, 2015). To assess strategies used in solving one-digit and two-digit problems, we designed a strategy questionnaire, which was completed by children before the experiment. The questionnaire contained four one-digit and four two-digit experimental problems, resulting in four matched versions with different problems each. After responding to each problem, children reported how they solved it. The reported strategies were categorized as retrieval, procedural, and other for the analysis (see also Grabner & De Smedt, 2011). The inter-rater reliability, which was calculated by Cohen's kappa, was .80.

PROCEDURE

All children were tested individually while seated comfortably in front of the touch screen in a light-attenuated room. During the 45-minute preparation of the combined fNIRS-EEG cap (cf. Fig 1c) by two experimenters, children watched a cartoon. Before the actual experiment, the children completed four practice trials. Children were tested on a computerized written production paradigm in which problems were presented without response options and children had to produce the solution as quickly and accurately as possible. They were instructed to read the problems silently and calculate mentally. As soon as they found the solution, they wrote it down on the touch screen with the help of a touch pen and then clicked on a gray box to continue (see Fig 1a). Note that the written response was not visible on the screen, to avoid any further correction. The task was self-paced with a limited response interval of 10 s for one-digit problems and 30 s for two-digit problems, respectively. Therefore, due to inter-individual differences, the number of solved problems differed between children. The inter-trial interval was set to 0.5 s. The experiment was a block design, and the multiplication problems of each condition were presented in 16 blocks (8 for one-digit and 8 for two-digit multiplication) of 45 s followed by 20 s of rest, resulting in a total experiment duration of approximately 18 minutes. The sequence of the blocks and of the problems was randomized. Whenever the total number of trials within a condition was reached, the same problems were presented again after randomization. No feedback was given.

Because this study was part of a larger training project that required two visits to the laboratory, the strategy questionnaire was completed during the first visit and the IQ and memory tests were conducted during the second visit.

ANALYSIS

BEHAVIORAL DATA

Response times (RTs) were defined as the time from stimulus onset to pressing the gray box after a written response. Only RTs for correct responses were entered into the analyses. Error rate was defined as proportion of incorrect and missed trials to total number of presented trials. Written responses by participants were read with the help of RON (ReadOutNumbers program; Ploner, 2014) to calculate error rates. Mean RTs and arcsine-square-root-transformed error rate, applied to approximate normal distribution (Winer et al., 1971), between two conditions were compared using paired t-tests. Relation of behavioral data with neuropsychological data was analyzed using bivariate correlation. The analysis was completed using SPSS version 23.0 (IBM SPSS Statistics for Windows).

FNIRS

The continuous concentration changes of O2Hb and HHb were recorded for 22 channels per hemisphere. Hemoglobin quantity was scaled in mM*mm, which is based on the idea that concentration changes depend on the path length of NIR light through the brain. Data were analyzed using a commercial software package, MATLAB (The MathWorks Inc., Natick, Massachusetts, United States). Signals were band-pass filtered with 0.008-0.25 Hz and large motion artifacts and non-evoked systemic influences such as heart rate and very low frequency oscillations were reduced using the correlation-based signal improvement (CBSI) method (Cui, Bray, & Reiss, 2010). Afterwards, this CBSI time course, which is based on an expected negative correlation of concentration changes of O2Hb and HHb, was used to indicate cortical activation. For every participant, remaining noisy channels were interpolated using the mean of the surrounding channels. The amplitude of each 45 s block was baseline-corrected using the 2 s before the respective block and averaged for each condition and participant. To investigate the brain activation in each condition, t-tests against zero were calculated, and a paired t-test was applied to assess the contrast of two-digit versus one-digit multiplication. The significance level was .05 and corrected using the Dubey/Armitage-Parmar (D/AP) method for multiple comparisons (Sankoh, Huque, & Dubey, 1997). D/AP is among the stepwise modified Bonferroni procedures which consist of readjusting the level of significance for the individual test, while taking into account auto-correlations in the data. This procedure is well suited to the analysis of fNIRS data, due to the usually strong correlations between neighboring fNIRS channels. Furthermore, to look at the lateralization of activation, the average amplitudes of the left and right hemispheres were compared for each condition using paired t-tests.

EEG

EEG data were analyzed using the Brainstorm toolbox (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011), a documented and freely available software (http://neuroimage.usc.edu/brainstorm). Data were offline-filtered using a band-pass of 0.1-40 Hz. Then, eye movement artifacts were detected based on the EOG signal with the peak beyond 2 standard deviations of the mean, and were removed using Signal Space Projections (SSP) from the continuous signal of EEG electrodes. Epochs of 45 s experimental and 20 s rest intervals were used for analysis. For frequency analysis, the power spectral density (PSD) for theta (4.1-7 Hz) and alpha (7.1-13 Hz), two frequently investigated frequency bands in cognitive tasks (Antonenko et al., 2010), was calculated. The PSDs of every epoch were calculated separately and averaged for each condition and participant, resulting in three PSDs per participant (for one-digit multiplication, two-digit multiplication, and rest). In the next step, ERS/ERD were calculated, which are related to cortical activation and functional changes of brain activity (Neuper & Klimesch, 2006; Pfurtscheller & Da Silva, 1999). Because of several factors that influence EEG variation, such as individual differences, age (Klimesch, 1999) and differences in brain volume (Nunez & Cutillo, 1995), it is recommended that investigators analyze changes in the EEG, rather than analyzing the absolute power of each frequency band, in order to increase the reliability of findings (Pfurtscheller & Da Silva, 1999). According to the expression ERS/ERD% = (PSD of activation – PSD of rest) / PSD of rest × 100 (Pfurtscheller & Da Silva, 1999), the percentage value for ERS/ERD for each of the multiplication conditions was calculated for every participant. If the PSD of a condition is larger than rest, the result will be positive, indicating ERS, while negative differences indicate ERD. For each condition, statistical analyses consisted of t-tests against zero for ERS/ERD% for each electrode and each frequency band. To investigate the contrast of conditions, paired t-tests were applied with a significance level of .001 and corrected for multiple comparisons using the Bonferroni method. Note that EEG electrodes record the average oscillations of the whole brain – including almost all cortical and subcortical structures – at each recording site, whereas fNIRS records the average reflected light from a maximum of approximately 3 cm surrounding cortical and subcortical structures. Therefore, to control the type I error, we used a more conservative correction method (i.e., Bonferroni) on EEG data than on fNIRS data.

RESULTS

BEHAVIORAL DATA

Children were faster in solving one-digit (4.77 s, SD = 0.89 s) than two-digit multiplication problems (10.73 s, SD = 2.61 s), $t(23) = 13.79$, $p < .001$. They also made fewer errors in one-digit (15.34%, SD = 7.06%) than in two-digit problems (29.08%, SD = 11.37%), $t(23) = 8.09$, $p < .001$.

fNIRS

In one-digit multiplication, left SPL, IPS and postcentral gyrus displayed significant activation, $t(23) > 3.09$, corrected $p < .05$, which extended to the precentral motor cortex. Moreover, significant deactivation was observed in left superior temporal gyrus, right superior and middle temporal gyri, precentral gyrus and IFG, $t(23) < -2.64$, corrected $p < .05$ (cf. Fig 2). In two-digit multiplication, bilateral SPL, IPS, and MFG, along with left IPL, postcentral and precentral gyri displayed significant activation, $t(23) > 2.84$, corrected $p < .05$. Moreover, significant deactivation was observed in the right superior and middle temporal gyri, and precentral gyrus, $t(23) < -3.22$, corrected $p < .05$ (see Fig 2).

The contrast between two-digit and one-digit multiplication revealed significantly stronger activation for the right MFG, $t(23) > 3.02$, corrected $p < .05$, extending into the IFG (cf. Fig 2). Additionally, a significantly greater activation was found in the left compared to the right hemisphere in both one-digit, $t(23) = 3.19$, $p < .01$, and two-digit multiplication, $t(23) = 3.79$, $p < .01$.

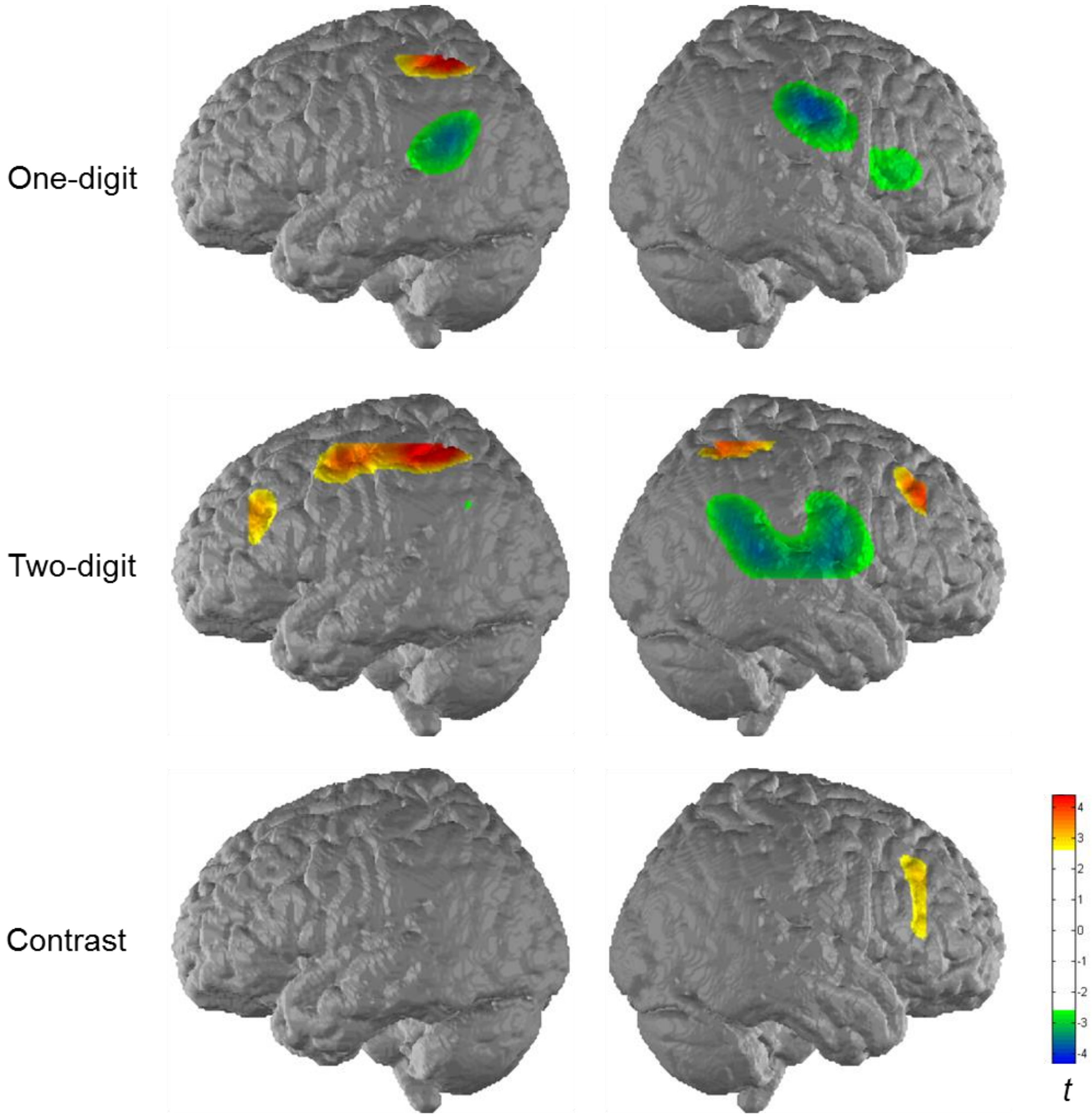

Fig2 fNIRS results for one-digit and two-digit multiplication, along with the contrast of two-digit versus one-digit (*t*-maps; red means activation and blue means deactivation). Significant activation increase was found in the right MFG for two-digit vs. one-digit multiplication.

EEG

In both one-digit and two-digit multiplication, theta ERS and alpha ERD were observed during the experiment. Theta band activity was found to be significantly above zero in middle and right occipito-parietal sites (Oz and O2 electrodes) in one-digit multiplication, $t(23) > 6.41$, corrected $p < .001$. The same significant activity was observed in bilateral occipito-parietal sites extending to the right temporal site (O1, O2, and TPP8h electrodes) in two-digit multiplication, $t(23) > 5.55$, corrected $p < .001$. These results suggest stronger theta power in these sites during the experiment than in rest intervals. Regarding alpha ERD, a significant difference from zero in the alpha band was found in bilateral occipito-parietal sites (O1 and O2 electrodes) for both conditions, $t(23) < -6.32$, corrected $p < .001$. These results suggest lower alpha power in these sites during the experiment than in rest intervals (see Fig 3a).

Based on prior studies (e.g., Ishii et al., 2014) that have found frontal midline theta increase during focused attention on mental calculation, we examined whether there would be a significant difference in theta ERS between two-digit and one-digit multiplication. We observed greater theta ERS in fronto-central sites (Fz and Cz electrodes) during two-digit than in one-digit multiplication, $t(23) > 2.12$, $p < .05$, but it did not survive correction for multiple comparisons. No significant difference was found between the two conditions in the alpha band. Furthermore, in the contrast of two-digit versus one-digit multiplication over all electrodes, a significant difference was observed in theta ERS, $t(23) = 1.98$, $p = .03$, but not in alpha ERD (see Fig 3b).

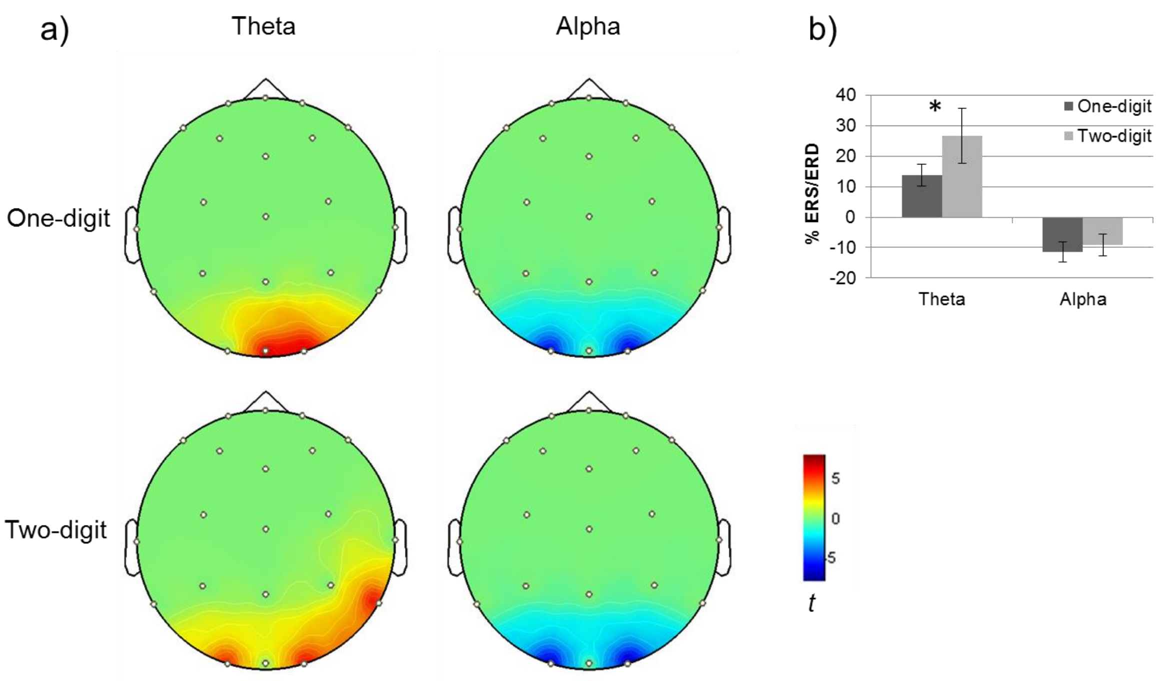

Fig3 (a) Theta ERS and alpha ERD in one-digit and two-digit multiplication problems (red means ERS and blue means ERD). (b) The difference of theta ERS and alpha ERD over all electrodes in one-digit and two-digit multiplication. A significant increase in theta ERS was found for two-digit vs. one-digit multiplication (marked by *).

Reanalysis of fNIRS and EEG data by adding RTs and error rates as covariates

As regards both fNIRS, ANCOVA analysis showed no significant activation or deactivation in the one-digit or two-digit condition after correction for multiple comparisons. The contrast of two conditions was not significant.

With respect to EEG, ANCOVA analysis displayed no significant difference in alpha and theta bands in the one-digit or two-digit condition. The contrast of two conditions was not significant.

Neuropsychological tests

The performance of children in the similarities and matrix reasoning subtests of the IQ test was within a normal range (cf. Table 1). Additional information regarding memory tests and strategy use are displayed in Table 1. Children reported significantly more retrieval strategy use, $t(23) = 4.66$, $p < .001$, and less procedural strategy use, $t(23) = -3.99$, $p < .001$, to solve one-digit versus two-digit multiplication.

Table1 Neuropsychological data. M ± SD are given for verbal (similarities) and non-verbal IQ (matrix reasoning), verbal and visouspatial short-term memory (STM) and working memory (WM) spans, and percentage of retrieval and procedural strategy use in one-digit (1) and two-digit (2) multiplication.

Similarities	Matrix reasoning	Verbal STM	Verbal WM	Visuospatial STM	Visuospatial WM	Retrieval		Procedural		Other	
						1	2	1	2	1	2
107.7 ± 11.5	107.7 ± 10.4	5.0 ± 0.9	4.0 ± 0.9	5.3 ± 0.8	5.3 ± 1.0	41	4	55	90	4	6

Because of inter-individual differences among children, correlation analyses between behavioral and neuropsychological data were conducted to investigate whether these neuropsychological factors influenced multiplication performance. We found that children with better visuospatial short-term and working memory were faster and made fewer errors in one-digit multiplication (see Table 2). Furthermore, children who reported higher reliance on a retrieval strategy in one-digit multiplication were faster in solving these problems, and children who reported higher reliance on procedural strategies were slower in responding to one-digit multiplication problems (cf. Table 2).

Table2 Correlation between one-digit multiplication performance and neuropsychological findings (one-tailed significance level of .05; significant correlations marked with *). No significant correlation was found in two-digit multiplication.

	Visuospatial STM	Visuospatial WM	Retrieval strategy use	Procedural strategy use
Error rate	-0.35*	-0.51*	0.07	-0.09
Response time	-0.29	-0.35*	-0.34*	0.37*

DISCUSSION

In the present study, the neural underpinnings of increased multiplication complexity were investigated with simultaneous fNIRS-EEG in children in a within-participant design. Behavioral findings revealed faster and more accurate responses in solving one-digit than in solving two-digit multiplication problems, which is congruent with the greater use of retrieval and fast compact procedural strategies for these problems (Lemaire & Siegler, 1995). Following previous findings showing that children use various strategies for solving one-digit multiplication (Cooney et al., 1988; Lemaire & Siegler, 1995), children used both retrieval and procedural strategies. Further, domain-general capabilities, i.e., visuospatial short-term and working memory, contribute to one-digit multiplication performance (see also Ashkenazi, Rosenberg-Lee, Metcalfe, Swigart, & Menon, 2013; Mojtaba Soltanlou et al., 2015).

During one-digit multiplication, activation was observed in the left SPL and IPS, while theta ERS and alpha ERD were observed over occipito-parietal regions. These activation patterns have already been reported in multiplication problem solving in adults (Dehaene et al., 1996; Chochon et al., 1999; Rickard et al., 2000; Kazui et al., 2000; Zago et al., 2001; Delazer et al., 2003; Kawashima et al., 2004; Zhou et al., 2007; Micheloyannis et al., 2005). Both theta ERS and alpha ERD in solving one-digit multiplication are also in line with neurophysiological changes in multiplication problem solving in adults (Micheloyannis et al., 2005). The findings suggest that children in this developing age still rely on quantity-based knowledge, aside from arithmetic fact retrieval, to solve one-digit multiplication problems (but see Kawashima et al., 2004), a conclusion that is additionally supported by the reported strategy use (see also Lemaire & Siegler, 1995). It has been shown that even adults do not always retrieve solutions, but rather use several back-up strategies, e.g., for large one-digit multiplication problems (LeFevre et al., 1996; Zhou et al., 2007).

Contrary to studies in adults (e.g., Delazer et al., 2003; Grabner et al., 2007) and a few studies in children (Cho et al., 2012; Peters et al., 2016), the activation of the left AG, which has been associated with retrieval strategies, was not observed in the present study. Delazer et al. (2005) found that depending on the strategy use, retrieval processes were associated with bilateral occipito-parietal areas including the precuneus (see also Andres, Pelgrims, Michaux, Olivier, & Pesenti, 2011; Prado et al., 2013) and not necessarily with the left AG. Note that previous studies in children found AG activation in small one-digit addition and subtraction problems (Cho et al., 2012; Peters et al., 2016), whereas in the present study the whole range of one-digit multiplication was utilized, which probably led to an overall increase in procedural processes in the one-digit condition (for more discussion about the AG see Grabner, Ansari, Koschutnig, Reishofer, & Ebner, 2013).

In two-digit multiplication, bilateral activation of the SPL, IPS, MFG, and left IPL were observed, as well as posterior theta ERS extending to right temporal sites, and alpha ERD over occipito-parietal sites (see also Grabner & De Smedt, 2011, 2012). Complex multiplication problems are usually solved via procedural step-by-step calculations (for a review see Zamarian et al., 2009), which recruit the bilateral fronto-parietal network (Gruber et al., 2001; Delazer et al., 2003; Delazer et al., 2005; Ischebeck et al., 2006). These procedural processes might be related to the observed theta ERS, which was stronger during two-digit than in one-digit multiplication problem solving. This was in line with the findings by Micheloyannis et al. (2005) that reported stronger theta ERS during complex multiplication problem solving in adults.

In regard to increased multiplication complexity, the children showed larger activation of right MFG and IFG (see also Fehr, Code, & Herrmann, 2007). This might be interpreted as reflecting the additional involvement of domain-general cognitive demands, such as working memory, sustained attention, and planning, in two-digit as opposed to one-digit calculation (Fehr et al., 2007; Gruber et al., 2001; Zago et al., 2001), since activation of the frontal cortex has been shown to be related to cognitive control and working memory (Cabeza & Nyberg, 2000; Ranganath, Johnson, & D'Esposito, 2003; Sylvester et al., 2003). Rivera et al. (2005) showed that older children, who solve arithmetic problems faster and more accurately than younger children, rely less on frontal regions (see also Prado et al., 2014). This finding is partially in line with the study by Rosenberg-Lee et al. (2011), which found frontal activation to be related to greater cognitive load in more complex calculations. However, in contrast to their findings, no significant activation of parietal cortex was observed related to the increased complexity. In the present study, the most commonly reported procedural strategy used in two-digit multiplication was separately multiplying the unit and decade digits of the two-digit operand with the one-digit operand (relying on retrieval strategies) and adding the results together (see also Tschentscher & Hauk, 2014). In this procedure, each step needs to be kept in working memory, and different cognitive control elements are involved, such as inhibiting operand-related mistakes, and performing self-monitoring and error detection during each step of calculation. Note that although some studies in children suggest a transitional role of the hippocampus in arithmetic development (e.g., Cho et al., 2012; Supekar et al., 2013; Qin et al., 2014), fNIRS is not capable of recording activation within subcortical and other non-surface structures.

Greater theta ERS with increased multiplication complexity is in line with a similar study in adults (Micheloyannis et al., 2005). Theta oscillations among frontal areas have been reported to originate from a cortico-hippocampal network and the medial prefrontal area (Klimesch, 1999; Mizuhara & Yamaguchi, 2007; Klimesch, 1996; Sauseng & Klimesch, 2008). Furthermore, simultaneous fMRI-EEG studies of subtraction (Mizuhara & Yamaguchi, 2007) and addition (Sammer et al., 2007) reported theta ERS over frontal areas as a function of cognitive control, working memory, encoding and self-monitoring. Nonetheless, increased multiplication complexity did not lead to a difference in alpha ERD as reported for adults (Micheloyannis et al., 2005). Alpha ERD has been suggested to be related to several cognitive functions including retrieving information from long-term memory (Harmony et al., 1999; Klimesch, 1999; Moeller et al., 2010; Antonenko et al., 2010). Therefore, we conclude that this similar pattern of alpha ERD is related to retrieval strategy use not only in one-digit multiplication, but also as part of an algorithm procedure in two-digit multiplication. By replicating the findings of Micheloyannis et al. (2005) and extending them to children, we conclude that theta ERS is more related to procedural strategies and additional cognitive processes, and alpha ERD is mostly related to retrieval processes in mental calculation (see also Harmony et al., 1999; Klimesch, 1999; O. Jensen & Tesche, 2002; Kahana, Seelig, & Madsen, 2001; Mizuhara & Yamaguchi, 2007; but see De Smedt et al., 2009; Grabner & De Smedt, 2011, 2012). Note that because the difference between one-digit and two-digit calculations is not very large, the contrast of two conditions does not survive correction for multiple comparisons and must be interpreted cautiously. However, this contrast interestingly corroborates previous ERD/ERS studies of arithmetic processing.

The activation of the left motor cortex may be explained by the type of response production, because all children responded with their right hand. Furthermore, it should be noted that although children were asked to calculate silently, it is possible that they were doing (additional) step-by-step calculation via inner speech, which may lead to the same results as subvocalization of the answers in silent verbal production tasks (e.g., Dehaene et al., 1996), and a trace of finger counting could have been present during mental calculation (Delazer et al., 2003; Zago et al., 2001). In regard to the lateralization of brain activation, in line with previous studies of multiplication in adults (Chochon et al., 1999; Dehaene et al., 1996; Rickard et al., 2000; Kazui et al., 2000; Zago et al., 2001), we found stronger activation in the left hemisphere for both one-digit and two-digit multiplication, which is assumed to reflect language-related processes in solving multiplication (Dehaene et al., 2004). However, it should be mentioned that direct comparisons of fNIRS data stemming from different brain hemispheres is difficult due to the different path lengths the light travels depending on anatomical characteristics of the underlying brain areas (see Zhao et al., 2002; Katagiri et al., 2010), which might explain a part of this difference.

We conducted additional ANCOVA by adding response times and error rates to the model. In the present block-designed study with a self-paced written production paradigm, the covariates, particularly response times, seemed to subserve the cognitive processes underlying the performance. Therefore, using response times as a covariate may not methodologically represent the best approach (G. A. Miller & Chapman, 2001). As conditions and response times are highly correlated, this may be a major problem for ANCOVA application. One often untested prerequisite of ANCOVAs is that the independent variable (i.e., condition) and covariate (i.e., response times) do not share a common variance. If they do, then it should be ensured that dependence arises just by chance, e.g., due to randomization processes. If dependence results not from chance, but from an inherent dependence of the two variables, then an ANCOVA may conceal effects that are actually there, or may even introduce non-existing effects (for a more thorough discussion see G. A. Miller & Chapman, 2001). As complexity influences both activation and response time, partialling out either dependent variable may result in biased effects. In sum, because the response time prolongation and the activation are subserved by the same neurocognitive processes, a closer look at significant regions in a t-test that are non-significant in an ANCOVA might be instructive.

CONCLUSIONS

Both activation patterns in frontal cortex and theta band data indicate that in children, increased multiplication complexity requires domain-general processing, or additional demands on cognitive control and working memory, consistent with the literature.

However, contrary to previous results in and conclusions reached from adults, the lack of a difference in activation patterns in SPL and IPS suggests that children in this developing age still rely on magnitude processing for both one-digit and two-digit multiplication problem solving. This finding is new since increased multiplication complexity in children tested in an ecologically valid setting is associated with additional cognitive load, but not with additional magnitude processing, as in previous adult studies. Interventions based on adult neuroimaging results may therefore be suboptimal. We suggest that to improve interventional and educational approaches for arithmetic complexity during development, neurocognitive studies with children are needed, ideally with simultaneous recording with fNIRS and EEG to reach integrated conclusions for development and intervention.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

ACKNOWLEDGMENT

We would like to thank all participating children and their parents. This research was funded by a grant from the Science Campus Tuebingen, project 8.4 to HCN supporting MS. MS was also supported by the DFG grant, no NU 265/3-1 given to HCN. CA, TD, ACE, AJF and HCN are members of the LEAD Graduate School & Research Network [GSC1028], funded by the Excellence Initiative of the German federal and state governments. Furthermore, ACE was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0). Finally, we thank our assistants who helped with recording EEG and fNIRS data and proofreading the manuscript.

STUDY 3: NO SUPPORT FOR ANGULAR GYRUS ENGAGEMENT IN ARITHMETIC LEARNING IN CHILDREN: EVIDENCE FROM A SIMULTANEOUS FNIRS-EEG STUDY

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Soltanlou, M., Artemenko, C., Ehlis, A.-C., Huber, S., Fallgatter, A. J., Dresler, T., & Nuerk, H.-C. (revision submitted). No support of angular gyrus engagement in arithmetic learning in children: Evidence from a simultaneous fNIRS-EEG study. *Scientific Reports.*

ABSTRACT

Neurocognitive learning studies of arithmetic in adults have revealed decreasing brain activation in the fronto-parietal network along with increasing activation of specific cortical and subcortical areas, both associated with a shift from procedural to retrieval processes. The critical research question is whether these neurocognitive changes in the learning process are also evident in children.

To address this question, 20 typically developing children were trained in simple and complex multiplication. The immediate and two-week training effects were monitored using simultaneous functional near-infrared spectroscopy and electroencephalography.

Two-week training improved performance and led to a decreased activation at the junction of left angular gyrus (AG) and middle temporal gyrus, and right middle frontal gyrus in complex multiplication. In both trained simple and complex problems, increased alpha power was observed compared to untrained control problems. Measurement immediately after training revealed decreased activation at the junction of left inferior parietal lobule and AG, and right superior parietal lobule and intraparietal sulcus for complex multiplication.

Contradictory to the previous multiplication training studies in adults, no change in activation of the left AG was observed. We conclude that shifts from procedural to retrieval strategies via arithmetic learning receive no support of AG engagement in children.

Keywords: children; arithmetic; learning; angular gyrus; fNIRS; oscillatory EEG

INTRODUCTION

ARITHMETIC LEARNING IN ADULTS

Arithmetic learning improves mathematical competence, which is necessary for successful daily life, job opportunities, etc. (Butterworth et al., 2011). However, little is known about the neural underpinnings of arithmetic learning during childhood because the vast majority of our knowledge about arithmetic learning comes from adult studies. Generally speaking, learning is characterized by a strategy shift from more effortful and algorithm-based to more retrieval- and memory-based processes (Zamarian et al., 2009). Multiplication training studies in adults illustrated that this strategy shift is accompanied by reduced fronto-parietal network activation and increased left angular gyrus (AG) activation (Pauli et al., 1994; Grabner & De Smedt, 2012; Grabner, Ansari, et al., 2009; Ischebeck et al., 2006; Ischebeck et al., 2007; Ischebeck et al., 2009; but see Bloechle et al., 2016; Delazer et al., 2005; Delazer et al., 2003). This strategy shift was also reported in an electroencephalography (EEG) study of complex multiplication training in adults (Grabner & De Smedt, 2012), which revealed an increased power in theta and alpha frequency bands over occipito-parietal measurement sites.

The fronto-parietal network underlying arithmetic processing includes inferior, middle and superior frontal gyri, which are associated with additional cognitive processes such as working memory and planning in mental calculation, and intraparietal sulcus (IPS), superior parietal lobule (SPL), and inferior parietal lobule (IPL), which are associated with magnitude processing of numerals (for review see Arsalidou & Taylor, 2011; Zamarian et al., 2009). According to the triple-code model, the left AG is involved with retrieving information from long-term memory (Dehaene & Cohen, 1997; Dehaene et al., 2003), even after only few repetitions of complex multiplication in adults (Ischebeck et al., 2007). However, it has been shown that in adults, AG activation depends on the learning method. (Delazer et al., 2005) indicated that drill learning of complex multiplication (directly finding the relation between operands and solutions) resulted in stronger left AG activation, while strategy learning (finding the result based on sequential algorithms) did not. Furthermore, a recently published study found no activation of the left AG in high-level mathematicians, but rather an extensive network of prefrontal, parietal, and inferior temporal regions (Amalric & Dehaene, 2016).

ACTIVATION SHIFTS IN CHILDREN

The critical question is whether the neural activation changes consistently observed in arithmetic learning experiments in adults can be generalized to children, i.e., to a period of our lives when virtually all of us learn arithmetic facts. Neurocognitive learning studies in children are scarce, but some information can be drawn from math tutoring, cross-sectional and longitudinal age-related changes.

A one-on-one math tutoring study in third-grade children demonstrated a similar strategy shift in arithmetic problem solving as in adults, and this shift was associated with changes in the morphometry of the hippocampus and its connectivity with frontal regions (Supekar et al., 2013), but not with changes in the typical regions such as IPS and AG involved in arithmetic processing in adults. A cross-sectional study of simple multiplication performance in children from grades 2 to 7 showed age-related decreases in inferior frontal gyrus (IFG) activation and increases in left middle temporal gyrus activation (MTG), accompanied by increased dependency on retrieval strategies as a function of age (Prado et al., 2014; for addition and subtraction see Rivera et al., 2005). In a longitudinal functional magnetic resonance imaging (fMRI) study of simple addition in 7 to 9 year-old children, Qin et al. (2014) reported a decreased involvement of a fronto-parietal network and increased involvement of the hippocampus over the course of one year of school education (see also Cho et al., 2012). They suggested that the medial temporal lobe, including the hippocampus, plays a critical transient role in arithmetic learning in children, but not in adults (Qin et al., 2014). Furthermore, several behavioral studies in children revealed this strategy shift as an indication of arithmetic development (e.g., Geary, 1994; Siegler, 1996). In sum, the aforementioned studies suggest that a similar strategy shift from procedural to retrieval strategies occurs in children's and adults' learning. However, although systematic standardized training studies have not yet been carried out, the available tutoring, longitudinal and cross-sectional data suggest that learning-related changes in activation in children may be different than in adults. In particular, these data do not show increased (or less deactivated) AG activation, which is the trademark of retrieval learning in adults.

However, there are some limitations regarding the transfer of these findings to children's arithmetic learning in general. In the tutoring study, children received training in several different mathematic domains and problem-solving strategies, and were tested on one-digit addition problems (for more details see SI in Supekar et al., 2013). However, although children received a planned training, they underwent a tutorial training based on their weaknesses. Therefore, there was a difference between the training – several different arithmetic skills – and experimental tasks. The other possible limitation in this study is that specific (numerical training) factors and unspecific factors (e.g., increased motivation) due to the one-on-one setting cannot be distinguished. With longitudinal (and even more so with cross-sectional) studies on arithmetic learning, there is another problem. Arithmetic learning throughout childhood is strongly associated with brain maturation. Therefore, it is difficult to determine whether activation changes are truly associated with the arithmetic learning process in school, or rather are a byproduct of maturation of the whole brain. Neurocognitive learning studies, which are conducted in a similar way as in adults, are useful because brain maturation should play a smaller role in brain activation changes over a very short period of time (immediate learning and maximally 2 weeks in our study) than in longitudinal studies with observation periods of one or more years.

THE PRESENT STUDY AND ITS OBJECTIVES

To examine learning processes in children, we used multiplication, the operation most frequently investigated in adults. To the best of our knowledge, brain activation changes after multiplication training in children have not been investigated so far. The present study aimed to explore the brain activation changes related to simple and complex multiplication learning in typically developing children. In order to evaluate the training-induced changes, we used simultaneous functional near-infrared spectroscopy (fNIRS) and EEG as pre- and post-training measurements in an ecologically valid setting that is comparable to school and normal learning situations (the sitting position; see also Dresler et al., 2009; Obersteiner et al., 2010), where the child can perform small movements and provide answers manually. The combination of these two neuroimaging methods increases the construct validity of the findings and allows for a multi-level assessment of underlying neurobiological processes including both an assessment of the involved areas and neural network dynamics. Although subcortical regions cannot be measured with fNIRS, recent studies in adults reveal considerable cross-task validity between fNIRS and fMRI signals for cortical regions (e.g., Haeussinger et al., 2014). Whereas fNIRS provides information about the localization of cortical activation, simultaneous EEG measures provide complementary information about subcortical activation. Further, combining fNIRS and EEG produces both direct and indirect measures of brain activation changes during arithmetic learning in children. Moreover, in addition to behavioral findings, EEG might be helpful to indicate strategies in use (for a review see Hinault & Lemaire, 2016).

As regards EEG, Pfurtscheller (2001) has suggested that cognitive processes lead to both event-related potentials (ERP) and event-related synchronization (ERS)/desynchronization (ERD). While ERP is phase-locked to the event, ERS/ERD is frequency-band specific and non-phase locked to the event (Pfurtscheller, 2001), providing quantified measures of brain dynamics (Pfurtscheller & Aranibar, 1977). In the present study, because we were interested in learning-related brain activation changes in a natural setting, a self-paced paradigm in a block-design experiment was utilized. Therefore, ongoing EEG was recorded during blocks of mental calculation and further analyzed by the ERS/ERD method. Note that ERS represents increased power, while ERD represents decreased power during mental processing as compared to rest (without particular cognitive processing). Furthermore, previous studies have mostly found that cognitive processes result in brain oscillation changes in theta and alpha bands (for a review see Antonenko et al., 2010). Therefore, similar to most of the previous studies in the field of numerical and arithmetic processing (e.g., De Smedt et al., 2009; Grabner & De Smedt, 2012, 2011; Harmony et al., 1999; Micheloyannis et al., 2005; Moeller et al., 2010), these two frequency bands were investigated in the present study.

In accordance with the findings of the training studies in children and adults, we hypothesized a shift from procedural to retrieval strategies after the training, which should lead to more efficient responses, i.e., faster responses and fewer errors (e.g., Fendrich, Healy, & Bourne Jr, 2014). This strategy shift is reflected in brain activation changes in the above-described fronto-parietal network and AG. Based on the literature, we expected reduced activation within the frontal gyri, IPS, SPL and IPL, but regarding activation of the left AG, two hypotheses can be formulated. If the multiplication training studies in adults (Zamarian et al., 2009) can be generalized to children, increased AG activation after training can be expected. If longitudinal and math tutoring studies in children (Supekar et al., 2013; Qin et al., 2014) can be generalized to systematic computerized multiplication training, then activation in AG may decrease. In accordance with studies in adults (Grabner & De Smedt, 2012), EEG oscillations are expected to increase in theta and alpha power after training, reflecting reduced cognitive demands of multiplication problem solving after the training (Antonenko et al., 2010).

Additionally, because studies in adults revealed a similar shift in brain activation patterns during training (Ischebeck et al., 2007) and after several sessions of training (e.g., Delazer et al., 2003), we aimed to measure both immediate (one session) and two-week (seven sessions) multiplication training effects in children. In accordance with the aforementioned studies, similar brain activation changes are expected after both periods. It is important to note that these hypotheses were derived from complex multiplication training studies in adults. However, since children in this developing age (grade 5) are already advanced in simple table multiplication problem solving, these training sessions may not be sufficient to elicit improvement in simple multiplication problems, but only for complex multiplication problems that are not learned via the multiplication table. Therefore, we used both simple and complex multiplication items in all pre- and post-training sessions.

We also investigated transfer effects of multiplication training (see Ischebeck et al., 2009) and changes in strategy use through training. In order to examine transfer effects of multiplication training to basic arithmetic operations, i.e., addition, subtraction, multiplication, and division, a modified math ability test designed by Huber et al. (2013) was used. In addition, because studies define arithmetic learning as a strategy shift (De Smedt et al., 2009; Grabner & De Smedt, 2011, 2012), we measured strategy changes by directly asking children before and after the training sessions about how they solved the problems.

MATERIALS AND METHODS

PARTICIPANTS

26 typically developing children from grade 5 participated in the study. After excluding participants due to technical reasons, noisy data, and one who quitted training, a total of 20 children (8 girls; 11.1 ± 0.5 years old) were included in the analyses (see SI). All children were right-handed and had normal or corrected-to-normal vision with no history of neurological or mental disorders. Children and their parents gave written informed consent and received expense allowance for their participation. All procedures of the study were in

line with the latest revision of the Declaration of Helsinki and were approved by the ethics committee of the University Hospital of Tuebingen.

MATERIAL

16 simple and 16 complex multiplication problems were used in the present study (see Appendices, Table A1). Half of each set was used as trained problems and the other closely matched half was used as untrained problems, resulting in four conditions: trained simple, untrained simple, trained complex, and untrained complex. 16 simple problems (e.g. 4 × 6) included two one-digit operands (range 2–9) with two-digit solutions (range 12–40). 16 complex problems (e.g. 7 × 13) included two-digit (range 12–19) times one-digit operands (range 3–8) with two-digit solutions (range 52–98). The sequence of small and large operands within the problems was counterbalanced. Problems with ones (e.g. 9 × 1), commutative pairs (e.g. 3 × 4 and 4 × 3) or ties (6 × 6) were not used.

fNIRS

FNIRS data were collected with the ETG 4000 Optical Topography System (Hitachi Medical Co., Tokyo, Japan) using two wavelengths of 695 and 830 nm to measure the absorption changes of oxygenated (O2Hb) and deoxygenated hemoglobin (HHb) according to the modified Beer-Lambert law. The data were recorded with 10 Hz sampling rate, and the fixed inter-optode distance was 30 mm. Using a 3×5 arrangement of the optodes (8 emitters, 7 detectors) in an elastic combined fNIRS-EEG cap (Brain Products GmbH., Herrsching, Germany), 22 measurement channels were shaped over each hemisphere. The AAL (automatic anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002) in SPM software (http://www.fil.ion.ucl.ac.uk/spm) was used to calculate the location of the corresponding cortical areas (Tsuzuki et al., 2007; Singh et al., 2005).

EEG

EEG data were recorded with a 32-channel DC-amplifier and the software Vision Recorder (Brain Products GmbH., Herrsching, Germany). 21 scalp EEG electrodes, attached to the combined fNIRS-EEG cap, were used for EEG data collection. Given the fixed optode distances, EEG electrodes were placed according to the extended international

10-20 system (Jasper, 1958; Oostenveld & Praamstra, 2001). In addition, eye movements were recorded using electrooculography (EOG) in one electrode placed below the right eye. The ground electrode was placed frontally on AFz, and the online reference electrode fronto-centrally on FCz. Electrode impedance was kept below 20 kΩ. Data were digitalized at a rate of 1000 Hz with an online bandpass filter of 0.1-100 Hz.

NEUROPSYCHOLOGICAL TESTS

In order to assess the homogeneity of the sample, Intelligence Quotient (IQ) and memory abilities were measured (see SI, Table S2). Two subtests (similarities and matrix reasoning) of the German Wechsler IQ test (Petermann et al., 2007) were utilized to assess intelligence. Furthermore, four memory components including verbal short-term and working memory, visuospatial short-term and working memory were assessed (Alloway et al., 2006). The letter span test was used to measure verbal memory capacity and the block tapping test (Corsi, 1973) was used to assess visuospatial memory capacity (for more details see Mojtaba Soltanlou et al., 2015). In verbal short-term memory, the child had to recall spoken sequences of letter (one letter per second). The test was started with sequences of two letters and increased by one letter if the child recalled correctly at least two out of three sequences. In short-term visuo-spatial memory, the child was asked to point to the cubes in the same order as the experimenter. The procedure was the same as in the letter span test. These forward spans were considered to represent short-term memory, while backward spans were considered to show working memory. Moreover, a modified math ability test (Huber et al., 2013) was used before and after training to assess the transfer effects of multiplication training to other basic arithmetic operations.

Furthermore, a brief self-developed strategy questionnaire was used before and after training. Because of time limitations, we could not ask children after each item, but children were briefly asked before and after the training to get at least some information about possible strategy shifts. The questionnaire contained eight multiplication problems, two from each set, resulting in four different matched lists. There was no time limit for responding to the problems. After responding to each trial, children reported how they arrived at the solution. According to the children's report, recorded strategies were categorized as retrieval, procedural, and other by the experimenters (Grabner & De Smedt, 2011). The inter-rater reliability as indicated by Cohen's kappa was .80.

Measurement procedure

In a within-subject experiment, performance and brain activation of children were measured during multiplication problem solving at three time points (cf. Fig. 1a): before training, immediately after one session of training (immediate effect), and after seven sessions of training (two-week effect). First, children performed the general math ability test and strategy questionnaire. The experiment was conducted after four practice trials in a light-attenuated room. Problems were presented on a touch screen and children had to write their answers as quickly and accurately as possible and then click on a gray box, presented on the right side of screen, to continue (see Fig. 1b). The written response was not visible to avoid any further correction and encourage children to calculate mentally. The problems of each condition were presented in four blocks of 45 s, each followed by 20 s of rest. The sequence of the blocks and of the problems within the blocks was pseudo-randomized. Whenever the total number of trials within a condition was reached, the same problems were presented again after randomization. No feedback was given during the experiment. The design was self-paced with a limited response interval of 10 s for simple and 30 s for complex problems. Therefore, due to inter-individual differences the number of solved problems varied between children. The inter-trial interval was set to 0.5 s. After the pre-training session, children performed one session of approximately 25-minute interactive training (see below). In order to investigate immediate training effects, the first post-training measurement was performed directly afterwards. The whole procedure lasted approximately 2.5 hours. After seven similar interactive seven training sessions performed at home over the course of two weeks, children were measured again in order to evaluate two-week training effects (cf. Fig. 1a). In this second post-training session, the general math ability test and strategy questionnaire were administered again, along with the other neuropsychological tests. The problems, but not the sequence of the blocks or problems, were identical for each condition in pre-training and post-training sessions. The experiment was run using Presentation® software version 16.3 (version 16.3, Neurobehavioral Systems Inc., www.neurobs.com).

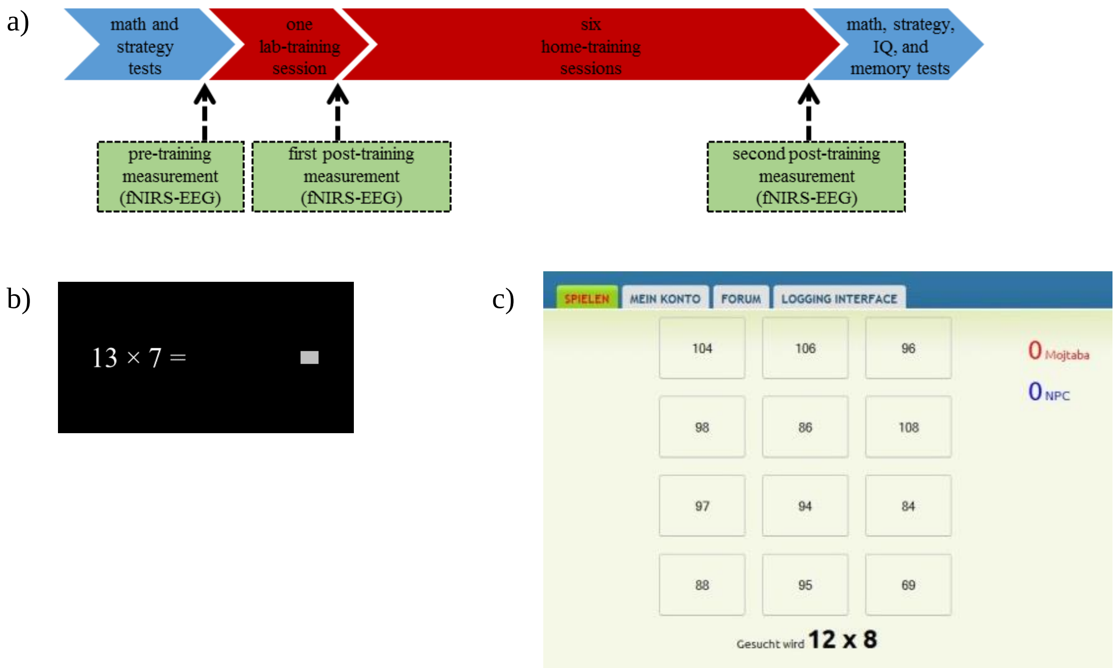

Fig. 1: a) The Experiment: in the first day after pre-training measurement, one session of training using an online learning platform was done and immediately afterward, a post-training measurement was conducted. A second post-training measurement was conducted after two weeks of training. b) After responding, pressing the gray box presented the next problem. c) Online learning platform: in a competition with a computer, children had to select the correct answer out of 12 possible choices.

INTERACTIVE TRAINING PROCEDURE

Training was done using an online learning platform (designed by ScienceCampus Tuebingen, Tuebingen, Germany, see Jung et al., 2015; Jung et al., 2016; Roesch et al., in press), which allow for at-home training. One training session (trained simple and trained complex conditions) was performed in the lab and six at-home sessions were performed by children during a two-week interval. The problems of each condition were randomly repeated six times in each training session. Each problem was individually presented along with 12 different choices including the correct solution (see Fig. 1c). Response intervals of simple problems ranged randomly between 4 and 10 s, jittered by 0.6 s, and of complex problems between 10 and 30 s, jittered by 2 s. Whenever the child did not respond within the response interval, the computer screen displayed the correct solution. Training was interactive in the sense that children had to compete with the computer. To provide feedback about the performance and to increase motivation, the scores of the child and computer were shown on the right side of screen. Both child and computer received one point for each correct answer and one point was deducted for each incorrect answer. The problem was presented until the child or computer responded correctly. In order to create a more realistic competition, the computer responded incorrectly in 30% of the problems. Children were instructed to solve the problems as quickly and accurately as possible.

ANALYSIS

BEHAVIORAL

Written responses by children were read out with the help of RON (ReadOutNumbers program; Ploner, 2014). Response times (RTs) were defined as time from problem presentation to pressing the gray box. Only median RTs for correct responses (78.7 % of problems across all measurement times) were included in the analyses. Error rate was defined as proportion of incorrect or missing responses to total number of presented trials. Furthermore, inverse efficiency scores, which represent quotients of median RTs divided by the percentage of correctly solved problems (Butterworth, 2003), were calculated. Smaller inverse efficiency scores indicate more efficient performance. Separated repeated measures analyses of variance (rmANOVAs) were conducted to investigate immediate and two-week training effects on median RTs, arcsine-square-root-transformed error rates (Winer et al., 1971), and inverse efficiency scores. The 2×2×2 rmANOVA comprised within-factors of measurement time (pre- versus post-training), training (trained versus untrained), and complexity (simple versus complex). Further rmANOVAs and paired t-tests were conducted separately for simple and complex multiplication. Note that because inverse efficiency is a combination of both RT and accuracy of responses, and also due to space limitations, only inverse efficiency is explained in the following. Separate results for RTs and errors on the training effect are reported in SI.

In order to uncover transfer effects of multiplication training to other arithmetic operations, a 2×4 rmANOVA consisting of measurement time (pre- versus post-training) and operation (addition, subtraction, multiplication, and division) as within-factors was conducted. In addition, paired t-tests were conducted separately on each operation. Additionally, to determine the effect of multiplication training on strategy use, paired t-tests were conducted on retrieval and procedural strategies separately. The analysis was completed using SPSS version 23.0 (IBM SPSS Statistics for Windows).

FNIRS

Continuous changes of O2Hb and HHb concentration were recorded for all channels during the measurements. O2Hb and HHb concentration changes depend on the path length of NIR light through the brain, i.e., the scaling is mM*mm. Data were analyzed with customized MATLAB routines (The MathWorks Inc., Natick, Massachusetts, United States). The continuous signals were bandpass-filtered with 0.008-0.09 Hz[2] in order to remove long-term drift of baseline and high-frequency cardiac and respiratory activities (Haeussinger et al., 2014; Sasai, Homae, Watanabe, & Taga, 2011; Tong, 2010). It has been shown that the fNIRS signals, the same as other blood-related brain measures, are low-frequency oscillations, which are mostly detectable between 0.01 and 0.1 Hz (Tong, 2010; Zuo et al., 2010). Further, to deal with possible motion artifacts, particularly in children, we used the correlation-based signal improvement (CBSI) method (Cui et al., 2010). In addition to reduction of motion artifacts, especially head movements in children (Brigadoi et al., 2014), the CBSI method reduces non-evoked systemic influences such as heart rate, Mayer waves or very low-frequency oscillations (Haeussinger et al., 2014; Scholkmann et al., 2014). Note that among different motion correction methods, we applied the CBSI method; however, because the optimal correction method is data-dependent, the CBSI method might not be the optimal motion correction method for every design (for a detailed discusison see Brigadoi et al., 2014). This CBSI time course, which is calculated based on the negative correlation of O2Hb and HHb concentrations, was used for further analysis[3]. Remaining noisy channels were interpolated using the average of surrounding channels for

[2] Applying more liberal low-pass filters of 0.2 Hz, which is one of the commonly used band-pass filter in fNIRS data analyses, and 0.7 Hz led to almost the same result. We believe that our findings are reliable since they were not dependent on the particular filtering methods. Furthermore, in order to remove some confounding signals such as Mayer waves, cardiac and respiratory activities, and also calculations of frequency of neuronal signals in our experiment, and in line with several previous studies, we decided to apply this band-pass filter in our data.

[3] Additionally, similar analyses were conducted on oxy-hemoglobin without applying any motion correction. Interestingly, analysis of both CBSI-Hb and oxy-hemoglobin lead to almost the same brain activation pattern, showing the suitability of the of CBSI-Hb analysis in our data. Moreover, particularly in the current study with children many movement artifacts can be expected, which are specifically targeted by the CBSI correction method.

each participant. The general linear model (GLM) analyses were performed for each participant and condition. The model-based signal, which was a convolved boxcar regressor, indicating the beginning and 40[4] s of each block, with the hemodynamic response function (HRF), was used for further analysis (Haeussinger et al., 2014). Thereafter, means of least-square linear regression were applied to calculate the beta-values of each channel.

Three steps of analysis have been conducted on fNIRS data: rmANOVA on regions of interests (ROIs), rmANOVA on parietal channels, and paired t-tests on the whole brain. Similar to our behavioral data analysis, a 2×2×2 rmANOVA comprising the within-factors of measurement time (pre- versus post-training), training (trained versus untrained), and complexity (simple versus complex) was conducted to find the immediate and two-week training effects separately on each ROI. To this end, four ROIs within the fronto-parietal network, including four channels for each, were defined: left and right frontal, and left and right parietal regions (see Appendices, Fig. A1 and A2). The frontal network comprised middle frontal gyrus (MFG) and IFG, and the parietal network comprised SPL, IPS, IPL, and AG (cf. Appendices, Table A2 and A3). A rmANOVA was conducted for each ROI separately. Furthermore, in the case of a significant three-way interaction, additional rmANOVAs and paired t-tests were conducted separately for simple and complex multiplication. The significance level was .05 uncorrected.

In the next step, since there are distinct networks within the parietal network (Dehaene et al., 2003), similar 2×2×2 rmANOVAs were conducted over the channels within each parietal ROI. Furthermore, in the case of a significant three-way interaction, additional rmANOVAs and paired t-tests were conducted separately for simple and complex multiplication. The significance level was .05 uncorrected. Results for the channel analysis are reported in SI.

Furthermore, in order to examine the training effects on the whole brain, multiple paired t-tests between trained versus untrained conditions were calculated for each channel. To this end, the contrasts in immediate post-training measurement (trained versus untrained) were compared with the contrasts in the pre-training measurement (trained

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[4] Although the duration of blocks were 45 s, however, because of some noises appearing on BOLD signal about the end of blocks, the last 5 s of the blocks were excluded from analysis.

versus untrained) separately for simple and complex conditions. The same contrasts were applied between pre-training and second post-training measurements to evaluate the two-week training effect (for instance in complex multiplication: [trained complex in post-training - untrained complex in post-training] – [trained complex in pre-training - untrained complex in pre-training]). The significance level was .05, and correction for multiple comparisons was performed using the Dubey/Armitage-Parmar (D/AP) method (Sankoh et al., 1997).

EEG

EEG data were analyzed using the Brainstorm toolbox (Tadel et al., 2011), a documented and freely available software package (http://neuroimage.usc.edu/brainstorm). EEG signals of 21 electrodes were offline-filtered using a bandpass of 0.1-40 Hz. Based on the EOG signal, eye movement artifacts were detected and removed from the EEG signals using Signal Space Projections (SSP). In the next step, block duration of 45 s and rest duration of 20 s were epoched. The power spectral density (PSD) in the theta (4-7 Hz) and alpha band (8-12 Hz) was calculated and individually averaged for each condition and measurement time. To measure the cortical activation and functional changes of brain activity (Neuper & Klimesch, 2006; Pfurtscheller & Da Silva, 1999), ERS/ERD was calculated. The percentage values of ERS/ERD were calculated by this expression: ERS/ERD% = (PSD of activation – PSD of rest) / PSD of rest × 100 (Pfurtscheller & Da Silva, 1999) (for more information, see SI).

Six regions of interests (ROIs) within the fronto-parietal network were defined: left, right, and middle fronto-central, left, right, and middle occipito-parietal regions (see Appendices, Fig. A1 and Table A2). Within theta and alpha frequency bands, a 2×2×2 rmANOVA was conducted for each ROI separately. Furthermore, in each step in the case of significant interaction, additional rmANOVAs and paired t-tests were conducted separately for simple and complex multiplication. Additionally, similar to the fNIRS data, paired t-tests between pre- and post-training sessions were calculated in order to examine the training effects on the whole brain. The significance level was .05 uncorrected.

RESULTS

BEHAVIORAL

The immediate training effect on inverse efficiency scores indicated a significant main effect of complexity, $F(1,19) = 55.17$, $p < .001$, $\eta^2 = 0.74$, showing a better performance in simple than in complex multiplication (see Fig. 2a). The other main effects and interactions did not reach statistical significance after just one session, $Fs(1,19) < 2.2$, $ps > .15$, $\eta^2 < 0.11$.

The two-week training effect on inverse efficiency scores revealed significant main effects of measurement time, training, and complexity, $Fs(1,19) > 7.4$, $ps < .013$, $\eta^2 > 0.27$. A significant interaction of measurement time × training showed that training led to a performance improvement in trained compared to untrained conditions, $F(1,19) = 6.45$, $p = .02$, $\eta^2 = 0.25$. A marginally significant interaction of measurement time × complexity, $F(1,19) = 4.02$, $p = .059$, $\eta^2 = 0.18$, and a significant interaction of training × complexity, $F(1,19) = 6.64$, $p = .018$, $\eta^2 = 0.26$, were also observed.

Moreover, a marginally significant interaction of measurement time × training × complexity revealed that after training, children improved mostly in solving the trained complex problems, $F(1,19) = 3.14$, $p = .093$, $\eta^2 = 0.14$ (cf. Fig. 2b). In order to explore training effects for simple and complex problems separately, two rmANOVAs were conducted. In the simple condition, a significant main effect of measurement time was observed, $F(1,19) = 18.16$, $p < .001$, $\eta^2 = 0.49$. A significant interaction of measurement time × training demonstrated that after training, children improved in trained compared to untrained simple problems, $F(1,19) = 13.79$, $p = .001$, $\eta^2 = 0.42$ (cf. Fig. 2a). The main effect of training was not significant in simple conditions. With respect to complex multiplication, significant main effects of measurement time and training were observed, $Fs(1,19) > 5.7$, $ps < .027$, $\eta^2 > 0.22$. The interaction of measurement time × training showed a significant training effect in trained complex multiplication compared to untrained complex problems, $F(1,19) = 4.75$, $p = .042$, $\eta^2 = 0.20$ (cf. Fig. 2a).

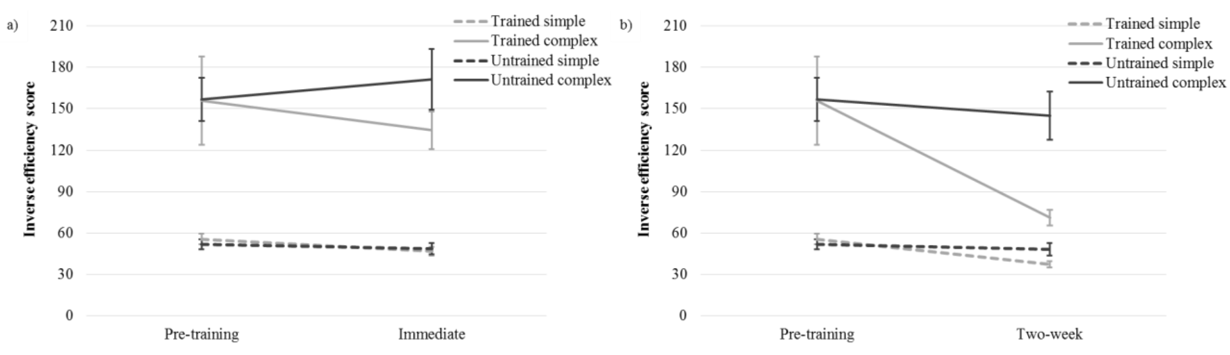


Fig. 2: Inverse efficiency score changes as a) immediate training effect, and b) two-week training effect. Smaller inverse efficiency scores indicate more efficient performance. Error bars reflect SEs.

fNIRS

ROI results

In the absence of immediate behavioral improvement, the rmANOVA on the ROIs revealed a significant immediate training effect in the left parietal region. We observed a significant interaction of measurement time × training, $F(1,19) = 6.33$, $p = .021$, $\eta^2 = 0.25$, and also a marginally significant interaction of measurement time × training × complexity in the left parietal region, $F(1,19) = 3.74$, $p = .068$, $\eta^2 = 0.16$. To delineate this trilateral interaction, two separate 2×2 rmANOVA for simple and complex conditions were conducted. In simple conditions, a significant main effect of measurement time demonstrated a decreased activation of the left parietal region after the training, $F(1,19) = 5.97$, $p = .024$, $\eta^2 = 0.24$ (see Fig. 3a). No other significant effect was found in simple conditions. In complex conditions, a significant interaction of measurement time × training showed a decreased activation in trained complex multiplication, while an increased activation in untrained complex multiplication was observed in the left parietal region, $F(1,19) = 8.25$, $p = .01$, $\eta^2 = 0.30$ (see Fig. 3a). The main effects of measurement time and training were not significant. No significant immediate training effect was observed in other ROIs.

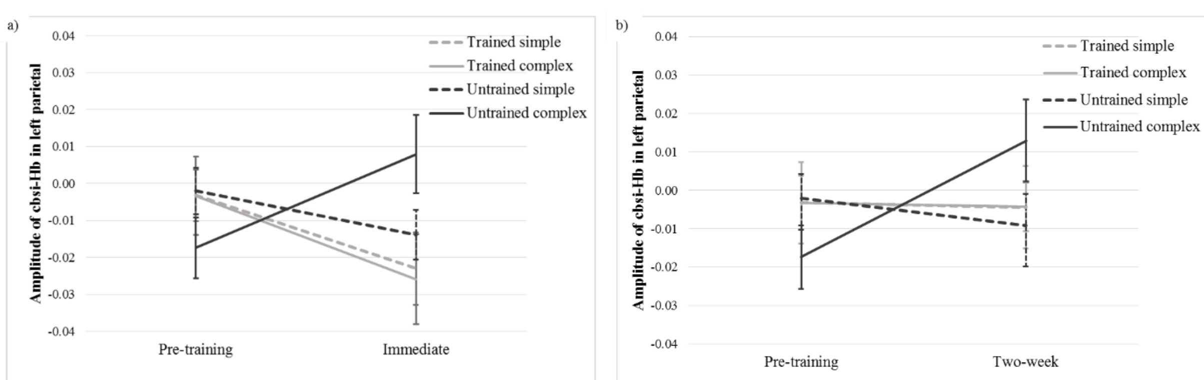


Fig. 3: Brain activation changes in the left parietal region as a) immediate training effect, and b) two-week training effect (the lines representing trained simple and trained complex are almost over each other). Error bars reflect SEs.

Similar to the immediate training effect, the rmANOVA on ROIs in the two-week training revealed significant effects of two-week training only in the left parietal region. A significant interaction of measurement time × training × complexity was observed, $F(1,19) = 8.40$, $p < .01$, $\eta^2 = 0.31$. Further rmANOVA analyses, conducted separately for simple and complex conditions, revealed no significant training effect in simple conditions. In complex conditions, a significant interaction of measurement time × training showed a decreased activation in the trained condition, while an increased activation in the untrained condition was observed in the left parietal region, $F(1,19) = 5.53$, $p = .03$, $\eta^2 = 0.23$ (see Fig. 3b). The main effects of measurement time and training were not significant. No significant two-week training effect was observed in other ROIs.

WHOLE-BRAIN RESULTS

In order to assess the immediate training effect at the whole-brain level, all channels were taken into account. In the complex condition, multiplication training led to a significantly decreased activation at the junction of the left AG and IPL (channel 10), and in the right SPL and IPS (channel 44), $ts(19) < -2.75$, $ps < .05$ (cf. Fig. 4). This decrease showed less bilateral parietal engagement in trained than untrained complex multiplication after one session of training. No significant brain activation change for simple multiplication problems was found. Results of contrasts of trained versus untrained conditions within each measurement time are reported in SI (cf. SI, Fig. S4).

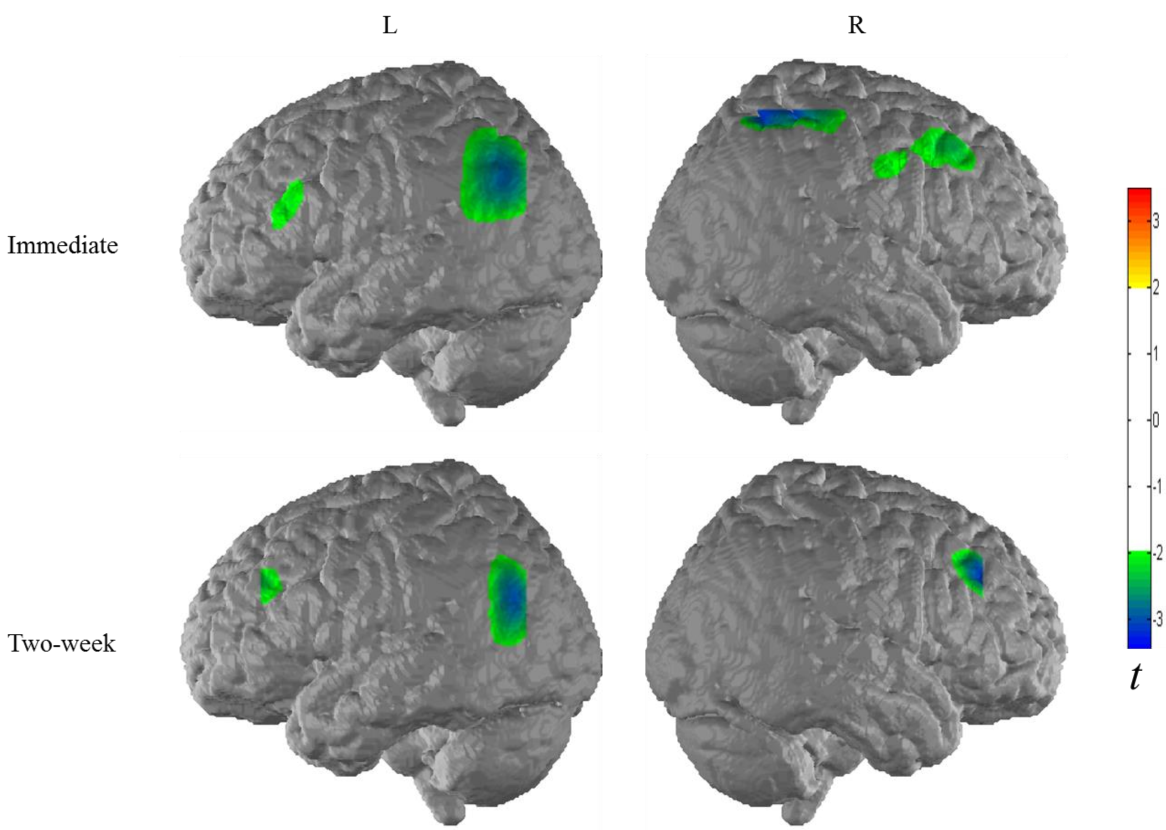


Fig. 4: The upper panel shows the immediate training effect and the lower panel shows the two-week training effect of complex multiplication on brain activation in fNIRS. No significant difference was observed for simple multiplication. Blue represents reduced activation, and green represents non-significant reduction of activation. L: left; R: right.

Two-week training effects at the whole-brain level were assessed by taking all channels into account. In the complex condition, multiplication training led to a significantly decreased activation at the junction of the left AG and MTG (channel 5) (cf. Fig. 5), and in the right MFG (channel 36), *ts*(19) < -2.93, *ps* < .05 (see Fig. 4). This decrease showed less engagement of left parietal and right frontal cortex in trained than untrained complex multiplication after two weeks of training. No significant brain activation change was observed in training of simple multiplication problems. The full results of contrasts of trained versus untrained conditions for the second post-training measurements are reported in SI (cf. SI, Fig. S4).

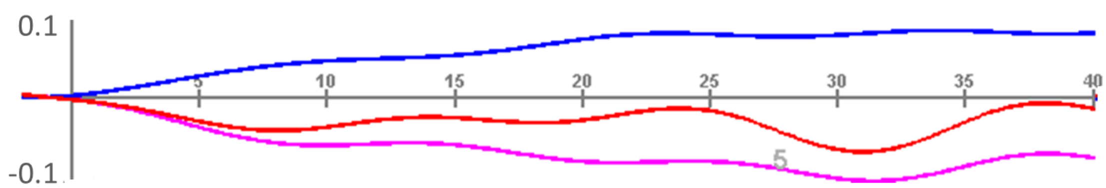


Fig. 5: Exemplary time course of the fNIRS signal. The block average B-values of oxy-hemoglobin (red), deoxy-hemoglobin (blue) and CBSI-corrected signal (pink) are given for the two-week contrast of contrast at the junction of the left AG and MTG (channel 5), which revealed a significant decrease of activation. The results of all three signals (oxy-hemoglobin, deoxy-hemoglobin, and CBSI-Hb) show reduced activation in this area in trained complex problems as compared to untrained complex problems after two-week training.

EEG

ROI RESULTS

The rmANOVA on ROIs showed no significant immediate training effect neither in the theta nor the alpha band. With respect to two-week training, the rmANOVA on ROIs revealed a significant main effect of complexity in the left occipito-parietal and in middle fronto-central regions in theta band, *Fs*(1,19) > 4.7, *ps* < .042, $\eta^2 > 0.19$, showing greater theta ERS in complex than simple conditions. No other significant effect was observed in the theta frequency band.

In the alpha band, two-week training led to a significant main effect of measurement time in occipito-parietal regions bilaterally, *Fs*(1,19) > 4.7, *ps* < .042, $\eta^2 > 0.19$, which demonstrated increased alpha ERD after the training. No other significant effect was observed in the alpha frequency band.

WHOLE-BRAIN RESULTS

However, to see plausible immediate training effects at the whole-brain level, the contrasts were additionally calculated for each electrode, similarly as for the fNIRS data. No significant training change was found for simple multiplication problems. In complex multiplication training, significantly greater alpha ERD over parietal areas (Pz) was observed in the contrast of trained versus untrained problems, $t(19) = -2.36$, $p < .05$ (see Fig. 6), which stems mostly from the post-training comparison (see SI, Fig. S5). Therefore, children's behavioral performance in these two conditions was directly compared in post-training measurement. They showed significantly better performance in trained complex than in untrained multiplication, $t(19) = 3.37$, $p = .003$. No significant difference was observed in the theta frequency band in any of contrasts. Results of contrasts of trained versus untrained conditions within each measurement time are reported as SI (cf. SI, Fig. S5).

In order to identify activation changes at the whole-brain level due to two-week training, similar contrasts as for the fNIRS data were calculated. For training of simple multiplication problems, significantly decreased alpha ERD at the central site (Cz) in post-training compared to pre-training was found, $t(19) = 3.11$, $p < .05$. For complex multiplication, significantly decreased alpha ERD was observed at the left occipital site (O1), $t(19) = 2.44$, $p < .05$ (cf. Fig. 6). No significant difference was observed in the theta frequency band in any of the contrasts. Results from contrasts of trained versus untrained conditions within each measurement time are reported as SI (cf. SI, Fig. S5).

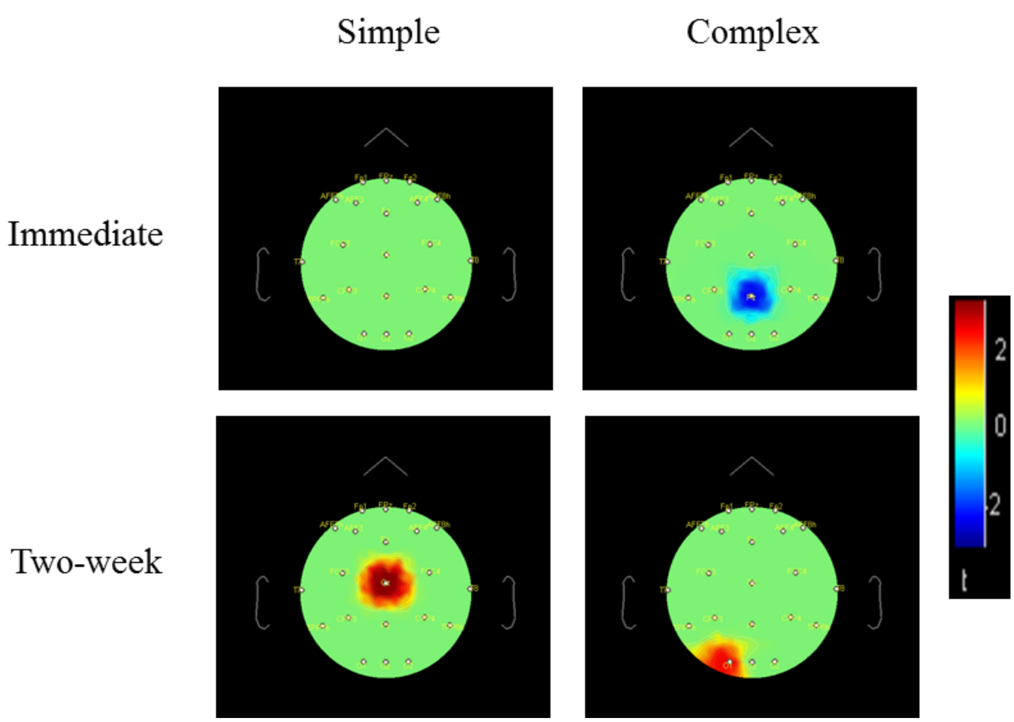


Fig. 6: The upper panel shows the immediate training effect and the lower panel shows the two-week training effect of simple and complex multiplication on the alpha ERD in children. No

significant difference was observed in theta ERS. The red represents reduced alpha ERD and blue represents increased alpha ERD.

Other neuropsychological and arithmetic tests

Regarding the transfer of multiplication learning to other arithmetic operations, a significant main effect of measurement time showed that children responded correctly to more problems after the training, $F(1,19) = 6.12$, $p = .02$, $\eta^2 = 0.24$. A significant main effect of operation revealed that children have different competence in responding to different basic arithmetic operations, $F(1,19) = 30.89$, $p < .001$, $\eta^2 = 0.62$. Additional analysis revealed that children had better performance in the order of: addition > subtraction > multiplication and division, $ts(19) > 3.03$, $ps < .007$. However, the interaction of measurement time × operation was not significant.

The result of strategy use revealed that after training, children use significantly more retrieval strategies, $t(19) = 3.87$, $p = .001$, and fewer procedural strategies, $t(19) = -2.70$, $p = .014$, compared to pre-training.

Discussion

In the current study, a group of typically developing children received training on simple and complex multiplication, which led to improved performance after two-week training but not immediate training (one session). Nevertheless, even after immediate training, brain activation changes were observed in parietal regions. After the two-week training, the behavioral improvement, which was associated with a strategy shift from procedural to retrieval strategies, was accompanied by reduced activation of the fronto-parietal network and alpha ERD.

Immediate training effect

In the absence of any significant behavioral improvement, fNIRS findings showed reduced activation at the junction of the left AG and IPL, and also the right SPL and IPS after one training session in the trained complex condition. This finding is in line with the longitudinal (non-learning) study by Qin et al. (2014), who found that one year of academic education led to reduced activation of bilateral parietal regions in addition problem solving in children. Decreased parietal activation, which is related to quantity-based processing, indicated that after the training, children needed less "manipulation" of the numeral magnitudes. This finding was in line with a study by Ischebeck et al. (2007) that reported similar brain activation changes in adults after eight repetitions of complex multiplication problems. Moreover, in the present study, a production paradigm was used. Therefore, the problems require an exact calculation, so other plausible strategies such as approximation cannot be used (for a discussion see Delazer et al., 2003). Decreased activation of parietal regions, which are needed for exact calculation (e.g., Dehaene et al., 2004), is a reasonable explanation. However, an increased alpha ERD as a result of immediate training of complex multiplication was unexpected. One possible explanation is that alpha ERD is also sensitive to visual attentional processes (Klimesch, Sauseng, & Hanslmayr, 2007). Better performance in trained complex conditions, i.e., faster responses and fewer errors, led to more problems being presented and therefore, more visual processing in trained complex condition was needed that induced alpha ERD.

In simple multiplication, no significant difference was observed, which might be due to insufficient training, because children in this developing age are advanced in solving simple multiplication problems, and more repetitions than just a single session are needed to improve their performance.

BRAIN ACTIVATION CHANGES IN CHILDREN

The two-week training data illustrate that children became more efficient in the trained compared to untrained multiplication problems, which means faster responses with fewer errors. With respect to the trained simple condition, no significant change was observed in the fNIRS data. However, decreased alpha ERD (i.e., increased alpha power) was found in EEG data for both trained simple and complex multiplication (see also Grabner & De Smedt, 2012). This decrease suggests more retrieval processing in both trained conditions through training. This finding is in line with previous studies in which working memory training led to decreased alpha ERD, representing less cortical activation (Gevins et al., 1997). According to Pfurtscheller (2001), ERD represents a reduction of localized amplitudes, which is associated with an increased excitability of cortical regions. This cortical excitability reflects increased information processing. Therefore, decreased alpha ERD in both trained conditions in the present study can be interpreted as a decreased cortical effort. However, regarding the EEG findings, it is important to note that results were reported at an uncorrected significance level (despite multiple statistical comparisons). Nevertheless, we believe that, in combination with the fNIRS data, the EEG data help to strengthen the validity of the findings.

In the trained complex condition, the fNIRS findings showed a reduced activation at the junction of the left AG and MTG, along with the right MFG after training. It has been shown that learning changes general purpose/domain-general to more domain-specific processing, which is indicated by reduced activation in several brain regions (Poldrack, 2000). These findings were partially in line with previous multiplication training studies in adults, which reported a decreased activation within the fronto-parietal network (Zamarian et al., 2009, for a review). In agreement with this finding, in the present study, the right MFG, which is involved in executive control and working memory, showed reduced activation after the training. This indicates faster calculation processes after complex multiplication training that do not depend as much on sequential cognitive processes compared to before training (see also Prado et al., 2014).

It should be noted that there was an unexpected increase in activation of these areas in untrained complex multiplication in the post-training compared to the pre-training session. This increased activation may reflect improved performance (i.e., faster responses; see SI, Fig. S1) in untrained complex multiplication via training, which might be due to increased recruitment of these domain-general regions. This is different from trained complex multiplication, which showed less brain effort with improved performance via training, probably because effort-saving retrieval processes are recruited here. In sum, this shows that better performance might be subserved by different neurocognitive mechanisms: (i) efficient recruitment of specific areas associated with strategy change (e.g., procedural to retrieval processes) when the particular items have been trained or (ii) recruitment of more brain areas associated with domain-general processes within the same (procedural) strategy when the particular items have not been trained, but the outcome of the procedural strategy itself is improved.

In the present study, decreased activation at the junction of the left AG and MTG was detected, while no brain activation change was observed in the left AG. This finding is in agreement with longitudinal and training studies in children (Qin et al., 2014; Supekar et al., 2013), but is contradictory to multiplication training studies in adults, which reported increased activation of the left AG after training (for a review Zamarian et al., 2009; but see Bloechle et al., 2016). It seems that although a shift from procedural effortful to retrieval memory-based strategies is represented as a shift from fronto-parietal network to left AG engagement in adults, the same is not necessarily true for children (see also Supekar et al., 2013). This difference might be due to more stable neural substrates of arithmetic processes in adults compared to children (Qin et al., 2014). Furthermore, this strategy shift is not represented by similar brain activation changes from childhood into adulthood (Qin et al., 2014; Kawashima et al., 2004). The reduced activation around the left AG is in line with the study by Menon et al. (2000), which reported a decreased AG activation with an increase of expertise (see also Amalric & Dehaene, 2016). It should be noted that even for adults, different brain areas, and not only the left AG, lead to retrieval processes after multiplication training (Bloechle et al., 2016; Delazer et al., 2005). Furthermore, several studies showed an unspecific role of AG activation in arithmetic learning (Ischebeck et al., 2006; Grabner, Ischebeck, et al., 2009; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). To sum up, we conclude that the

AG might have an intermediate role during development, with a nonlinear relation (over age and development) between AG activation increase/decrease and arithmetic learning. However, this assumption needs to be tested in larger future studies that use the same learning paradigm over a wide range of age groups.

Further, it seems that short-term arithmetic training leads to a restricted generalization to the other problems of the same operation. This restricted generalization means training leads to an improvement in both trained and untrained problem solving, but this improvement is much stronger in the case of trained problems. In the current study this restricted generalization has been detected in the response time after two-week training (cf. SI). Children responded faster to not only both trained sets, but also to both untrained sets. However, this improvement was much stronger in trained sets as compared to untrained sets. This restricted generalization has been already shown in adults (Ischebeck et al., 2009), and also depends on the training method (Delazer et al., 2005).

TRANSFER EFFECTS

With respect to transfer effects, a generally improved performance in all basic arithmetic operations was found after multiplication training in children, which was not specific to any one operation (but see Ischebeck et al., 2009). However, even though the time interval between pre- and post-training measurement was short (two weeks) and children in grade 5 do not receive direct training of basic arithmetic, the absence of a control group makes it difficult to interpret this improvement as the result of multiplication training.

POSSIBLE METHODOLOGICAL AND ANALYSIS DIFFERENCES

While the different findings of arithmetic training between adults and children can be explained by above neurocognitive accounts focusing on different brain-behavior relations between children and adults, there are some alternative methodological explanations (e.g., Shallice, 2003) that should be mentioned and possibly be tested in future studies. First, while most of the training studies used verification paradigms to reduce movement artifacts in the MRI scanner, the present study applied a written production paradigm. This means that children calculated almost every single trial without using any shortcut strategies, which in other studies might lead to more retrieval strategies because of the priming role of the presented solutions. Secondly, previous studies usually employed a fixed number of trials, while in the present study a self-paced design was utilized, leading to different numbers of answered trials across individuals. With a self-paced design, more calculation time is usually spent on more complex trials. Therefore activation differences might be partially due to the actual time needed for calculation, and not only to different strategy use.

Furthermore, because calculation times differ quite strongly across individuals and problems, the BOLD fitting might differ for fast (trained) and long (untrained) items, making at least event-related designs susceptible to misfits of the BOLD function in one or the other condition. In our design, we used blocked conditions and self-paced design (as in most cognitive and educational settings). The self-paced design ensures that the child is continuously performing the task without larger resting times between items for the faster condition. This is achieved by a higher number of trials in the easier (faster) condition, because children move to the next item as soon as they respond. This may partially explain the lack of activation change in the left AG in the present study. Moreover, a recent study by Bloechle et al. (2016) revealed increased activation of AG in the comparison of trained versus untrained in post-training measurement in adults, but not in the comparison of trained condition in post-training versus pre-training. However, in our study, increased activation of AG was not observed in any of these comparisons. Because of the convergence with other longitudinal studies in children, it seems unlikely that the differences to adult studies are only due to methodological differences, but in our view, the issue of the duration of activation and the goodness-of-fit of the BOLD function deserves more attention in future training studies. Despite these limitations, there is a clear take-home-message from this study: The results of experimental neurocognitive studies in adults do not generalize to children's neurocognitive activation in an ecologically valid setting that resembles how they solve tasks at school.

CONCLUSION

The present study showed that performance improvement via arithmetic learning in children is accompanied by brain activation changes, as measured by simultaneous fNIRS-EEG measurements. However, these changes clearly differed from those induced by arithmetic training in adults. While studies in adults reported a shift from procedural to retrieval strategies as indexed by a decreased activation of fronto-parietal network structures and an increased activation of the left AG, the present training study in children revealed generally decreased brain activation in a fronto-parietal network. We interpret these differences in brain activation changes as an effect of age, suggesting that the strategy shift in children has a different neural pattern than in adults, although some alternative methodological accounts should be addressed in future studies. Independent of the explanations for our results, one take-home message is quite clear: previous findings from experimental neurocognitive studies in adults cannot be simply generalized to children's learning of arithmetic in an ecological setting that closely resembles arithmetic performance in schools. Therefore, in a more general conclusion, we argue that this study is an example of the Educational Neuroscience Approach, studying educational contents and settings with neuroscientific methods, is needed to understand (neurocognitive) development and learning in children – experimental neurocognitive studies in adults alone will not be sufficient.

ACKNOWLEDGMENT

We would like to thank all participating children and their parents. This research was funded by a grant from the Science Campus Tuebingen, project 8.4 to HCN supporting MS. CA, TD, ACE, AJF and HCN are further supported by the LEAD Graduate School & Research Network [GSC1028], a project of the Excellence Initiative of the German federal and state governments, and SH is supported by Leibniz-Institut für Wissensmedien of Tuebingen. Furthermore, ACE was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0). We would also thank Minako Uga and Ippeita Dan for great help in preparing the spatial registration and anatomical labeling of fNIRS channels. Finally, we thank our assistants who helped with recording EEG and fNIRS data and proofreading the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

SUPPLEMENTARY MATERIALS

MATERIAL AND METHODS

TRAINING PROCEDURE

It should be noted that because of online training at home, it was not possible to fully control it. Due to technical and personal reasons, a few children quit some training sessions early and completed them again, which led to a different number of presented trained simple and complex problems across participants (Table S1). Seven children completed 6 and one child completed 5 training sessions out of 7.

Table S1: Mean (and SD) of a number of presented trained simple and complex problems per training session.

Session	1	2	3	4	5	6	7
Simple	49.8 (3.1)	52.3 (8.6)	50.1 (11.2)	52.9 (13.1)	51.6 (9.5)	51.2 (8.7)	50.5 (12.3)
Complex	49.9 (3.4)	52.8 (10.1)	50.8 (11.9)	53.4 (14.1)	51.2 (9.1)	51.2 (10.1)	52.0 (12.8)

For each problem, one correct solution and 11 distractors were presented. Each distractor was made based on one of the following rules: adding 1 to or subtracting 1 from the first or second operand, adding or subtracting 1, 2, 10 from the correct solution, or inversing the unit and decade of the correct solution.

Neuropsychological tests

Children's performance in IQ subtests of similarity and matrix reasoning, along with memory components (verbal STM, verbal WM, visuospatial STM, visuospatial WM), are presented in Table S2. To investigate the transfer effect of multiplication training to other operations (addition, subtraction, multiplication, division), we used two closely matched sets of all four basic arithmetic before and after the training. The test was a modified version of an arithmetic test designed by Huber et al. (2013) with two levels of complexity resulting in eight lists of problems. Children had 45 s for each simple list and 60 s for each complex list, and they were required to answer as many problems as possible while avoiding errors.

Table S2: Mean and SDs of IQ subtests and memory components. STM: short-term memory; WM: working memory.

Similarities	**Matrix reasoning**	**Verbal STM**	**Verbal WM**	**Visuo-spatial STM**	**Visuo-spatial WM**
108.5 ± 11.71	108.0 ± 10.44	4.95 ± 0.76	3.95 ± 0.89	5.35 ± 0.81	5.30 ± 1.13

Analysis

FNIRS

In order to investigate the difference of trained and untrained conditions within each measurement time (pre-training, first post-training, and second post-training), multiple paired t-tests were applied: trained simple vs untrained simple; trained complex vs untrained complex. The significance level was .05 and corrected using the Dubey/Armitage-Parmar (D/AP) method for multiple comparisons (Sankoh et al., 1997).

EEG

Theta and alpha frequency bands are frequently investigated in cognitive tasks (Antonenko et al., 2010). The ERS/ERD are quantificational measures of brain dynamics (Pfurtscheller & Aranibar, 1977). Because of the sensitivity of the EEG signal to several factors such as individual differences, age (Klimesch, 1999), and brain volume (Nunez & Cutillo, 1995), analysis of changes in the EEG signal is more reliable than the absolute power of the frequency band (Pfurtscheller & Da Silva, 1999). ERS is indicated as larger power spectral density (PSD) of a condition than at rest, which leads to a positive value, while ERD is indicated as a negative value because the PSD of a condition is smaller than at rest. For each condition, statistical analyses comprised t-tests against zero for ERS/ERD% of each electrode and each frequency band. Within each measurement time, the contrast of trained versus untrained conditions was calculated with paired t-tests. The significant level was .05 uncorrected.

RESULTS

BEHAVIORAL

RT

The analysis of median RT after immediate training revealed a significant main effect of complexity showing that children responded faster to simple compared to complex problems, $F(1,19) = 188.82$, $p < .001$, $\eta^2 = 0.91$. No other significant main effect or interaction was found in analysis of median RTs with respect to immediate training (cf. Fig. S1a).

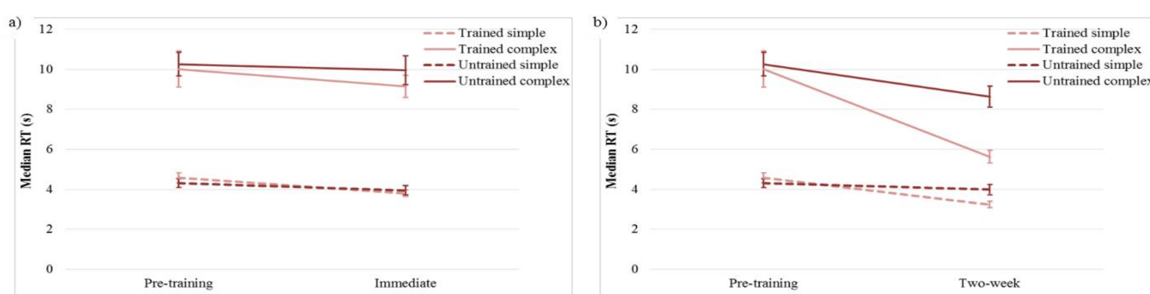


Fig. S1: a) Immediate training effect and b) Two-week training effect on median RT. Error bars reflect SEs.

In regard to the median RT after two-week training, significant main effects of measurement time, training, and complexity were observed, $Fs(1,19) > 19.3$, $ps < .001$, $\eta^2 > 0.49$. A significant main effect of measurement time indicated that children became faster after training in multiplication problem solving. A significant interaction of measurement time × training showed that training led to improved performance in trained compared to untrained conditions in terms of response time, $F(1,19) = 16.14$, $p < .001$, $\eta^2 = 0.46$. Additional analysis revealed significantly faster responses in trained conditions than untrained conditions after training, $t(19) = 7.37$, $p < .001$. Moreover, a significant interaction of measurement time × complexity, $F(1,19) = 16.44$, $p < .001$, $\eta^2 = 0.46$, and a significant interaction of training × complexity, $F(1,19) = 15.68$, $p < .001$, $\eta^2 = 0.45$, were observed (see Fig. S1b).

Furthermore, a marginally significant interaction of measurement time × training × complexity was observed, $F(1,19) = 3.67$, $p = .07$, $\eta^2 = 0.16$. In order to explore training effects for simple and complex problems, two separate rmANOVAs were conducted for simple and complex multiplication. With respect to simple multiplication, a significant main effect of measurement time showed that children provided faster responses after training, $F(1,19) = 27.66$, $p < .001$, $\eta^2 = 0.59$. Moreover, the significant interaction effect of measurement time × training revealed a two-week training effect in trained simple compared to untrained simple multiplication, $F(1,19) = 26.18$, $p < .001$, $\eta^2 = 0.58$. Further analysis showed that children responded faster to trained simple than untrained simple problems in post-training measurement, $t(19) = 4.68$, $p < .001$. The main effect of training did not reach significance in simple conditions. Regarding complex multiplication, a significant main effect of measurement time, demonstrating faster responses after training, $F(1,19) = 24.28$, $p < .001$, $\eta^2 = 0.56$, and a significant main effect of training, $F(1,19) = 20.70$, $p < .001$, $\eta^2 = 0.52$, were observed. A significant interaction effect of measurement time × training revealed that after training, children provided faster responses to trained complex compared to untrained complex problems, $F(1,19) = 9.32$, $p = .007$, $\eta^2 = 0.33$. Additional analysis showed children responded faster to trained complex than untrained complex problems in post-training measurement, $t(19) = 7.29$, $p < .001$ (cf. Fig. S1b).

Error rate

Regarding the error rate after immediate training, a significant main effect of complexity demonstrated that children responded more accurately to simple compared to complex problems, $F(1,19) = 105.23$, $p < .001$, $\eta^2 = 0.85$. Moreover, a significant interaction of training × complexity was observed, $F(1,19) = 7.89$, $p = .011$, $\eta^2 = 0.29$. Further analysis revealed significantly fewer errors in trained complex compared to untrained complex multiplication, $t(19) = 2.18$, $p = .042$, but no significant difference was observed in simple conditions. No other significant effect was found in analysis of error rate after immediate training (see Fig. S2a).

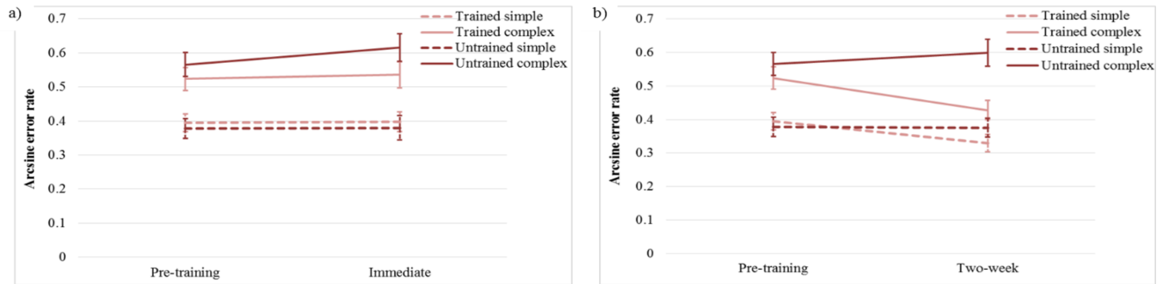


Fig. S2: a) Immediate training effect and b) Two-week training effect on arcsine error rate. Error bars reflect SEs.

With respect to two-week training, similar rmANOVA over the arcsine-root-square error rate displayed a significant main effect of training, $F(1,19) = 9.83$, $p = .005$, $\eta^2 = 0.34$, and a significant main effect of complexity, showing that children responded more accurately to simple compared to complex problems, $F(1,19) = 91.13$, $p < .001$, $\eta^2 = 0.83$. A significant interaction of measurement time × training revealed fewer errors in trained than untrained conditions after training, $F(1,19) = 6.19$, $p = .022$, $\eta^2 = 0.25$. Further analysis showed children made fewer errors in responding to trained conditions than untrained conditions in post-training measurement, $t(19) = 4.16$, $p < .001$ (see Fig. S2b). Furthermore, a significant interaction of training × complexity was observed, $F(1,19) = 12.74$, $p = .002$, $\eta^2 = 0.40$.

fNIRS

Channel results

The rmANOVAs on parietal channels were conducted separately. With respect to immediate training, at the junction of the left AG and MTG (channel 5), a significant interaction of measurement time × training was observed, $F(1,19) = 4.61$, $p = .045$, $\eta^2 = 0.20$, although further analysis did not reach significance in any comparison, *ts*(19) < 1.9, *ps* > .08. There were no other significant effects in this region.

At the junction of the left AG and IPL (channel 10), a significant interaction of measurement time × training was observed, $F(1,19) = 5.74$, $p = .027$, $\eta^2 = 0.23$. Additional analysis revealed significantly reduced activation of trained conditions compared to untrained conditions, $t(19) = 2.33$, $p = .03$. In addition, a significant interaction of measurement time × training × complexity in this region was observed, $F(1,19) = 4.96$, $p = .038$, $\eta^2 = 0.21$. In order to explore training effects for simple and complex problems separately, 2×2 rmANOVAs were conducted in simple and complex conditions separately. No significant training effect in simple conditions was found. In complex conditions, a significant interaction of measurement time × training showed a decreased activation in trained conditions and an increased activation in untrained conditions, $F(1,19) = 8.61$, $p = .009$,

η^2 = 0.31. Further analysis revealed significantly increased activation in the untrained complex condition after training, $t(19) = 2.12$, $p = .047$. The main effects of measurement time and training were not significant in complex conditions (cf. Fig. S3a).

In the left SPL and IPS (channel 19), a significant main effect of measurement time showed a decreased activation after training, $F(1,19) = 5.79$, $p = .026$, $\eta^2 = 0.23$. There was no other significant effect in this region. In addition, no significant training effect was observed in the left AG (channel 14).

In right SPL and IPS (channel 44), a significant interaction of measurement time × training was observed, $F(1,19) = 4.82$, $p = .041$, $\eta^2 = 0.20$. Additional analysis illustrated significantly decreased activation in trained conditions after training, $t(19) = 2.43$, $p = .025$. Moreover, a significant interaction of measurement time × training × complexity was observed, $F(1,19) = 6.04$, $p = .024$, $\eta^2 = 0.24$. In order to explore training effects for simple and complex problems separately, 2×2 rmANOVAs were conducted in simple and complex conditions separately. No significant training effect was observed in simple conditions. In complex conditions, a significant interaction of measurement time × training was found, $F(1,19) = 10.50$, $p = .004$, $\eta^2 = 0.36$. Further analysis illustrated significantly decreased activation in trained complex compared to untrained complex multiplication in the first post-training measurement, $t(19) = 2.52$, $p = .021$. The main effects of measurement time and training were not significant (see Fig. S3b). No significant training effect was observed at the junction of right AG and MTG (channel 31), at the junction of the right AG and IPL (channel 35), or in the right AG (channel 40).

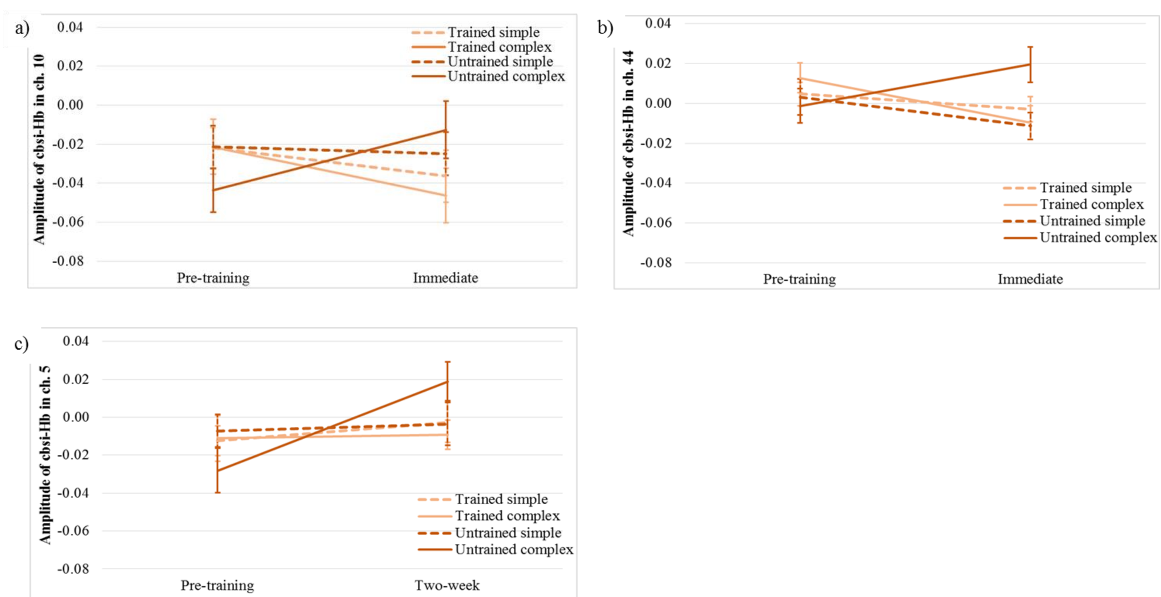


Fig. S3: Immediate training effect on brain activation changes: a) at the junction of the left AG and IPL (channel 10), and b) in right SPL and IPS (channel 44). c) Two-week training effect on brain activation changes at the junction of the left AG and MTG (channel 5). Error bars reflect SEs. Ch.: channel.

In order to indicate two-week training effect on channels level, rmANOVAs were conducted separately on parietal channels. At the junction of the left AG and MTG (channel 5), a main effect of measurement time surprisingly demonstrated an increased activation after training, $F(1,19) = 4.41$, $p = .049$, $\eta^2 = 0.19$. Furthermore, a significant interaction of measurement time × training × complexity was observed, $F(1,19) = 7.02$, $p = .016$, $\eta^2 = 0.27$. In order to explore two-week training effect for simple and complex problems, two separate rmANOVAs were conducted for simple and complex multiplication. No significant training effect was found in simple conditions. In complex conditions, a significant interaction of measurement time × training showed a decreased activation at the junction of the left AG and MTG in trained complex multiplication and an increased activation in untrained complex multiplication, $F(1,19) = 8.23$, $p = .01$, $\eta^2 = 0.30$ (cf. Fig. S3c). Further analysis illustrated significantly increased activation in untrained complex multiplication, $t(19) = 3.74$, $p = .001$. The main effects of measurement time and training were not significant in complex conditions.

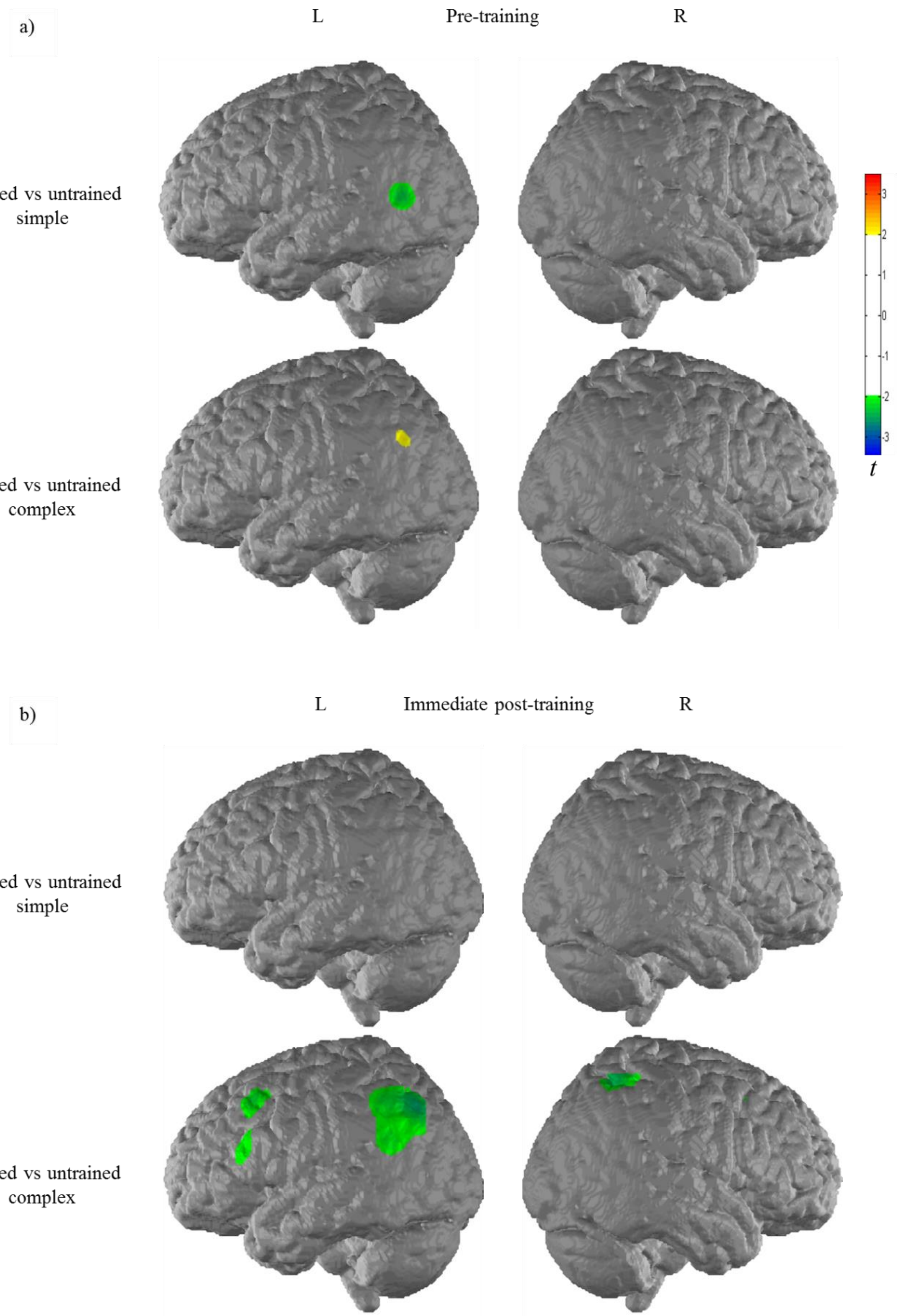
At the junction of the left AG and IPL (channel 10), a significant interaction of measurement time × training × complexity was observed, $F(1,19) = 10.33$, $p = .005$, $\eta^2 = 0.35$. However, 2×2 rmANOVA analysis, conducted separately for simple and complex conditions, illustrated no significant training effect in either simple or in complex conditions.

In the right hemisphere, the only significant finding was interaction of measurement time × complexity at the junction of the right AG and MTG (channel 31), $F(1,19) = 6.86$, $p = .017$, $\eta^2 = 0.27$. No significant training effect was observed in bilateral SPL, IPS (channels 19, and 44), bilateral AG (channels 14, and 40), or in the right junction of AG and IPL (channel 35).

Whole-brain results of each measurement time

Furthermore, differences between trained and untrained conditions within each measurement time were investigated for fNIRS data. In the pre-training measurement, there was no significant difference in the contrast of trained simple versus untrained simple multiplication, or in the contrast of trained complex versus untrained complex (cf. Fig. S4a).

In the immediate post-training measurement, in the contrast of trained complex versus untrained complex multiplication, right SPL and IPS (channel 44) displayed significantly decreased activation, $t(19) = -2.52$, D/AP corrected $p < .05$ (see Fig. S4b). Although reduced activation of the left AG (channel 14) and surrounding areas was observed, it did not survive correction for multiple statistical comparisons. No significant difference was found in the contrast of trained simple versus untrained simple multiplication.



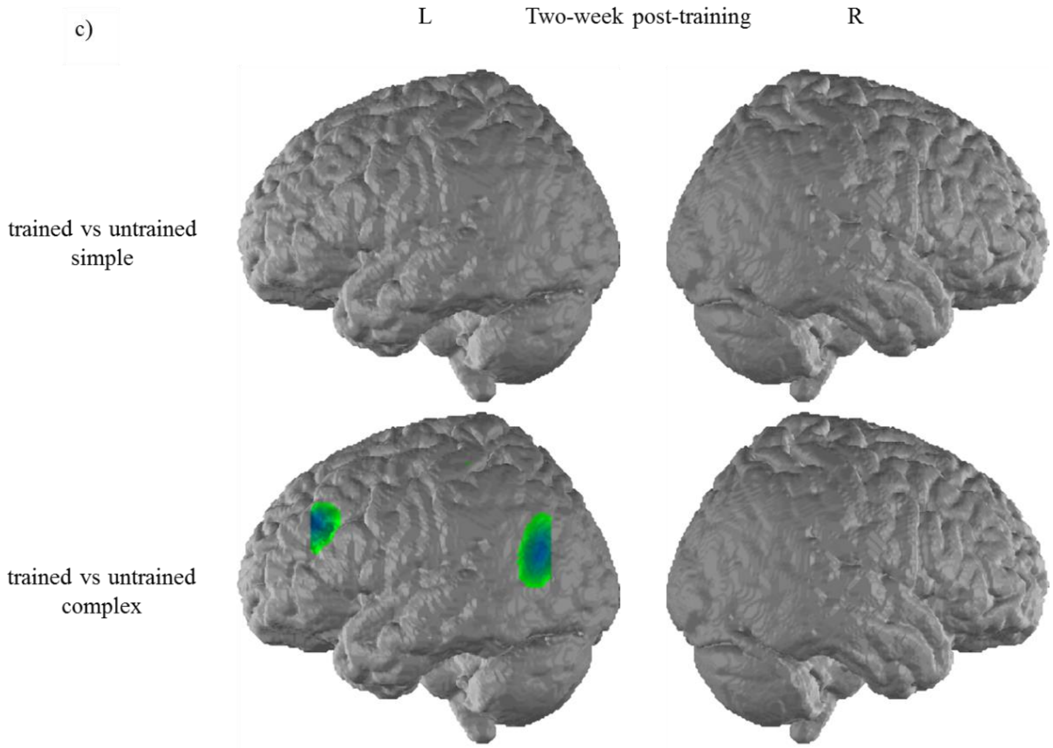


Fig. S4: a) FNIRS data showed no difference between trained and untrained conditions before the training. b) Although no immediate effect of training was observed in simple conditions, decreased activation of right SPL and IPS was found in trained complex compared to untrained complex multiplication. In the contrast of complex conditions, the huge deactivated area in the left parietal region did not survive correction for multiple comparisons. c) FNIRS data showed no two-week training effect in simple condition. The lower panel shows reduced activation of the left MFG for trained complex condition in the two-week post-training session. In the contrast of complex conditions, the deactivated area in the left parietal region did not survive correction for multiple comparisons. The blue represents reduced activation, and the green represents non-significantly reduced activation.

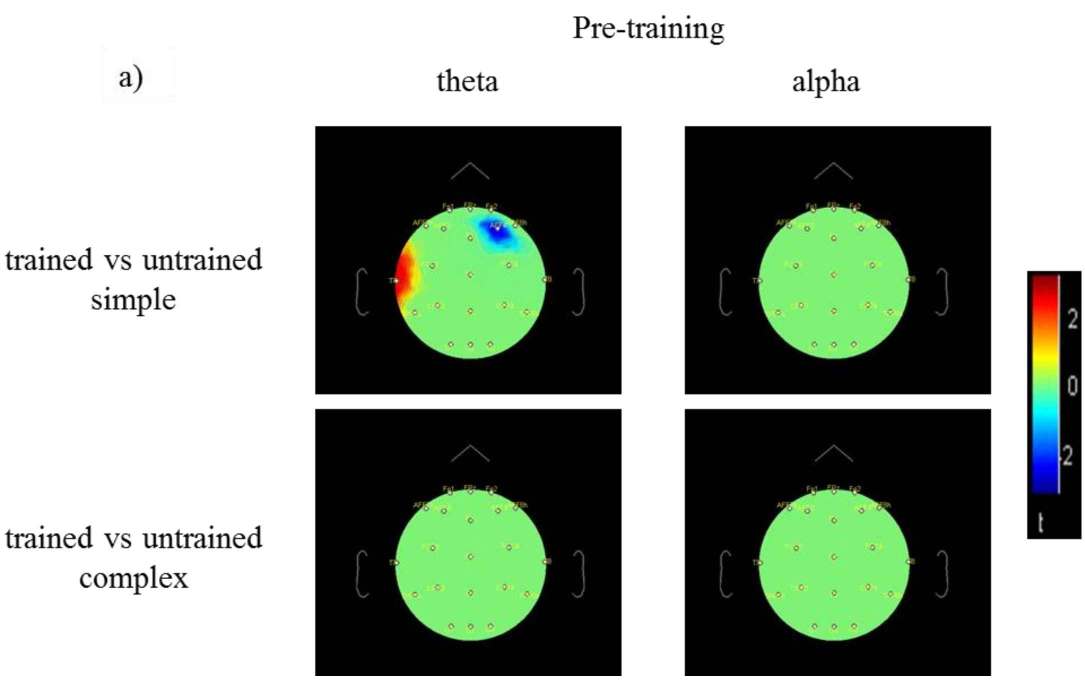
In the two-week post-training measurement, in the contrast of trained complex versus untrained complex multiplication, left MFG (channel 18) showed significantly decreased activation, $t(19) = -2.94$, D/AP corrected $p < .05$ (cf. Fig. S4c). Although reduced activation of the left AG and STG (channel 5) was observed, this effect did not survive correction for multiple statistical comparisons. In the two-week post-training measurement, no significant difference between trained simple and untrained simple conditions was observed.

EEG

Regarding EEG, differences between trained and untrained conditions within each measurement time were investigated. In the contrast of trained simple versus untrained simple multiplication in pre-training, greater theta ERS in the left temporal site (T7), $t(19) = 2.29$, $p < .05$, and lower theta ERS on the right frontal site (AFF4), $t(19) = -2.30$, $p < .05$, was observed (cf. Fig. S5a). No difference in alpha band in this contrast was demonstrated. In the contrast of trained complex versus untrained complex multiplication, no significant difference was found in the theta or alpha band (see Fig. S5a).

In the immediate post-training measurement, in the contrast of trained complex versus untrained complex multiplication, no significant difference was observed in the theta band, while in alpha band, greater alpha ERD on the occipito-parietal site (Pz, O2) was observed, $ts(19) < -2.10$, $ps < .05$ (cf. Fig. S5b). No significant difference was found in the contrast of trained simple versus untrained simple multiplication in the theta or alpha band (cf. Fig. S5b).

Regarding EEG, differences between trained and untrained conditions within each measurement time were investigated, the same as for fNIRS data. In the contrast of trained complex versus untrained complex multiplication, significantly decreased alpha ERD at the left occipital site (O1) was found, $t(19) = 2.85$, $p < .05$. In the contrast of trained simple versus untrained simple multiplication, an increased alpha ERD on the right temporal site (T8), $t(19) = -2.17$, $p < .05$, and a decreased alpha ERD on the right occipital site was observed (O2), $t(19) = 2.20$, $p < .05$. No significant difference was found in the theta band in any of the contrasts (cf. Fig. S5c).



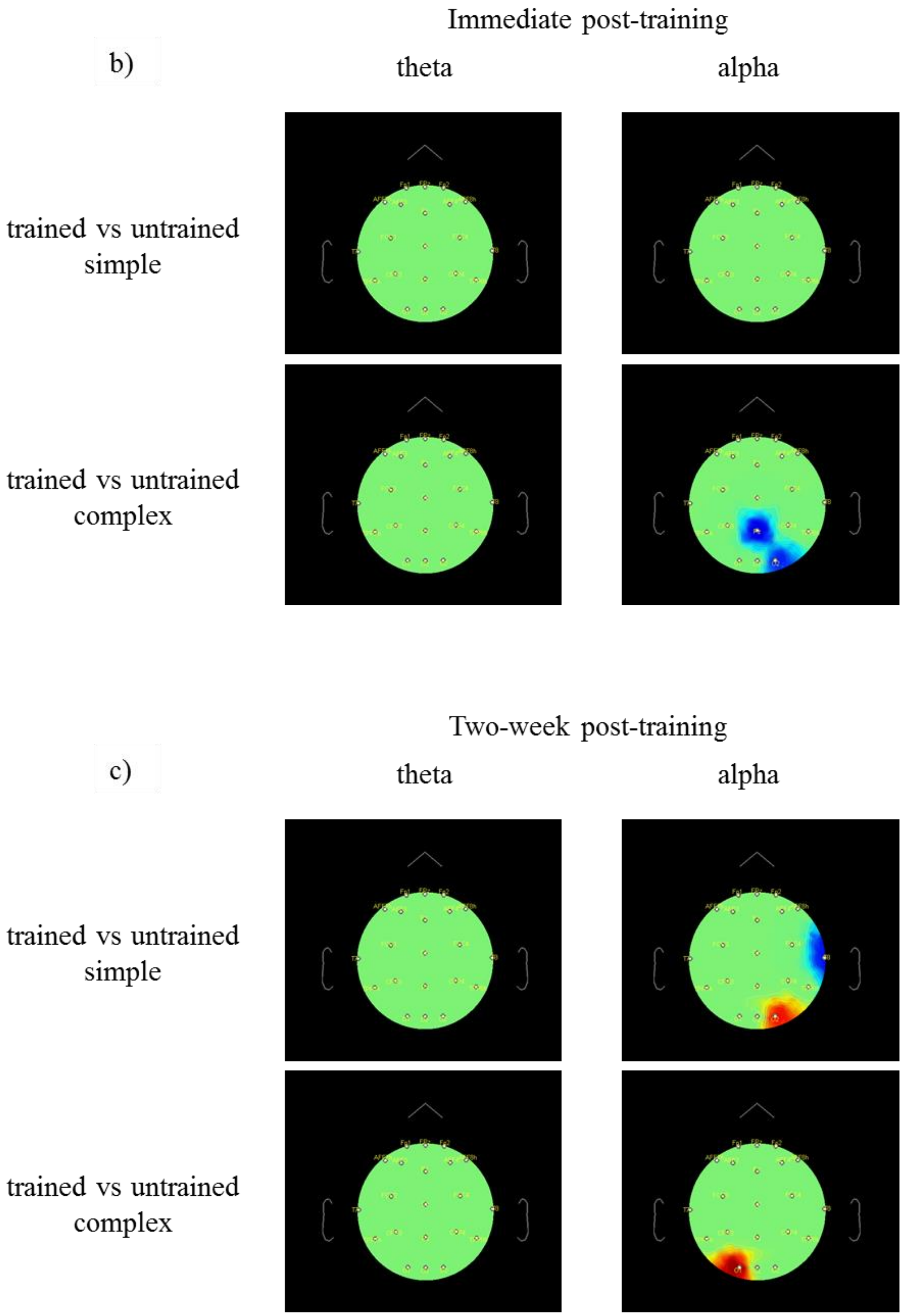


Fig. S5: a) Pre-training measurement showed no difference between trained and untrained conditions, except on theta band in the simple multiplication contrast. b) Immediate post-training measurement shows no training effects in simple condition, but increased alpha ERD in the trained complex compared to untrained complex multiplication. c) Alpha ERD changes were observed in both trained simple and complex conditions in the two-week post-training session. While no training change was observed in theta ERS, training led to changes in alpha ERD in both simple and complex multiplication. Red represents increased theta ERS/decreased alpha ERD, and blue represents decreased theta ERS/increased alpha ERD.

In each measurement time, there were some significant correlations between performance factors including error rates, RTs, and inverse efficiency score with neuropsychological tests, especially verbal working memory in two-week measurement time (cf. Table S3).

Table S3: The correlation between error rates, RTs, and inverse efficiency scores in each measurement time with neuropsychological tests. The other performance measures were not correlated with any of neuropsychological tests. TS: trained simple; TC: trained complex; US: untrained simple; UC: untrained complex; STM: short-term memory; WM: working memory (two-tailed correlation; the significant correlation with p-values of < .05 are marked with *).

Measurement time	Performance	Verbal IQ	Visuo-spatial IQ	Verbal STM	Verbal WM	Visuo-spatial STM	Visuo-spatial WM
Pre-training	US error rate	-0.30	-0.01	-0.09	-0.36	-0.53*	-0.64*
	US efficiency	-0.28	-0.07	0.01	-0.48*	-0.36	-0.44
Immediate post-training	US error rate	-0.34	-0.21	-0.21	-0.45*	-0.34	-0.64*
Two-week post-training	TS RT	-0.41	-0.33	0.19	-0.53*	-0.24	-0.40
	TS efficiency	-0.34	-0.20	0.15	-0.47*	-0.29	-0.40
	TC RT	-0.27	-0.10	0.13	-0.51*	-0.05	-0.37
	TC efficiency	-0.14	0.01	0.05	-0.46*	0.02	-0.31
	US error rate	-0.17	-0.15	0.17	-0.54*	-0.21	-0.44
	US efficiency	-0.17	-0.08	0.34	-0.48*	-0.26	-0.40
	UC error rate	-0.25	-0.15	-0.03	-0.45*	-0.01	-0.30
	UC RT	-0.48*	-0.41	0.20	-0.34	-0.36	-0.65*
	UC efficiency	-0.28	-0.19	0.16	-0.49*	0.03	-0.25

APPENDICES

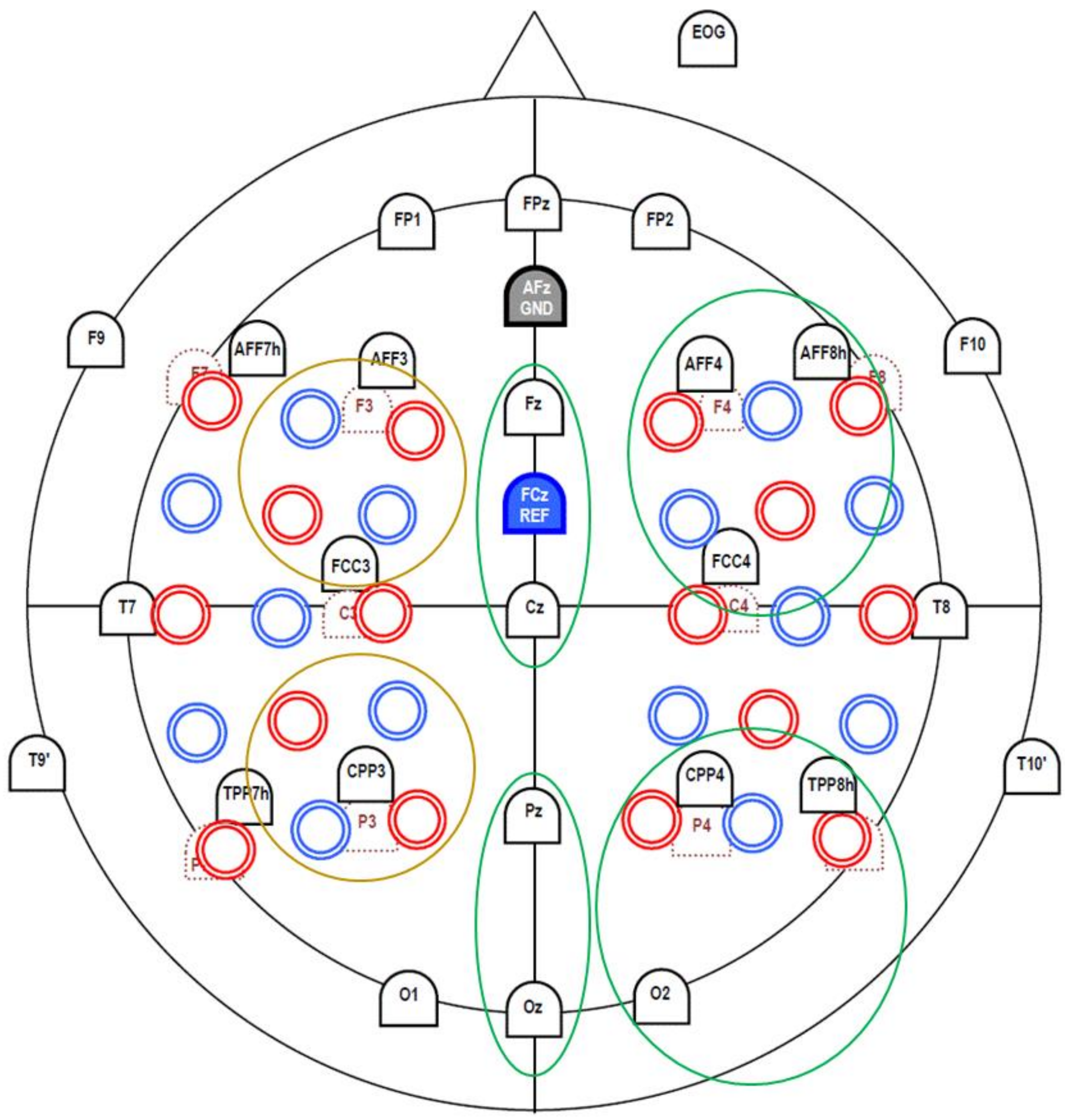
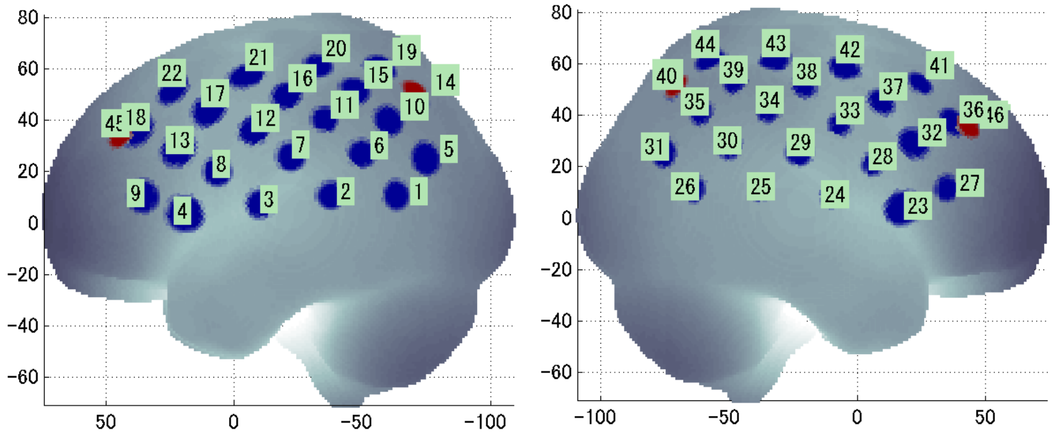


Fig. A1: Schematic positions of fNIRS optodes and EEG electrodes. Small red circles indicate emitters and blue ones indicate detectors in the two arrays of 3 × 5. Small white shapes indicate positions of the EEG electrodes. Red dotted shapes indicate the original position of some EEG electrodes according to the international 10-20 system. FNIRS ROIs are shown on the left side with brown circles, and EEG ROIs are shown on the middle and right side with green circles. The other side was identical to displayed ROIs in both fNIRS and EEG.



Left Side View Right Side View

Fig. A2: FNIRS channels layout and numbers. Blue circles indicate areas of channels projected on the brain surface. Red circles indicate P3, P4, F3 and F4 points projected on the brain surface.

Table A3: List of problems in four conditions.

Trained simple	**Trained complex**	**Untrained simple**	**Untrained complex**
3 × 4	13 × 4	6 × 2	18 × 3
5 × 3	3 × 19	7 × 2	6 × 12
2 × 8	5 × 13	3 × 7	4 × 19
6 × 3	18 × 4	4 × 6	7 × 12
3 × 9	6 × 13	8 × 3	14 × 6
7 × 4	15 × 6	7 × 5	17 × 5
5 × 6	12 × 8	4 × 9	5 × 18
8 × 4	7 × 14	5 × 8	13 × 7

Table A2: FNIRS and EEG ROIs.

	ROIs	**Channels/Electrodes**
fNIRS	L frontal	9, 13, 18, 22
	L parietal	5, 10, 14, 19
	R frontal	27, 32, 36, 41
	R parietal	31, 35, 40, 44
EEG	L frontal	AFF3, AFF7h, FCC3
	L parietal	CPP3, TPP7h, O1
	R frontal	AFF4, AFF8h, FCC4
	R parietal	CPP4, TPP8h, O2
	M frontal	Fz, Cz
	M parietal	Pz, Oz

Table A3: The coordinates of fNIRS channels.

Channel	Corresponding areas	Channel	Corresponding areas	Channel	Corresponding areas
1	Temporal_Mid_L	14	Angular_L	29	SupraMarginal_R
2	Temporal_Mid_L Temporal_Sup_L	15	Parietal_Inf_L	30	SupraMarginal_R Angular_R Temporal_Sup_R
3	Temporal_Sup_L Postcentral_L Rolandic_Oper_L Heschl_L Temporal_Mid_L	16	Parietal_Inf_L Postcentral_L SupraMarginal_L	31	Occipital_Mid_R Temporal_Mid_R Angular_R
4	Frontal_Inf_Tri_L Frontal_Inf_Oper_L Temporal_Pole_Sup_L Rolandic_Oper_L Frontal_Inf_Orb_L	17	Precentral_L Frontal_Mid_L	32	Frontal_Inf_Tri_R Frontal_Inf_Oper_R
5	Angular_L Occipital_Mid_L Temporal_Mid_L	18	Frontal_Mid_L	33	Postcentral_R
6	SupraMarginal_L Temporal_Sup_L	19	Parietal_Inf_L Parietal_Sup_L Angular_L	34	SupraMarginal_R
7	SupraMarginal_L Postcentral_L	20	Postcentral_L Parietal_Inf_L	35	Parietal_Inf_R Angular_R
8	Postcentral_L Frontal_Inf_Oper_L Precentral_L	21	Precentral_L Postcentral_L	36	Frontal_Mid_R
9	Frontal_Inf_Tri_L	22	Frontal_Mid_L	37	Precentral_R Frontal_Mid_R
10	Angular_L Parietal_Inf_L	23	Frontal_Inf_Oper_R Frontal_Inf_Tri_R Rolandic_Oper_R Temporal_Pole_Sup_R Frontal_Inf_Orb_R	38	Postcentral_R SupraMarginal_R
11	SupraMarginal_L Parietal_Inf_L	24	Temporal_Sup_R	39	Parietal_Inf_R
12	Postcentral_L	25	Temporal_Sup_R Temporal_Mid_R	40	Angular_R
13	Frontal_Inf_Tri_L Frontal_Inf_Oper_L	26	Temporal_Mid_R	41	Frontal_Mid_R
		27	Frontal_Inf_Tri_R	42	Frontal_Mid_R Precentral_R
		28	Precentral_R Postcentral_R	43	Postcentral_R Parietal_Sup_R Parietal_Inf_R
				44	Parietal_Sup_R Parietal_Inf_R Angular_R

STUDY 4: EARLY OSCILLATORY EEG CHANGES UNDERLYING INTERACTIVE ARITHMETIC LEARNING IN CHILDREN

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Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A. J., Nuerk, H.-C. & Ehlis, A.-C. (under review). Early oscillatory EEG changes underlying interactive arithmetic learning in children. *BMC Neuroscience.*

ABSTRACT

The majority of our knowledge about neurophysiological changes of arithmetic learning comes from adult studies. However, it is still unclear whether these findings can be generalized to children, who are closer to the age when we learn most of our mathematical knowledge. Moreover, studies mostly investigate brain activation changes after the course of arithmetic learning, and the question is whether these changes are detectable during the course of learning as well.

To address these questions, 24 typically developing children solved multiplication problems while ongoing electroencephalography (EEG) was recorded from the whole brain. The arithmetic training was embedded within a computer game environment. The arithmetic training induced power increase of theta (4–7 Hz) and lower alpha (8–10 Hz) bands, which were more dominant in posterior sites. No significant effect was observed in the upper alpha band (10–13 Hz). Moreover, behavioral data revealed improved performance over the course of training.

The observed neurophysiological changes during arithmetic learning in children were similar to results from previous post-training measures in adults. The increased power of theta and lower alpha subserve a shift from slow, procedural strategies to fast, compact procedural strategies and retrieval, which lead to more efficient performance over the course of arithmetic learning in children. We suggest that increased theta power is associated with the domain-general cognitive demands of procedural and retrieval strategies used in arithmetic problem solving and increased lower alpha power is associated with increased automaticity.

Keywords: children, arithmetic, multiplication, learning, oscillatory EEG

INTRODUCTION

Arithmetic skills are mostly learned in childhood and are applied in everyday life. Because of lack of systematic neuroimaging study of arithmetic learning in children, the majority of our knowledge about brain activation changes due to acquiring these skills comes from adult studies. However, it has been repeatedly argued that these findings from mature brains are not easily applicable to the developing brain (e.g., Ansari et al., 2005; Kaufmann & Nuerk, 2005; Kaufmann et al., 2011). Indeed, previous behavioral and event-related potentials (ERP) studies comparing children and adults have suggested that they differ in selecting and executing strategies in arithmetic problem solving (Lemaire, 2016; Zhou et al., 2011; Prieto-Corona et al., 2010). Therefore, it seems to be essential to investigate neurophysiological changes via arithmetic learning in children.

In adults, arithmetic learning seems to be basically a shift in problem-solving from more procedural, algorithm-based strategies to more retrieval, memory-based strategies (Zamarian et al., 2009). Electroencephalography (EEG) studies of arithmetic processing in adults demonstrated that these arithmetic strategies are mostly related to theta and alpha frequency bands (Antonenko et al., 2010; Hinault & Lemaire, 2016). For instance, training in complex multiplication elicited increased power in theta and in lower alpha bands in adults (Grabner & De Smedt, 2012). These training-related power changes were found in parietal and parieto-occipital sites, which have been interpreted as contributing to enhanced retrieval of information, namely the solutions to complex multiplication problems from long-term memory (Grabner & De Smedt, 2012). Moreover, a recent oscillatory EEG study found a significant training effect in theta, alpha and beta bands, for adults whose division performance improved after 10 minutes of training (Skrandies & Klein, 2015). It might conclude that neurophysiological changes in post-training measurement and also during the course of training leads to increase power in theta and alpha bands in adults, which represent a shift from procedural to retrieval processes.

However, hypothetical models of arithmetic learning in children have suggested different steps during development. For instance, the overlapping-wave model (Siegler, 1996) suggests that while there is a constantly greater use of retrieval strategies during development, several mixtures of procedural strategies might be used at different steps as well (see also Shrager & Siegler, 1998). In an agreement with Siegler's model, Von Aster (2000) proposed a model of multi-stage developmental dynamics of number processing and mental calculation. According to this model, three representational modules of the triple-code model (Dehaene et al., 2003), i.e., semantic, visual-Arabic, and verbal modules, are differentially important at different steps of development. Based on this model, these modules are semi-autonomous during development and depend on each other (for more details see Von Aster, 2000). In line with these models, neuroimaging studies have shown a developmental fronto-parietal shift in arithmetic processing (e.g., Rivera et al., 2005). For instance, a cross-sectional neuroimaging study in children suggested that development of arithmetic is not only achieved by a strategy shift from procedural to retrieval-based strategies, but also from less to more efficient procedural strategies (Prado et al., 2014). Rosenberg-Lee et al. (2011) observed increased activation in both frontal and parietal regions due to one-year schooling in children. Therefore, it seems that arithmetic achievement is associated with both domain-general cognitive processes, e.g., working memory and executive functions, and domain-specific magnitude processes, i.e., manipulating the numerals. Astonishingly, however, despite school age being the crucial time of learning basic arithmetic, the underlying neurophysiological changes of arithmetic learning have not been systematically studied in children (see also Hinault & Lemaire, 2016). Therefore, the remaining question is whether the neurophysiological findings of mature brains in adult studies can be generalized to children.

Additionally, most of the studies investigated arithmetic achievement in a post-training measurement, which took place after some sessions of daily training (Zamarian et al., 2009). However, few is known about neurophysiological changes during the course of learning. One of the few fMRI studies, which investigated this issue, revealed similar changes gradually during complex arithmetic learning in adults (Ischebeck et al., 2007). Moreover, Skrandies and Klein (2015) observed these changes after less than 10 minutes of training. With respect to children, no study has indicated brain activation changes during the course of arithmetic learning. Hence, it is not clear whether post-training neurophysiological changes are similar to the changes during the course of learning. Again this might differ in children from adults. For instance, Fischer, Wilhelm, and Born (2007) found different the off-line memory consolidation between children and adults: while adults gained from the off-line sleep-related consolidation, children revealed a memory deterioration. Moreover, daytime retention period led to the deterioration of memory in adults, but not in children (Fischer et al., 2007). Therefore, it is important to investigate these changes during arithmetic learning in children. The findings might help to improve the relation between the education and neuroscience: monitoring online neurophysiological changes during arithmetic learning for particular interventions such as brain stimulation, particularly in individuals with math disabilities.

The aim of the present study was to uncover early neurophysiological changes during arithmetic learning by means of oscillatory EEG in a group of typically developing children. To this end, ongoing EEG was recorded, to measure the state of functional neural networks during task performance (e.g., da Silva, 1991). It has been shown that even in the absence of behavioral changes, and without directly gauging strategy use, for instance through verbal reports, EEG is a fruitful measure to assess changes in arithmetic processing and strategy use (for a review see Hinault & Lemaire, 2016). Based on the literature, we hypothesized increased power in theta and lower alpha bands, especially in posterior sites, and no considerable changes in the upper alpha band (see also Grabner & De Smedt, 2012). We suggest that these power changes are due to increased retrieval and fast procedural strategies, and reduced slow procedural strategies in the course of arithmetic learning in children. Overall, positive correlations are expected between arithmetic performance and EEG frequency power.

As regards theta activity, it has been interpreted as a function of different cognitive processes in previous studies of mental calculation. Various studies have reported associations between an increase in theta power, mostly in frontal areas, and sustained attention (Ishihara & Yoshii, 1972; Harmony et al., 1999), workload (Skrandies & Klein, 2015; Sammer et al., 2007), executive functions and numerical visual imagery (Mizuhara & Yamaguchi, 2007). A recent study in children by M. Soltanlou et al. (in press) revealed greater theta in the more complex calculation, which was interpreted as additional demands of working memory and executive function. These functions have been described as domain-general cognitive demands required for arithmetic problem-solving. On the other hand, Grabner and De Smedt (2011) demonstrated an association between increased theta power, mostly in bilateral parieto-occipital areas, and retrieval strategies during addition and subtraction problem-solving in adults (see also Earle et al., 1996; De Smedt et al., 2009).

As regards the alpha frequency band, inverse correlations have been reported between alpha power and mental activity (Davidson et al., 2000), as well as between alpha power and procedural strategies in arithmetic processing (Hinault & Lemaire, 2016; De Smedt et al., 2009; Micheloyannis et al., 2005). The alpha band is split into lower and upper frequencies, which show a dissociation in cognitive tasks (Fink, Grabner, Neuper, & Neubauer, 2005). Fink et al. (2005) showed that with increased task demands, the correlation between lower and upper alpha declines. While lower alpha is more related to the general cognitive demands of a task such as paying attention, upper alpha is associated with more specific demands of the task such as semantic memory processing (Klimesch, 1999; Klimesch, Vogt, & Doppelmayr, 1999).

All in all, this study tries to uncover whether the neurophysiological changes of arithmetic learning in adults can be generalize to children, which is usually the most critical time of knowledge acquisition during the life. Moreover, while few studies in adults investigated brain activation changes during the course of learning (e.g., Ischebeck et al., 2007), this online monitoring of the changes in the brain has not yet been done in children. To our best of knowledge, the present study is the first study concerning this issue in children. In line with educational neuroscience approach, this study combines educational interventions with neurophysiological measures, which enable us to uncover brain function during knowledge acquisition in children (Ansari & Lyons, 2016). Furthermore, this approach is helpful for a better interpretation of behavioral findings (Szűcs & Goswami, 2007), and for developing educational and therapeutic interventions and assessing the outcomes of interventions.

MATERIAL AND METHODS

PARTICIPANTS

26 typically developing children from grade 5 participated in the study. Two children were excluded because of technical problems in the online learning platform and in EEG recording. Therefore, the data of 24 children (9 girls, 11.09 ± 0.46 years old, range = 10.40–12.20 years) were analyzed. All children were right-handed and had a normal or corrected-to-normal vision with no history of neurological or mental disorders. The verbal and non-verbal IQ scores, measured by similarities and matrix reasoning subtests of the German Wechsler IQ test (Hamburg-Wechsler-Intelligenztest für Kinder-IV: HAWIK-IV; Petermann et al., 2007), were 107.92 ± 11.97 and 108.13 ± 10.51 respectively. Children and

their parents gave informed written consent and received an expense allowance for their participation. All procedures of the study were in line with the latest revision of the Declaration of Helsinki and were approved by the local ethics committee of the University Hospital of Tuebingen.

MATERIAL

16 multiplication problems were used in the present study: eight problems included two one-digit operands (range 2–9) with two-digit solutions (range 12–40) and eight problems included two-digit (range 12–19) times one-digit operands (range 3–8) with two-digit solutions (range 52–98). The order of small and large operands within the problems was counterbalanced. Problems with ones (e.g., 6 × 1), commutative pairs (e.g., 4 × 8 and 8 × 4) or ties (9 × 9) were not used. In a multiple-choice paradigm, each problem was individually presented along with 12 different choices, including only one correct solution (see Figure 1). The choices were presented in random positions on the screen. Distractor choices were calculated based on the following rules: first operand ± 1, second operand ± 1, correct solution ± 1 or ± 2 or ± 10, and inversing the unit and decade of the correct solution.

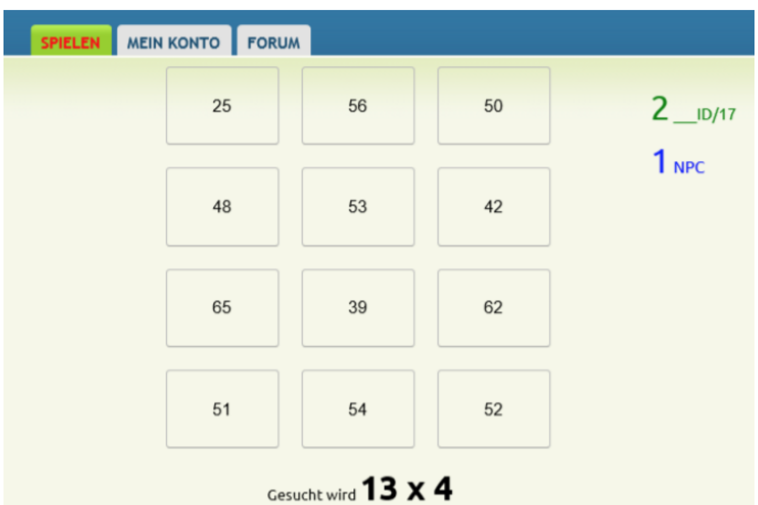

Figure 1: Screenshot of the multiplication training on the web-based online learning platform: in competition with a computer, children had to select the correct solution out of 12 presented choices.

MEASUREMENT PROCEDURE

In the present study, behavioral performance and neurophysiological changes were measured individually during multiplication problem-solving in children. The training was comprised of six repetitions of each problem, and was conducted by means of an online learning platform (designed by ScienceCampus Tuebingen, Tuebingen, Germany, see Jung et al., 2015; Jung et al., 2016; Roesch et al., in press). The design was self-paced with limited response intervals. Based on a response time (RT) distribution obtained in a behavioral multiplication study in a comparable age (Huber et al., 2013), we selected response intervals randomly from the range between 4 and 10 s, jittered by 0.6 s, for one-digit × one-digit problems, and from the range between 10 and 30 s, jittered by 2 s, for one-digit × two-digit problems, such that the children were often, but not always winning against the computer. Training was interactive in the sense that children had to compete with a computer. The problems were presented until the child or computer responded correctly. The computer responded whenever the child did not produce an answer within the jittered response interval, and in order to make a more realistic competition, the computer responded incorrectly to 30% of the problems. To provide feedback about performance and to increase motivation, the scores of the child and computer were shown on the right side of the screen (see Figure 1). Both child and computer received one point for each correct answer, and one point was taken away for each incorrect answer. Children were instructed to solve the problems as quickly and accurately as possible by using a computer mouse to select the correct solution. The whole recording required one session of between 20 and 30 minutes, depending on children's proficiency, without any break in between.

EEG

EEG data were recorded from 21 scalp EEG electrodes by means of a 32-channel DC-amplifier and the software Vision Recorder (Brain Products GmbH., Herrsching, Germany). This study was a part of a larger project using combined functional near-infrared spectroscopy and EEG. Therefore, EEG electrodes were placed (cf. Figure 3) according to the extended international 10-20 system (Jasper, 1958; Oostenveld & Praamstra, 2001) in a combined cap. In addition, eye movements were recorded via electrooculography (EOG) applying one electrode below the right eye. The ground electrode was placed on AFz and the online reference electrode on FCz. Electrode impedance was kept below 20 kΩ. Data were digitalized at a rate of 1000 Hz with an online bandpass filter of 0.1–100 Hz.

ANALYSIS

BEHAVIORAL DATA

RTs were defined as the duration from stimulus onset to button press. Median RTs for only correct responses (78.4 % of total problems) were taken into account after sequential trimming with ± 3SD beyond mean RT for each individual child (Nuerk, Weger, & Willmes, 2001). Percentage of error rate was defined as the proportion of incorrect or non-responded trials – the problems that the computer solved more quickly – to the total number of presented trials. Note that the problem was counted as correct only if the child's first response to the problem was correct. Thus, trials where the child "lost" to the computer, either by giving a wrong response or by exceeding the response interval, were counted as errors.

To examine the learning effect parametrically, the slopes (unstandardized coefficients) of the linear regression line were calculated (e.g., Cipora et al., 2015) across the six repetitions for each child. The learning slopes were separately calculated for median RT and error rate. A more negative slope corresponds to a stronger learning effect, showing the child got faster or made fewer error over the course of training. To examine whether there is a significant learning effect, the slopes were tested against zero with one-sample t-tests. Since we had a direct prediction regarding arithmetic learning, one-tailed tests were conducted. The analysis was done with SPSS version 23.0 (IBM SPSS Statistics for Windows).

EEG

EEG data were analyzed using the Brainstorm toolbox (Tadel et al., 2011), a documented and freely available software (http://neuroimage.usc.edu/brainstorm). The EEG signals were offline-filtered using a bandpass of 1–40 Hz. Thereafter, based on the EOG signal and the topography, artifacts of eye blinks and eye movements were detected and removed from the EEG signals using Signal Space Projections (SSP). In the next step, bad segments were detected and excluded by visual inspections. Note that because of interand intra-individual differences in the self-paced design, the duration of repetitions was not identical within or between participants. In order to measure the changes in brain waves, fast Fourier Transform (Welch, 1967) was used to estimate power density (μV2) in theta (4–7 Hz), lower alpha (8–10 Hz), and upper alpha (10–13 Hz) bands, which were calculated separately and individually averaged for each repetition.

For statistical analysis, according to the topography of frequency oscillation in previous studies (e.g., Gevins et al., 1997; Grabner & De Smedt, 2012), regions of interest (ROIs) were defined as three anterior regions including left, right, and middle fronto-central sites, and three posterior regions including left, right, and middle occipito-parietal sites (cf. Figure 3). Similar to the behavioral data, the learning slopes (unstandardized coefficients) were calculated for each ROI and each frequency band separately. A more negative slope corresponds to a decreased power density, and a more positive slope corresponds to an increased power density over the course of learning. To examine whether there is a significant learning effect, the slopes were tested against zero with one-sample t-tests for each ROI and each frequency band in the same way as for the behavioral analyses. The significance level was .05 and corrected according to the false discovery rate (FDR) method for multiple comparisons (Benjamini & Hochberg, 1995). Since we had directed hypotheses (more pronounced theta and alpha power) regarding arithmetic learning, one-tailed tests were conducted. Finally, the correlation between behavioral and brain-physiological data was calculated as well.

RESULTS

BEHAVIORAL DATA

In the analysis of median RT, negative slope showed that children tended to get faster during the course of learning; however, this improvement was not significant, $t(23) = -0.78$, $p = .22$ (cf. Figure 2). The analysis of the learning slopes for error rates revealed significantly improved performance over the six repetitions of multiplication problems, $t(23) = -2.59$, $p = .02$ (cf. Figure 2).

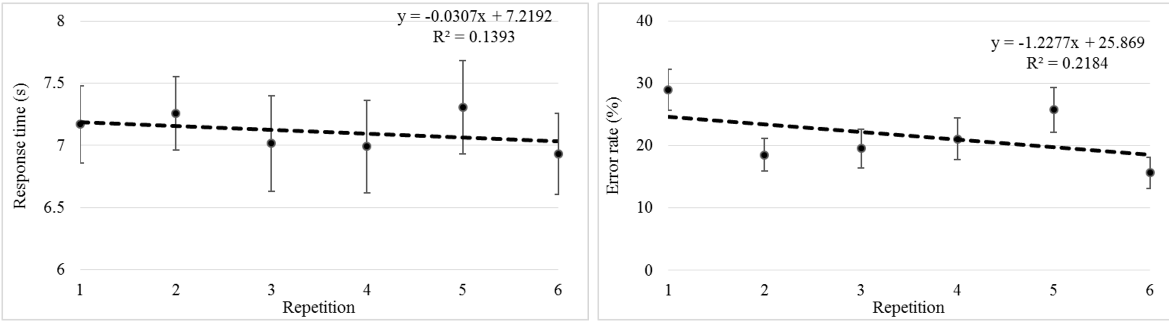

Figure 2: Children's performance regarding median RT and error rate during six repetitions. Dashed lines show the learning slopes. Error bars depict SEs.

EEG

For the power density in theta band, the analysis of learning regression slopes revealed a significant increase in the middle and right fronto-central sites, and also in the left, middle and right parieto-occipital sites, $t(23) > 1.86$, FDR corrected $p < .05$ (cf. Figure 3).

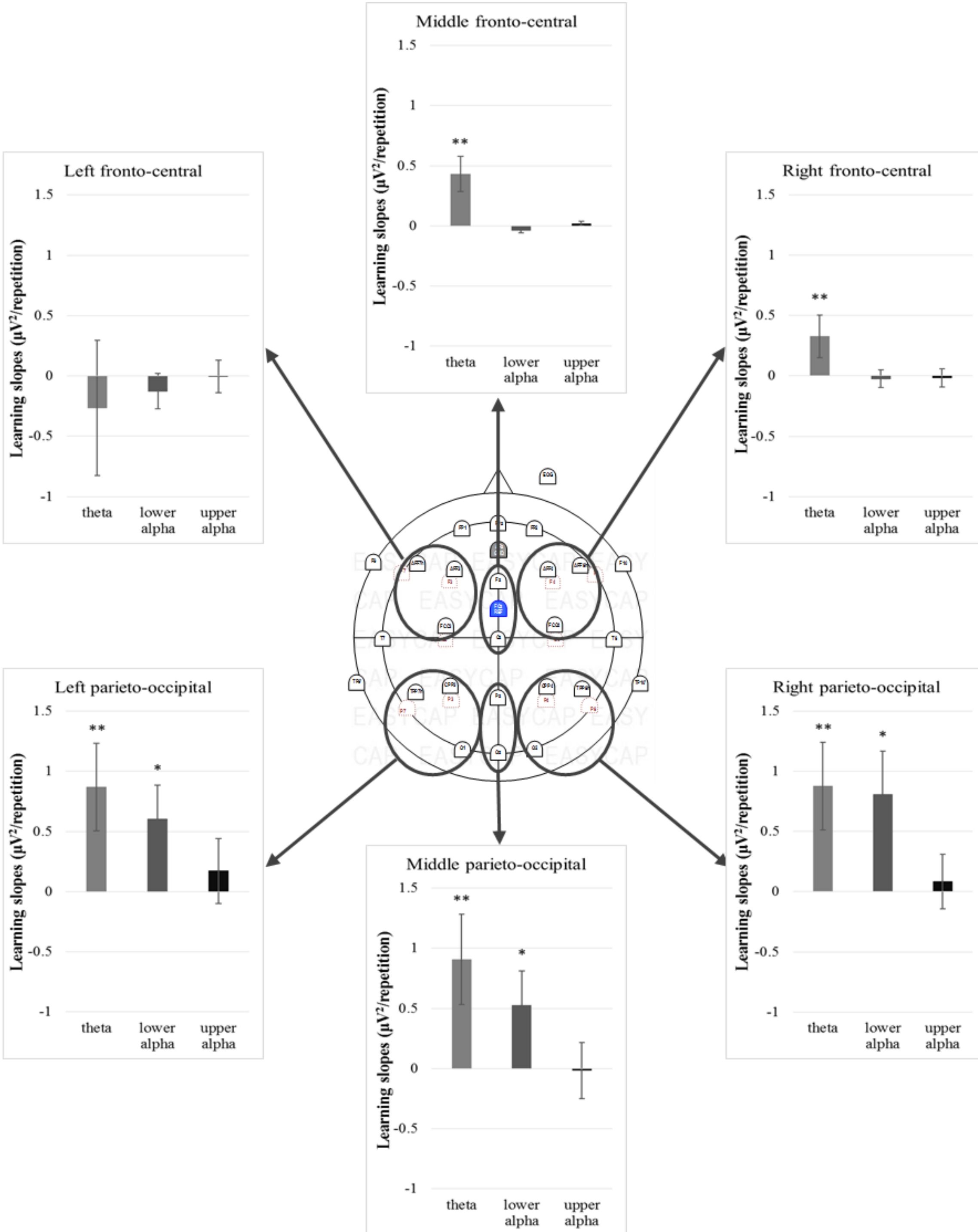

Figure 3: Unstandardized coefficients of learning slopes of EEG power density in theta, lower alpha, and upper alpha bands for each ROI. Positive values, which reflect positive learning slopes, display increased power density. Negative values, which reflect negative learning slopes, display decreased power density. Error bars depict SEs. Small white shapes indicate positions of the EEG electrodes. Red dotted shapes indicate the original position of some EEG electrodes according to the international 10-20 system. EEG ROIs are shown with black circles. **: $p < .05$ FDR corrected; *: $p < .05$ uncorrected [schematic brain coordinates from EASYCAP GmbH, Herrsching, Germany].

For the power density in the lower alpha band, three posterior sites showed a significant increase, $t(23) > 1.83$, uncorrected $p < .05$, which did not survive FDR correction for multiple comparisons. No significant power changes were found in upper alpha frequency band, $t(23) < 1.01$, uncorrected $p > .16$ (see Figure 3).

Brain-behavior correlation

As outlined in the introduction, correlations of behavioral learning and EEG frequency power were to be expected based on the literature on adults. Our correlation analysis in children indeed revealed a significant negative correlation between median RTs and theta power density in the left fronto-central site, $r(22) = -.37$, $p = .04$, which shows that faster responses are associated with increased theta power. Significantly positive correlations between median RTs and upper alpha power density in the left parieto-occipital site, $r(22) = .36$, $p = .04$, and right parieto-occipital site, $r(22) = .41$, $p = .02$, revealed that faster responses are associated with decreased upper alpha power. No correlation was observed between error rates and EEG power density in any frequency band, $r(22) < .20$. Note that the correlation findings have not been corrected for multiple comparison testing and should, therefore, be considered exploratory and interpreted carefully.

Discussion

In the present study, the neurophysiological changes during interactive arithmetic learning in children have been investigated. The findings show gradually increasing power in theta and lower alpha frequencies during six repetitions of multiplication problems. This theta increase is in line with previous arithmetic and cognitive training studies in adults. For instance, Klimesch et al. (1999) reported more theta power in individuals with high math skills, which corresponds to training in the present study, as opposed to individuals with low calculation skills. Moreover, with respect to the topography, theta increase was predominant in the posterior sites in the present study, which is also in line with previous multiplication learning data in adults (Grabner & De Smedt, 2012). We not only found theta increase in parietal sites like Grabner and De Smedt (2012) in adults but also in right and middle fronto-central sites (see also Skrandies & Klein, 2015). The reason for this finding might be the interaction of occipital and frontal cortices in working memory function (H. Lee, Simpson, Logothetis, & Rainer, 2005), which may play a bigger role in children than in adults. H. Lee et al. (2005) suggest that theta oscillations are part of a recurrent interaction mechanism between occipital and frontal neurons, which underlies working memory (see also Stam, van Walsum, & Micheloyannis, 2002).

In the present study, increased theta power during multiplication training in children might be due to increased engagement of both working memory and inhibition in retrieval strategies (see also Galfano et al., 2011). Theta activity has mostly been associated with acquiring new information (Klimesch, 1999), which usually needs additional attention and mental effort, rather than retrieving existing knowledge (e.g., Gevins et al., 1997; Ishihara & Yoshii, 1972; Mizuhara & Yamaguchi, 2007; Skrandies & Klein, 2015; Sammer et al., 2007). Gevins et al. (1997) found a theta increase resulting from short-time working memory training in adults and attributed it to the extra effort required to focus attention on an extended amount of time (see also Harmony et al., 1999). Furthermore, it has been shown that executive functioning is involved even in arithmetic fact retrieval (Hinault & Lemaire, 2016; Bäuml, Pastötter, & Hanslmayr, 2010). For instance, Galfano et al. (2011) reported increased inhibition during arithmetic fact retrieval in one-digit multiplication problem-solving. Inhibition might also account for the findings of Grabner and De Smedt (2012). In this study, theta power increased after two days of complex multiplication training (30 repetitions of each problem) in adults, and this was interpreted as a result of increased retrieval strategy (Grabner & De Smedt, 2012).

Because of the difficulty and few repetitions of multiplication problems, increased theta power may not be explained exclusively by a strategy shift from procedural processes to memory retrieval. Long-lasting response times support this assumption. However, note that these slow responses are partially because of the time children spend finding the correct solution, moving the mouse cursor and pressing the button for their answer choice. In our interpretation, we follow the model by Baroody (1983), i.e., that mathematical training entails a shift from slow procedural processes towards compacted procedural strategies and principled knowledge. As stated in this model, these compacted strategies and procedural knowledge are more automatic and lead to faster responses. Therefore, increased theta power seems to indicate more efficient performance, and does not necessarily imply that information is retrieved from long-term semantic memory. In line with this interpretation, a recent ERP study found that high-skilled participants showed a larger late positive component compared to low-skilled participants (Núñez-Peña & Suárez-Pellicioni, 2012). This larger late positive component, which is related to procedural processes, was interpreted to indicate more engagement of efficient strategies in high-skilled participants (but see Pauli, Lutzenberger, Birbaumer, Rickard, & Bourne, 1996). Furthermore, Prado et al. (2014) showed that arithmetic achievement in children relies not only on arithmetic fact retrieval but also on efficient quantity-based strategies. In the present study, it seems that children practiced more procedural and algorithm-based strategies during six repetitions of the multiplication problems, which led to fewer errors. Furthermore, the relation between behavioral performance and power density in EEG frequency bands nicely corroborates the above interpretation: the trend of providing faster responses correlates with increased theta but decreased upper alpha power. According to our assumptions, the increased theta power is most probably related to fast efficient procedural strategies.

Thus, we conclude that increased theta power is related to domain-general cognitive demands of retrieval strategies and also more efficient procedural strategies in our childhood sample. This explanation suggests that the interpretation of increased theta power in multiplication training in adults may not be readily generalized to children. In adults, we usually interpret the data as a shift from procedural to retrieval strategies. This interpretation does not fully capture the EEG data in children. Children not only shift to full retrieval mode; rather, during the course of short-term learning, they also seem to develop more efficient procedural and algorithmic strategies. That such shifts are not observed in adults is not necessarily surprising, since they have had years of multiplication experience and have probably already developed their most efficient procedural and algorithmic strategies (see also Menon, 2010).

However, our data point to the idea that – in contrast to adults – procedural strategies still improve in children towards greater efficiency as a function of learning. This difference in strategy use and learning between adults and children is in line with the available literature. Lemaire (2010) showed that children differ from adults in arithmetic strategies, and use less efficient strategies compared to adults (see also Lemaire, 2016). In accordance with Siegler and Shrager (1984), this difference is a result of a less developed arithmetic facts network in children relative to adults. An ERP study of one-digit addition and multiplication by Zhou et al. (2011) supports this difference at the neurophysiological level as well. They showed that seven-year-old children rely more on parietal quantitative processes, while adults rely more on frontal verbal strategies (see also Prieto-Corona et al., 2010). In sum, the interpretation of increased theta power as an index of more efficient procedural strategies is in line with our knowledge about domain-general and domain-specific processing in children, both behaviorally and neurophysiologically.

In addition to theta band changes, a limited increase in power of the lower alpha in the posterior sites was observed in the present study over the course of training. This is in line with previous arithmetic and cognitive training studies in adults (Gevins et al., 1997; Grabner & De Smedt, 2012). Gevins et al. (1997) suggested that increased automaticity via training is associated with increased power in the lower alpha band. It has also been shown that decreased alpha power is related to increased cortical processing (Pfurtscheller, 2001), task difficulty (e.g., Gevins et al., 1997) and attentional demands of tasks (Ray & Cole, 1985). Therefore, this increased power of lower alpha indicates that multiplication training elicits less excitation of cortical networks and reduced information processing (Pfurtscheller, 2001). Pfurtscheller et al. (1996) demonstrated that the magnitude of the decrease in the alpha band reflects the mass of neural networks engaged in the performance. Hence, if we assume that the human brain works according to principles of the economy (e.g., Attwell & Laughlin, 2001), it is logical that increased lower alpha power is used to save energy consumption since limited networks are involved (Pfurtscheller et al., 1996). It has been found that procedural strategies demand more cognitive processes compared to retrieval strategies in multiplication problem-solving in children (Koshmider & Ashcraft, 1991; Lemaire, Barrett, Fayol, & Abdi, 1994). Therefore, in agreement with Grabner and De Smedt (2012), we conclude that decreased alpha power is associated with more procedural strategies. We interpret increased power in lower alpha as representing more automatic, presumably retrieval-based strategies in arithmetic problem-solving.

However, this increased alpha power was not so remarkable in the present study. Possible reasons are that children first shift to more efficient procedural strategies (see above) before they shift to retrieval strategies. We do not wish to preclude that children would also shift to retrieval strategies after (much) more than a short-term training of six repetitions. All we can say is that – in contrast to some adult samples (Ischebeck et al., 2007; Skrandies & Klein, 2015) – the present group of children did not shift to retrieval strategies after those few training sessions.

With respect to the upper alpha band, as we expected and in line with the study of multiplication training in adults (Grabner & De Smedt, 2012), we did not find significant changes over the course of this short-term training in children. Although several studies reported the engagement of the upper alpha band in sensory and cognitive processes, it seems that this frequency band is not involved in short-term multiplication learning, or at least does not change due to short-term arithmetic training in children (see also Grabner & De Smedt, 2012). Here the data from adults and children do not differ.

LIMITATIONS AND PERSPECTIVE

In the present study, there were some limitations and methodological issues, which need to be taken into account for future studies. We used both one-digit times one-digit and one-digit times two-digit multiplication problems, which could be solved using different strategies. However, we were not able to separately them for the analysis. Therefore, it is suggested to use only one kind of problems, to refrain possible confounding effect. Additionally, most of our knowledge about neural correlates of arithmetic learning comes from multiplication training studies, while previous studies have shown that the neural networks of different arithmetic operations might differ (e.g., Fehr et al., 2007). Therefore, it is essential to investigate training effects of other basic arithmetic operations as well in order to achieve a conclusive result. Moreover, it would be beneficial to have an adaptive computer game, in which the opponent's performance is adjusted to the child's performance so that the game becomes more challenging and also motivating for children. The findings of the current study are due to a very short-time training, which is not probably enough to observe a strategy shift to the most optimal strategy, namely fact retrieval from long-term semantic memory. Therefore, future studies with a longer training session and the probably fewer number of training problems would lead to this strategy shift, which might lead to a different oscillatory change.

CONCLUSION

While neurophysiological studies of arithmetic learning investigating brain activation changes after the course of learning (Zamarian et al., 2009), a few studies considered the brain activation changes during the course of learning, i.e., online monitoring of the changes in the brain (e.g., Ischebeck et al., 2007). To our best of knowledge, the present study is the first study concerning this issue in children. Moreover, a few neurophysiological studies systematically explored neural correlates of arithmetic learning in children, which is usually the most critical time of knowledge acquisition during the life. The findings of the current study on neurophysiological changes during arithmetic learning extend the findings of adult studies to children. Multiplication training led to increased power of theta and lower alpha bands, but no change was observed in the upper alpha band. These neurophysiological changes seem to subserve a shift from slow to fast, compacted and more efficient procedural strategies, beyond possible shifts from procedural to retrieval strategies usually observed in adults. In line with the literature, the neurophysiological changes in multiplication training in children can be interpreted in terms of developing more efficient procedural strategies and increasing automaticity, and not necessarily as a shift to retrieval strategies as reported in adults. More generally, we conclude that neurophysiological changes induced by arithmetic learning in adults should not be easily generalized to children's arithmetic learning (see also Kaufmann et al., 2011; Menon, 2010). Furthermore, the majority of previous neurophysiological studies have considered arithmetic training effects transversally, usually after a course of training. The present study provides the first evidence of brain oscillation changes throughout the time of arithmetic training in children.

ACKNOWLEDGMENT

We would like to thank all participating children and their parents. This research was funded by a grant from the Science Campus Tuebingen, project 8.4 to HCN supporting MS. CA, TD, ACE, AJF, and HCN are further supported by the LEAD Graduate School & Research Network [GSC1028], a project of the Excellence Initiative of the German federal and state governments. ACE was also partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0). Finally, we thank our assistants who helped with collecting the data and proofreading the manuscript.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GENERAL DISCUSSION

The aim of this dissertation project was to uncover the neural and behavioral correlates of arithmetic development and learning in children. Understanding these correlates, particularly underlying neurobiological markers (Supekar et al., 2013), might help us to diagnose math problems even before a child starts going to school, leading to early interventions and better therapeutic outcomes. Therefore, the findings of this project may help to indicate the neural dysfunctions in individuals with math learning problems and also to develop advanced therapeutic and interventional approaches. Multiplication achievement was investigated, as one of the arithmetic operations most frequently studied in adults (Zamarian et al., 2009). In Study 1, the transition from 3rd to 4th grade, which is a critical step in multiplication development, was studied. The remaining studies were conducted in 5th graders, at a time when children have learned all four basic arithmetic operations and are not immediately being taught these operations. Generally speaking, it is shown that arithmetic development and learning in children are not similar to learning in adults, which has been mostly reported as a shift from procedural to retrieval strategies. It seems that arithmetic achievement in children occurs in two steps, first from slow effortful procedural processes to fast compacted procedural processes, and in the next step to retrieval processes. Therefore, arithmetic development and learning in children do not necessarily imply reduced engagement of domain-general cognitive processes (see the theoretical model below).

SUMMARY OF FINDINGS

Study 1 showed that children in 4th grade provided faster responses to simple multiplication problems than children in 3rd grade. However, the accuracy of responses did not differ between grades. Interestingly, the results show that the contributions of verbal and visuospatial WM changed with the grade. The accuracy of responses was predicted by verbal WM in 3rd grade, while in 4th grade it was predicted by visuospatial WM. This finding indicates a primarily linguistic learning of and access to multiplication in 3rd grade, which is probably based on verbal repetition of the multiplication table, heavily practiced in 2nd and 3rd grade. However, the relation to visuospatial semantic WM in 4th grade suggests a shift from verbal to visual and semantic learning in 4th grade. This shift may be induced because later in elementary school, multiplication problems are more often carried out via written, i.e., visual tasks, which engage spatial processes. Interestingly, in Study 2, visuospatial WM predicted multiplication performance in 5th grade, which supports the findings of Study 1. It seems that mathematical development is not generally characterized by a steady progress in performance; rather the contributions of verbal and non-verbal memory to performance shift over time.

In the next step, the behavioral and neural correlates of arithmetic complexity were investigated in 5th graders. The behavioral data showed quicker and more accurate responses in simple calculation compared to complex calculation. The fNIRS findings of Study 2 indicated that simple multiplication was associated with brain activity in the left superior parietal lobule (SPL) and IPS extending to the left motor area, but notably, not the AG, and complex multiplication was associated with activity in bilateral SPL, IPS, MFG, and the left motor area. The complexity of calculation was investigated by the contrast between complex and simple multiplication, which showed greater activity in the right MFG. Oscillatory EEG data indicated theta increase and an alpha decrease in parietooccipital sites for both simple and complex multiplication. The complexity of calculation was indicated by greater theta increase in frontocentral sites in complex multiplication relative to simple multiplication. Complementary activation in frontal areas and increased theta indicated additional cognitive control and working memory demands for arithmetic complexity in children. The lack of difference in parietal activation suggests that 5th graders rely on magnitude processing for both simple and complex calculations. It can be concluded that in children, arithmetic complexity is associated with domain-general cognitive processes and not with alteration of domain-specific magnitude process.

In Study 3, the behavioral and neural correlates of arithmetic learning were tested in children. Measurement immediately after training revealed decreased activation at the junction of the left inferior parietal lobule and the left AG, and right superior parietal lobule and IPS for complex multiplication, without improved behavioral performance in trained problems. Two-week training improved behavioral performance and led to decreased activation at the junction of the left AG and MTG, and right MFG in complex multiplication. For both trained simple and complex problems, increased alpha power was observed compared to untrained control problems. These findings indicate decreased activation of a frontoparietal network associated with arithmetic learning in children.

Surprisingly, no change in activation of the left AG was observed. It is concluded that shifts from procedural to retrieval strategies via arithmetic learning receive no support from the engagement of the AG in children (see Bloechle et al., 2016 for the same findings in adults).

In Study 4 the early behavioral and neurophysiological changes over the course of arithmetic learning were investigated. Behavioral data revealed that children's performance improved after six repetitions. They made fewer errors, while their response time did not change. The oscillatory EEG indicated increased power in theta (4–7 Hz) and lower alpha (8–10 Hz) bands, which were more dominant in posterior sites. No significant effect was observed in the upper alpha band (10–13 Hz). The increased power of theta and lower alpha bands can be interpreted as subserving a shift from slow procedural strategies to fast compact procedural strategies, which led to more efficient performance after a short training in children. This interpretation is also supported by Study 2, which showed that 5th graders did not exclusively use retrieval and relied partially on procedural strategies even in simple multiplication problem-solving. It is suggested that increased theta power is associated with domain-general demands of procedural and retrieval strategies used in arithmetic problem-solving, and increased lower alpha power is associated with increased automaticity.

THE FRONTOPARIETAL SHIFT SUBSERVES ARITHMETIC DEVELOPMENT AND LEARNING

According to our findings in this dissertation project, the findings on arithmetic learning in adult studies are not easily transferable to children (for a meta-analysis see Kaufmann et al., 2011). While adults remain at a stable level of arithmetic proficiency and use math skills informally in daily life, children receive direct and indirect instruction in these skills while at school. Therefore, the differences in arithmetic learning between adulthood and childhood are probably due to the frontoparietal activation shift in numerical and arithmetic processing with age and experience (Menon, 2010). This shift, which has also been observed in arithmetic learning, consists of the reduced activation of frontal cortex and increased activation of the parietal cortex, and thereafter a shift within parietal cortex from SPL and IPS to the AG (Zamarian et al., 2009). Previous developmental studies have shown this frontoparietal shift (e.g., Kawashima et al., 2004; Menon, 2010; Prado et al., 2014; Qin et al., 2014; Rivera et al., 2005). Rivera et al. (2005) showed that older children, who solve arithmetic problems faster and more accurately than younger children, rely less on frontal regions (see also Prado et al., 2014; Rosenberg-Lee et al., 2011). Moreover, as our findings revealed, children rely on more diverse strategies for arithmetic problem solving compared to adults (Cooney et al., 1988; Lemaire & Siegler, 1995; Sherin & Fuson, 2005; Siegler, 1988). Therefore, it is essential to investigate the neural and behavioral correlates of arithmetic development and learning directly in children (Kaufmann et al., 2011).

The findings of our studies support this frontoparietal activation shift with some qualifications, which are explained in our proposed model (see below). Regarding the fact retrieval network itself, the findings suggest that retrieval is faster and more efficient in 4th grade than in 3rd; however, the lack of change in the operand-relatedness effect with age may suggest that in children's fact retrieval network both the automatic association and reciprocal inhibition of concurrent responses may increase. Furthermore, the findings demonstrated an age-related shift from verbal to visuospatial WM in one-digit multiplication problem-solving from 3rd to 4th grade (Study 1). This finding is in line with a similar shift in domain-general factors influencing mathematical reasoning from 2nd to 3rd grade (Meyer et al., 2010). It also supports a developmental change in the domain-general cognitive demands of math, whereby the relationship between verbal and mathematical skills gradually attenuates with age (A. R. Jensen, 1980; Meyer et al., 2010; Swanson, 2006). Accordingly, there is a weak relationship between these two skills in adulthood (Heathcote, 1994; Logie et al., 1994; Logie & Baddeley, 1987), which might be because of the shift from a verbal representation of multiplication in young children to more abstract semantic retrieval in older children and adults (see also Fürst & Hitch, 2000). It seems that while verbal WM facilitates the early stages of arithmetic learning and performance, visuospatial WM supports later arithmetic performance during development. Note that the relation between these domain-general processes and different math skills might differ from age to age. For instance, Meyer et al. (2010) were concerned with mathematical reasoning and reported the same shift from verbal to visuospatial processes from 2nd to 3rd grade. During the elementary school multiplication is introduced in 2nd grade, verbally trained in 3rd grade, and then integrated into visual tasks in 4th grade;

therefore the shift from verbal to visual representation makes sense for multiplication at exactly that age.

Interestingly, Study 2 revealed that in older children, in 5th grade, only visuospatial WM is correlated with arithmetic performance, and not verbal WM. Furthermore, neuroimaging studies have shown the engagement of frontal areas in verbal WM, and parietal areas in visuospatial WM (Cabeza & Nyberg, 2000; Dumontheil & Klingberg, 2012). Therefore, the shift from verbal to visuospatial WM might be also interpreted in line with the frontoparietal shift of cortical activation during arithmetic development. In addition, behavioral correlates of arithmetic development, namely longitudinally increasing fluency with multiplication facts, were observed in Study 1. Children in 4th grade were faster in verifying one-digit multiplication problems, in the absence of any improvement regarding the accuracy of responses. The behavioral changes were found in our training studies (Study 3 and 4) as well. 5th graders demonstrated more efficient performance in trained compared to untrained multiplication problems, namely faster and more accurate responses. Therefore, the frontoparietal shift, which is accompanied by improved performance, involves a shift from domain-general areas to more domain-specific areas and also to other domain-general areas.

The investigation of increased arithmetic complexity supported the frontoparietal shift during development (Study 2). Children showed parietal activation, namely in the left SPL and IPS, as well as theta ERS and alpha ERD over occipitoparietal regions in solving one-digit multiplication problems. This finding demonstrates that 5th graders rely on both domain-general and domain-specific processes to solve one-digit multiplication problems. In order to solve two-digit multiplication problems, they showed activation not only in bilateral SPL and IPS, and the left IPL, but also in bilateral frontal areas, particularly MFG, along with posterior theta ERS extending to right temporal sites, and alpha ERD over occipitoparietal sites. This finding shows that solving two-digit multiplication problems relies more heavily on both domain-general and domain-specific areas. The contrast of two-digit versus one-digit calculation, showing increased multiplication complexity, revealed greater bilateral activation of MFG and IFG, which was accompanied by a greater increase of theta ERS in the frontocentral area. According to the frontoparietal shift, because children are more advanced in one-digit calculation, they do not need the additional support of frontal cognitive processes, while this is not the case for two-digit calculation. The difference is interpreted as reflecting the involvement of additional domain-general cognitive demands such as working memory, sustained attention, and planning in two-digit compared to one-digit calculation, since activation of the prefrontal cortex has been shown to be related to cognitive control and working memory (Cabeza & Nyberg, 2000; Ranganath et al., 2003; Sylvester et al., 2003). Altogether, it was concluded that the frontoparietal shift had already occurred for one-digit calculation, but not for two-digit calculation at this developmental stage. One-digit calculation is more automatized compared to two-digit calculation at this age; therefore, it relies less on the domain-general cognitive processes of the frontal areas. This conclusion is also in line with previous findings that complex calculation is carried out through procedural step-by-step processes (Zamarian et al., 2009). With regards to oscillatory EEG, it has been shown that additional domain-general cognitive processes such as cognitive control, working memory, encoding, and self-monitoring are related to theta ERS, as shown in adult studies (e.g., Micheloyannis et al., 2005; Mizuhara & Yamaguchi, 2007; Sammer et al., 2007). This finding was also replicated in Study 3, showing greater theta ERS in the two-digit calculation as compared to the one-digit calculation. Therefore, theta ERS is interpreted as a result of domain-general processes, which increase with complexity but decrease with development.

Arithmetic training also supported the frontoparietal shift during development. One session of multiplication training (the immediate training effect in Study 3) led to decreased activation at the junction of the left AG and IPL, and in the right SPL and IPS, along with greater alpha ERD over parietal areas, in two-digit calculations. Note that it is not possible to measure deep brain structures such as the hippocampus by means of fNIRS. Therefore, there might be activation changes in this structure as well (e.g., Bloechle et al., 2016; Klein et al., 2016; Qin et al., 2014; Supekar et al., 2013) that were not detected because of limitations in our study. Seven sessions of multiplication training (the short-term training effect in Study 3) led to a decreased activation at the junction of the left AG and MTG and in the right MFG, along with decreased alpha ERD at the left occipital site, in two-digit calculations. In one-digit multiplication, only decreased alpha ERD at the central site was observed as a short-term training effect. With respect to the fNIRS findings, both immediate and short-term training showed reduced activation within the frontoparietal network. This finding shows that generally, after arithmetic training fewer brain areas are involved in processing, which means that brain activation becomes more specific and efficient by excluding unnecessary circuits (Poldrack, 2000). However, with a closer look at the findings of these training courses, reduced frontal activation was found only after seven sessions of training and not after a single session. This difference, interestingly, points to the emergence of a frontoparietal shift after multiple training sessions. Therefore, it seems that development and arithmetic learning meet each other, and lead to similar brain activation changes. In agreement with arithmetic training studies in adults (Zamarian et al., 2009), the right MFG, which is involved in executive control and working memory, showed reduced activation after training. This shift is also detected in the alpha frequency band after seven sessions of training, because it shows, indeed, attenuation of domain-general cognitive processes and stronger domain-specific magnitude processes in arithmetic. It shows that over a course of arithmetic training, the brain works in a more specific way and relies less on additional areas that are not essential in processing numbers (see also Gevins et al., 1997). According to Pfurtscheller (2001), alpha ERD is associated with an increased excitability of cortical regions, which reflects increased information processing. In accordance with the frontoparietal shift, this oscillatory finding points towards reduced involvement of domain-general processes during mental calculation.

The findings of Study 4 mainly point to the above-mentioned additional considerations of the frontoparietal shift, which are explained in more detail in the proposed model (see below). As a result of the short training of six repetitions of multiplication problems, increased theta power in in the middle and right frontocentral sites, and also in the left, middle and right parietooccipital sites, along with increased power of lower alpha in the posterior sites were observed in 5th graders. These findings suggest a more tuned and efficient performance within the same network, rather than any shift (see also Klimesch, 1999). On the one hand, increased theta power demonstrates increased engagement of domain-general cognitive processes, while on the other hand, increased power in lower alpha shows increased automaticity, which means the same sequential procedures occur faster than before. It has been shown that the development of arithmetic in children is not necessarily a shift from procedural to retrieval processes, but rather a shift from slow procedural strategies to fast compact procedural strategies. For instance, Robinson et al. (2006) found that although children from 4th to 7th grades became faster and more accurate in solving simple division problems, they did not use retrieval strategies more frequently with increasing age. This is also in line with Prado et al. (2014), showing that one-digit multiplication achievement relies on verbal retrieval, whereas one-digit subtraction achievement relies on the greater use of efficient procedural processes in children. Therefore, the early neurophysiological findings of our study were similar to the only oscillatory EEG study of arithmetic training in adults (Grabner & De Smedt, 2012). However, these findings were interpreted differently from results of a study in adults, because adults are more advanced than children in arithmetic problem-solving, and may not need the transitional step of efficient procedural strategies. Theta oscillation in our study was also found in right and middle frontocentral sites in addition to parietal sites. This might be because of the interaction of parietal and frontal cortices in working memory function (H. Lee et al., 2005), which may play a bigger role in children than in adults.

According to the above-mentioned findings of our studies, our conclusions are that the improvement of math competence is not only represented as a shift from domain-general processes to domain-specific processes, but furthermore as a shift within domain-general processes, and involves a transitional increase of certain domain-general processes. Therefore, in order to extend the model of the frontoparietal shift during development, we suggest that two more points need to be taken into account: i) at some developmental and learning steps there is an increased engagement of both domain-general and domain-specific processes, ii) at some steps the involved areas are not extended or diminished, but rather they work more efficiently.

THE ROLE OF THE ANGULAR GYRUS IN ARITHMETIC DEVELOPMENT AND LEARNING IN CHILDREN

According to the triple-code model of number processing (Dehaene & Cohen, 1995; Dehaene et al., 2003), the AG is an area related to general language-related domains. Therefore, it might be interpreted as only one of several additional domain-general areas involved in mental calculation. Its role has been shown mostly in adult studies (Zamarian et al., 2009), and only a few studies in children have reported it (e.g., Cho et al., 2012). Even in adults, published findings on the role of the left AG in arithmetic, particularly in multiplication, have been controversial (Grabner et al., 2013). Although some studies reported the involvement of the left AG in the rote retrieval of arithmetic solutions (e.g., Delazer et al., 2003; Grabner et al., 2007), others did not (e.g., Chochon et al., 1999;

Dehaene et al., 1996; Prado et al., 2011; Prado et al., 2013; Rickard et al., 2000). Moreover, Grabner, Ischebeck, et al. (2009) revealed task non-specific activation of the AG, which was engaged in both multiplication and figural-spatial learning in adults (see also Simon et al., 2002). Engagement of the AG depends on the learning method as well. Delazer et al. (2005) reported activation of the left AG in multiplication learning only by training with drills (i.e., the relation of operands and result), but not by application of a backup strategy (i.e., sequential calculation). Activation of the left AG also depends strongly on mathematical competence and individual differences (Grabner et al., 2007). All of the above-mentioned findings demonstrate a domain-general and non-specific role of the AG in arithmetic processing in adults.

A few studies in children (Cho et al., 2012; Peters et al., 2016) have reported AG activation during small one-digit addition and subtraction problem-solving. However, in line with many other studies in children (e.g., Supekar et al., 2013; Qin et al., 2014), AG activation was found neither in our one-digit multiplication task in Study 2 nor in one-digit or two-digit multiplication training in Study 3. In Study 2, the whole range of one-digit multiplication was utilized, which probably led to an increase in procedural processes in the one-digit condition as well, and therefore, no activation of the AG was observed. Moreover, since children rely on a variety of strategies to solve simple one-digit multiplication and are not as competent in this task as adults, a lack of activation in the left AG is possible. It seems that neural correlates of arithmetic development and learning in children differ from the findings of several fMRI studies of arithmetic learning in adults, which reported a shift from the frontoparietal network to the left AG due to training (for a review see Zamarian et al., 2009; but see Bloechle et al., 2016). The lack of AG engagement in arithmetic development (Qin et al., 2014) and learning (Supekar et al., 2013) has already been reported in children. Instead of the AG, these studies suggested a critical transient role of the hippocampal system in arithmetic learning in children, which does not apply in adults (Qin et al., 2014; but see Klein et al., 2016). This difference might be due to the stability of neural substrates of learned arithmetic processes in adults compared to children (Qin et al., 2014). Furthermore, Qin et al. (2014) reported that a shift from procedural to retrieval strategies is not represented by similar brain activation changes from childhood into adulthood. Note that in Study 3 reduced activation around the left AG was observed. In contrast to the other studies, Menon et al. (2000) reported decreased AG activation with an increase of expertise. In sum, it is concluded that the AG is an additional supporting region, which depending on age, learning method, individual competence, the arithmetic task, and even the experimental design, may or may not be involved in mental calculation. It is evident that the AG might have an intermediate role during development, with a nonlinear relation over age and development between the AG activation increase/decrease and arithmetic learning (see also Amalric & Dehaene, 2016; Bloechle et al., 2016; Klein, Moeller, Glauche, et al., 2013; Klein et al., 2016). Klein et al. (2016) suggested that the neural correlates of arithmetic fact retrieval need to be extended to the network of the AG, the RC, the hippocampus, and ventro-medial prefrontal cortex in adults. However, they claimed that this network might not be specific to numerical facts, and is activated in non-numerical tasks that demand retrieval from long-term memory. Furthermore, they suggested that the AG, as a part of fact retrieval network, and the IPS, as a part of magnitude-related network, might be the regions of intersection between these two networks (for more details see Klein et al., 2016). However, the non-linearity function of the AG is explained further in our theoretical model below, which nevertheless still needs to be tested in larger studies that use the same learning paradigm over a wide range of age groups.

METHODOLOGICAL DIFFERENCES BETWEEN NEUROIMAGING STUDIES

It seems that the methodological differences between studies need to be taken into account, to partially explain the inconsistency of findings (Shallice, 2003). These differences include experimental paradigms, block or event-related designs, a fixed- or self-paced number of trials, etc. For instance, in a verification paradigm, shortcut strategies can be used, which might lead to more retrieval strategies because of the priming role of the presented solutions, while in written production, e.g., in Studies 2 and 3, individuals need to calculate for every single trial. With a fixed-paced design, more calculation time is usually spent on more complex trials. Therefore, activation differences might be partially due to the actual time needed for calculation, and not only to different strategy use. On the other hand, a self-paced design leads to different numbers of answered trials across individuals, as in Studies 2 and 3, but it ensures that the child is continuously performing the task without larger resting times between items for the faster condition. Regarding the design, an event-related design is well suited to investigate calculation complexity because calculation times differ quite strongly across conditions, and the fitting of the hemodynamic response function (HRF) might differ. In our view, the issue of the duration of activation and the goodness of fit of the HRF deserves more attention in future training studies. In addition, children's neurocognitive activation needs to be evaluated in an ecologically valid setting, as in the present studies that resembles how they solve tasks at school. Note that the spatial resolution of fNIRS is approximately 3 cm, and therefore the anatomical coordination of fNIRS findings is not as precise as with other brain imaging devices. This might be a potential reason for different findings in our studies compared to previous fMRI studies in adults. Therefore, it is suggested that brain activation changes are investigated using both event-related and block designs, while taking into account the self-paced versus fixed-paced paradigm. Furthermore, it seems to be important to compare different response types, i.e., production, multiple-choice, and verification, because of their differences in chance level accuracy and shortcut strategies. It is worthwhile to do so, because for instance, some IPS activations thought to be related to numerical processing may be related to difficulty in decision making, etc. In the following, the theoretical model which has been developed based on our studies is first explained, and then the evidence that supports our model will be discussed.

THEORETICAL MODEL OF ARITHMETIC DEVELOPMENT AND LEARNING IN CHILDREN

The brain is expensive, in the sense of consuming a disproportionate amount of energy relative to the space it occupies in the body (Bullmore & Sporns, 2012; Shulman, Rothman, Behar, & Hyder, 2004). However, the energy available to the brain is extremely limited, so that less than 1% of neurons can be active simultaneously (Lennie, 2003). Therefore, one important principle of brain networks is to minimize energy costs, while concurrently processing information with high efficiency (Attwell & Laughlin, 2001; Bassett et al., 2009; Bullmore & Sporns, 2012; Laughlin & Sejnowski, 2003; Lennie, 2003; Shulman et al., 2004). The brain's energy consumption increases with increased neural processes (Niven, Anderson, & Laughlin, 2007; Tomasi, Wang, & Volkow, 2013), but because of limited energy sources, the brain as a system is required to work with optimal proficiency (for more details see Friston, 2010). It has been also shown that the balance between these two principles is corrupted in neuropsychiatric disorders and abnormal development (Bassett et al., 2009; for a review see Bullmore & Sporns, 2012).

According to the above-mentioned principles, a theoretical model of neurocognitive and neurophysiological changes during arithmetic development and learning is proposed here. The optimal performance in mental calculation is to provide fast and precise responses, while the brain needs to minimize energy consumption by involving limited networks (Pfurtscheller et al., 1996). Based on these principles, we split arithmetic development into two developmental and learning phases: the *efficiency increase* and *strategy change* phases (cf. Fig. 6). For a good performance in the efficiency increase phase, more neural networks need to be involved, which leads to the engagement of several domain-general and domain-specific brain areas within the frontoparietal network, along with increased theta ERS (i.e., increased theta power) and increased alpha ERD (i.e., decreased alpha power). Gradually, because of limited energy sources, unnecessary domain-general networks are excluded from the process, which lets domain-specific networks access more energy sources and become more active. It seems that this gradual change occurs after reaching the optimal performance during development or over the course of math learning. This is the step in which the strategy change phase is started. In this phase fewer neural networks are involved, which leads to the engagement of very few domain-general areas and necessary domain-specific brain areas within the frontoparietal network, along with decreased theta ERS (i.e., decreased theta power) and decreased alpha ERD (i.e., increased alpha power). For instance, in the efficiency increase phase after a short course of multiplication training, the child is able to respond quickly and correctly to almost all problems, using considerable mental effort. By continuing the training, in the strategy change phase, the child keeps the same performance while spending less energy to solve the same problems.

The efficiency increase phase consists of the first steps of learning each mathematical skill, while the strategy change phase occurs when the individual needs much less effort to overcome familiar math problems. Based on several factors such as different math skills, calculation complexity, school grades, age, expertise, training courses, etc. (cf. Fig. 6) the efficiency increase and strategy change phases differ between skills. For instance, children learn one-digit multiplication in 2nd grade, while they are more advanced in this skill years later, in 5th grade. Therefore, 2nd grade constitutes the efficiency increase phase of one-digit multiplication, and 5th grade serves as the strategy change phase. However, these phases differ for other math problems such as computing fractions. Because children learn this skill in 5th grade, the efficiency increase phase for fractions begins in 5th grade. Indeed, children are advanced in solving one-digit addition, while they are beginners in solving fractions in 5th grade. Therefore, they rely on only a few domain-specific regions to solve one-digit addition, while they recruit several additional domain-general regions to solve fraction problems during this grade. These phases are not only defined by different math skills, but also between different arithmetic operations, and also within each operation. For example, children first learn one-digit and then multi-digit calculations; therefore, they are in the efficiency increase phase for one-digit calculations but not multi-digit calculations. In regards to age, younger children are in the efficiency increase phase more than older children, and generally, children are in the efficiency increase phase more than adults. Note that these phases are identified relatively, which means that arithmetic development is categorized in the comparison between two skills or two educational grades or two ages, etc. For instance, children are in the efficiency increase phase relative to adults, who are more advanced in mental calculation. Adults rely more on domain-specific areas to solve arithmetic problems, while children rely more on extended networks. This is the same for individuals with low math competence compared to individuals with high math competence. Individuals with low math competence need to recruit more additional domain-general regions to be able to solve arithmetic problems, while individuals with high math competence may be able to rely on domain-specific areas and have the same or even better performance. With respect to the training of a new math skill, individuals learn first how to solve the problem type, which most probably engages any necessary network at the beginning. After a long-lasting training, the brain gradually excludes less relevant areas to save energy while using more and more shortcut strategies.

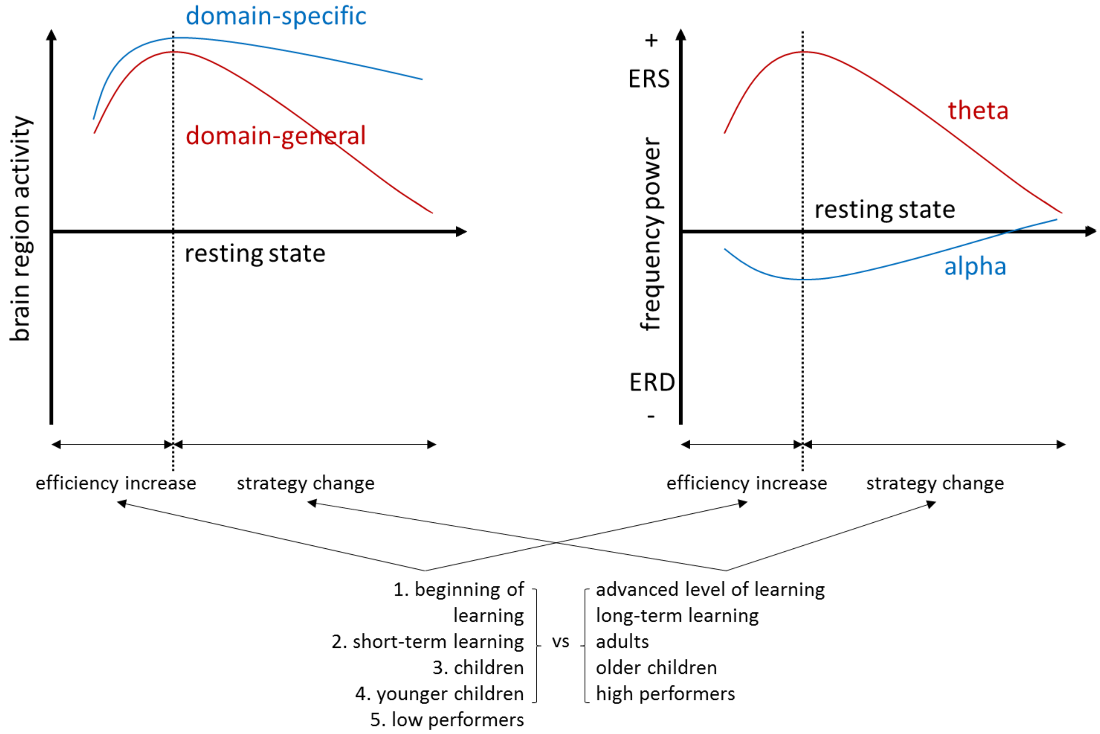

Fig. 6. A theoretical model of arithmetic development and learning. The above-left panel depicts neurocognitive changes in the frontoparietal network, which can be detected by fNIRS, fMRI, etc. The above right panel shows neurophysiological changes during arithmetic development and learning, which can be detected by oscillatory EEG. The below panels demonstrate some examples of the efficiency increase and strategy change phases in the model.

This model also explains the strategy use in mental calculation. According to the model by Baroody (1983), in the efficiency increase phase there is a gradual shift from slow procedural processes towards compacted procedural strategies and knowledge of principles. As stated in this model, these compacted strategies and procedural knowledge are more automatic and lead to faster responses. Therefore, at the peak of the curves, which represents the transition period from the efficiency increase to the strategy change phase, individuals are capable of using maximum domain-general processes in a very efficient way. This means that most probably individuals still rely on procedural strategies, but apply these strategies more automatically. Another important point is that activation levels in domain-general areas may not necessarily change in the same way. When one domain-general area such as the prefrontal cortex shows an activation decrease – for instance in the strategy change phase – another area such as the AG might be still at its peak. This is what has been shown several times in complex multiplication learning in adults, although this is not necessarily the case for other basic operations (for a review see Zamarian et al., 2009).

Further, depending on the training method, the AG can have a transition role between two phases, at least in multiplication learning (for more see Delazer et al., 2005). The frontoparietal shift – reduced frontal activation and increased parietal activation – has mostly been interpreted as representing a shift from using more procedural to more retrieval strategies during mental calculation. This shift can be easily explained by the strategy change phase of the model, showing reduced engagement of domain-general areas and brain oscillations with increased engagement of domain-specific areas. However, based on our model, there is a kind of inconsistency within activation changes in domain-general and -specific areas in arithmetic learning studies in adults. Most of these studies (e.g., Delazer et al., 2003) found increased activation in the AG and reduced activation in the IPS in trained problems compared to untrained problems. According to the triple-code model (Dehaene et al., 2003) the AG, which is a language-related area, is considered to be a domain-general area while the IPS is considered a domain-specific area for mental calculation. Therefore, our model cannot fully explain these changes, because according to the model, increased activation of the AG can be explained as part of the transition from the efficiency increase to the strategy change phase, while reduced activation of the IPS is expected to occur within the strategy change phase. Further, studies of experts (e.g., Amalric & Dehaene, 2016) reported that although mathematicians do not rely on language-related areas to solve different kinds of math tests, they recruit several brain areas, which are involved in both spatial and number processing. Therefore, while the reduced engagement of some domain-general areas is in line with our model, the increased engagement of some other regions is not easily interpreted by our model. Note that we did not aim to differentiate the development of different domain-general processes in our model, which might be interesting to add to the model after testing some more fundamental assumptions of the model in larger studies. For instance, it is still unclear how the domain-general and domain-specific areas involved in mental calculation are interacting with each other (see also Klein et al., 2016). Furthermore, more training studies in healthy and disordered children and adults, and also studies in high and low performers are needed to improve the current theoretical model.

Altogether, in the efficiency increase phase of arithmetic development and learning, the maximum accessible energy is consumed to reach the optimal performance, while in the strategy change phase, by maintaining the optimal performance – and even improving it –

the brain diminishes energy consumption while becoming more and more specialized. Below, the findings of our studies are explained along with some other studies supporting our proposed model. Although several brain imaging and neurophysiological studies support the proposed model, it still needs to be tested in larger future studies over a wide range of age groups.

EXPERIMENTAL FINDINGS OF NEUROCOGNITIVE CHANGES SUPPORTING AND CHALLENGING THE MODEL

The fNIRS findings of our studies in typically developing children support this model. In Study 2, children solved one-digit multiplication problems faster and more accurately than two-digit problems, which shows that they were more advanced in one-digit compared to two-digit problems. Therefore, according to the model, fewer activated areas in one-digit calculation – the strategy change phase – were expected, compared to two-digit calculation – the efficiency increase phase. The findings demonstrate less bilateral frontal activation in one-digit compared to two-digit calculation, which supports the model. In Study 3, children were trained in multiplication problem-solving for one and seven sessions, respectively. According to the model, reduced frontoparietal activation was expected after seven sessions of training – the strategy change phase – while increased frontoparietal activation was expected after one session of training – the efficiency increase phase. The findings show decreased frontoparietal activation after both seven sessions and one session of two-digit multiplication. While the results from seven sessions of training support the model, the finding from one session of training seems not to be in line with the expectation. In accordance with the model, brain activation changes in both the efficiency increase and strategy change phases lead to improved performance. Surprisingly, no improvement was observed in the behavioral data after one session of training, which means that to keep the same performance as in pre-training, the brain spent less energy by involving fewer networks (see also Poldrack, 2000). In other words, increased activation in the efficiency increase phase is expected if the performance improves, but otherwise, fewer brain networks are involved in achieving the same level of performance, and therefore, less energy is consumed. It is the same for the strategy change phase, in which faster calculation times were observed. It seems that in the absence of behavioral changes after one session of training, the human brain applies the second principle to save energy consumption.

However, this finding is not fully consistent with oscillatory EEG findings (see below). In this study, no significant activation change was observed in one-digit multiplication training in regard to fNIRS data. A more surprising finding was the increased parietal activation in the untrained two-digit calculations compared to the pre-training session. This increase can be interpreted based on our model. Although children were not trained for these problems, for two reasons their performance indicates they were within the efficiency increase phase. First, in the post-training session children were solving these problems for the second time, because they were already presented with similar problems in the pre-training session. Second, following the transfer effect within one operation (Ischebeck et al., 2009), they have indirectly received a sort of training for untrained two-digit problems as well. Therefore, according to the model, because of a very short and also indirect training, increased activation within the frontoparietal network is expected. This is exactly our finding in the parietal area after seven sessions of training.

In the following, some neurocognitive studies investigating age, school grade, expertise, strategy use, training, math complexity, and math disability are discussed in support of our model. In accordance with our model, domain-specific areas, namely horizontal IPS, showed first increased and then slightly decreased activation. Kawashima et al. (2004) reported bilaterally greater activation of IPS in adults compared to children, which fits to the efficiency increase phase of the model, because adults recruit domain-specific areas in calculation more than children. This finding was also supported by Ansari et al. (2005), where the engagement of parietal areas in adults, and frontal areas in children is reported in a number comparison task. Moreover, Rosenberg-Lee et al. (2011) reported greater activation in dorsal stream parietal areas, including the right SPL, IPS, and the AG as well as ventral visual stream areas, bilateral lingual gyrus, right lateral occipital cortex, and right parahippocampal gyrus in 3rd grade children compared to children in 2nd grade. 3rd graders showed also greater activation in the left dorsolateral prefrontal cortex, with reduced activation in the ventral medial prefrontal cortex. More interestingly, 3rd graders revealed greater functional connectivity between the left dorsolateral prefrontal cortex and dorsal stream parietal areas such as IPS and AG. These increases in domain-general and domain-specific areas in older children are in line with the efficiency increase phase of the model, because children at this age are not still advanced in complex addition. Therefore, they recruit more additional regions to be able to solve the problems more accurately than

2nd graders. Their performance corroborates this interpretation, because 3rd graders were more accurate than 2nd graders (Rosenberg-Lee et al., 2011). These findings are in line with the new study by Chang, Rosenberg-Lee, Metcalfe, Chen, and Menon (2015) reporting greater activation of IPS, ventral tempo-occipital, anterior temporal and dorsolateral prefrontal cortex in adults relative to children in solving both addition and subtraction problems.

Several studies of multiplication training revealed reduced activation of the IPS in trained versus untrained problems in adults (Zamarian et al., 2009). Although adults are more advanced in solving (untrained) arithmetic problems compared to children, they are still in the efficiency increase phase relative to post-training (see above). Due to training, they mostly move further to the strategy change phase, showing a slight reduction of IPS activation along with reduced activation of domain-general cognitive areas (Delazer et al., 2003; Delazer et al., 2005; Ischebeck et al., 2006; Ischebeck et al., 2007; Ischebeck et al., 2009; Grabner, Ischebeck, et al., 2009). Because the horizontal IPS is a domain-specific region in arithmetic processing (Andres et al., 2011), reduced IPS activation might be interpreted as more efficient activation even within the specialized area. Furthermore, a recent study by Bloechle et al. (2016) suggested an increase in hippocampal, parahippocampal, and retrosplenial structures in multiplication training in adults (see also Klein et al., 2016). An increased activation of these domain-general areas fits to the efficiency increase phase of the model, which indicates an activation increase in this transitional domain-general area after training. Note that, while they observed reduced activation of the frontal domain-general regions, the hippocampus, as a transitional area involved in shifting strategies, demonstrated increased activation. Therefore, it might be possible to observe both an increase and decrease of activation in different domain-general regions, showing their importance at different steps of arithmetic development and learning. This interpretation is supported by the finding of Qin et al. (2014), showing that hippocampus activation decreases with age from childhood to adulthood (see also Supekar et al., 2013).

Most of the multiplication training studies have shown an increased activation of the left AG in adults (Zamarian et al., 2009), which is interpreted as an increased engagement of the domain-general area near the end of the efficiency increase phase. Cho et al. (2012) reported that children (7-9 years old) with higher retrieval fluency and automaticity revealed greater activation in the right hippocampus, parahippocampal gyrus, lingual gyrus, fusiform gyrus, left ventrolateral prefrontal cortex, bilateral dorsolateral prefrontal cortex, and posterior AG. This finding supports the efficiency increase phase of the model, suggesting that children with better performance recruit more domain-general areas. Further training leads to reduced activation in the strategy change phase of the model. Amalric and Dehaene (2016) found that professional mathematicians do not rely on the AG and other language-related areas in mental calculation. This interpretation is further supported by Bugden, Price, McLean, and Ansari (2012), showing that children with more mature response modulation of the IPS, a domain-specific area, demonstrate higher arithmetic competence. Moreover, M Rosenberg-Lee et al. (2009) showed that the strategies learned in school involve more domain-general areas including the posterior superior parietal lobule (attentional mechanisms) and posterior parietal cortex (mental representation), compared to expert strategies in multi-digit multiplication problem-solving. This finding verifies the attenuation of activation in domain-general areas during development, and demonstrates that individuals with higher math competence depend on less domain-general processes in the strategy change phase.

Furthermore, according to the model, complex calculations are associated with the efficiency increase phase, while simple calculations are associated with the strategy change phase. This explanation is supported by the findings of cross-sectional studies. Rosenberg-Lee et al. (2011) found that arithmetic complexity is related to increased activation of the right inferior frontal sulcus and anterior insula, both domain-general cognitive areas. These findings are in line with the study by Cho et al. (2012) demonstrating that additional domain-general and -specific regions, such as left IPS, supramarginal gyrus, bilateral dorsolateral prefrontal cortex, and SFG, are engaged in solving complex addition relative to simple addition in children. Our model is further supported by the findings of math learning disability studies. Berteletti, Prado, and Booth (2014) found that children (3rd to 7th graders) with a math learning disability are not able to utilize both domain-general regions (left IFG, MTG, and STG) and domain-specific regions (right SPL and IPS), unlike typically developing children, when calculating small and large one-digit multiplication problems. However, children with a math learning disability revealed activation of SPL and IPS during the small one-digit calculation. Based on the efficiency increase phase of the model, this finding shows that children with a math learning disability are more advanced in solving small one-digit calculations than large one-digit calculations, which leads to better performance in small than in large problems. In another study, Iuculano et al. (2015) showed that before training, children with a math learning disability recruited several additional frontal and parietal areas to solve arithmetic problems relative to typically developing children. However, after eight weeks of one-to-one cognitive tutoring, no difference was observed between the two groups. This reduction of activated areas accompanied improved behavioral performance in children with a math learning disability (Iuculano et al., 2015; Kucian et al., 2011). According to the strategy change phase, while these children recruited fewer brain regions to solve the problems after training, their behavioral performance improved.

EXPERIMENTAL FINDINGS OF THETA AND ALPHA OSCILLATORY CHANGES SUPPORTING THE MODEL

The oscillatory EEG findings of our studies in typically developing children support the proposed model. In Study 2, children solved one-digit multiplication problems faster and more accurately than two-digit problems, which show they are more advanced in one-digit than in two-digit problems. Therefore, according to the model, less theta ERS and alpha ERD in one-digit calculation – the strategy change phase – is expected in comparison to two-digit calculation – the efficiency increase phase. The findings demonstrate less theta ERS in frontocentral sites in one-digit than in two-digit calculation, which supports the model. However, in the alpha band, no difference was observed between one-digit and two-digit problem-solving. In Study 3, children were trained in multiplication problem-solving for one and seven sessions. According to the model, reduced theta ERS and alpha ERD after seven sessions of training – the strategy change phase – are expected, while increased theta ERS and alpha ERD are expected after one session of training – the efficiency increase phase. The findings show increased alpha ERD after one session of two-digit multiplication, but reduced alpha ERD after seven sessions of two-digit multiplication training, which again corroborate the model. Interestingly, the findings hold for both one-digit and two-digit multiplication problem solving, showing that even one-digit calculation, in which children are more advanced, can be even more improved, with fewer networks engaged after additional training sessions. Again it is important to mention that these phases are relative, meaning that while untrained one-digit calculation shows the strategy change phase in comparison to the untrained two-digit calculation (Study 2), it shows the efficiency increase phase when compared to trained one-digit calculation (Study 3). In this study, no theta change was observed. In Study 4, children repeatedly solved a set of multiplication problems, six times. Because of the small number of repetitions, increased theta power (greater theta ERS) and decreased alpha power (greater alpha ERD) – the efficiency increase phase – were expected. The findings show increased theta power, along with (marginally) increased power of lower alpha. Increased power in the lower alpha band does not fit the predictions of the model. This might be explained by one of a few different reasons. One reason is that alpha oscillation allows for the desynchronized activity of "independent" areas. After training, these areas still work but are more synchronized with each other, which leads to increased alpha power. Another reason is that in Study 4, the alpha band was split into lower and upper alpha, because some studies assume different functions for different alpha bands (for more see Study 4). Moreover, the alpha increase did not survive corrections applied for multiple testing. Therefore, because of the power issue, it needs to be tested in the future with more repetitions or a larger sample size. In addition, our model generally refers to the alpha frequency band, which contains the whole range of 8–13 Hz. However, because very few studies in the field of numerical cognition make use of oscillatory EEG, more studies on split alpha frequency bands are needed to develop the proposed model for lower and upper alpha bands. According to Klimesch (1999), lower alpha reflects the attentional demands of a task, and upper alpha reflects semantic memory performance and retrieval of semantic information, which are arithmetic facts in our case. Therefore, based on our model, power decrease and then increase in lower alpha in the efficiency increase and strategy change phases, respectively, can be expected. With respect to upper alpha, constant power in the efficiency increase phase and then a decrease in power in the strategy change phase can be expected.

Previous oscillatory EEG studies support our theoretical model of neurophysiological changes of arithmetic development and learning. Regarding an age effect, Hinault, Lemaire, and Phillips (2016) showed reduced power of theta, lower and upper alpha in older adults (73-year-old) compared to young adults (22-year-old). As discussed previously, in our model theta power decreases with age and experience, but alpha power increases. Therefore, these findings are partially in line with the model. Note that older adults, surprisingly, had a better performance not only in the experimental task but also in arithmetic fluency than younger adults. This behavioral finding may partially explain the unexpected alpha decrease in older adults, because they were engaging more cortical resources. However, because there is very limited knowledge about the neurophysiology of arithmetic processing in the elderly, it needs to be investigated in future studies.

Zhuang et al. (1997) found that explicit learning of a motoric task, i.e., pressing a key with different fingers, leads to stronger mu ERD (decrease in mu power) over the contralateral site. When the participants learned the task and did the movement more automatically, mu ERD declined. This finding was interpreted as revealing increased activation of the primary sensorimotor regions while learning a new motoric task, while this activation decreases after the task is learned (Zhuang et al., 1997; see also Pfurtscheller & Da Silva, 1999). These findings fit very well with our model, with two phases of development. Note that mu activity is related to the motoric and motor imagery tasks and not arithmetic processing; however, this training study from another domain might affirm the proposed model in arithmetic achievement. In another study, Gevins et al. (1997) found increased theta and alpha power due to short-term working memory training in adults. They interpreted increased theta power as a result of applying more effort in focusing attention after an extended measurement time, and increased alpha power as a result of the engagement of fewer cortical resources after skill development (Gevins et al., 1997). Grabner and De Smedt (2012) found increased power in theta and lower alpha bands after two days of training in two-digit multiplication problems and figural-spatial problems in adults. According to our model, increased theta is considered to occur within the efficiency increase phase of learning. It is possible that during the short training sessions in both of the above studies, participants learned how to apply more efficient and automated strategies, which most probably caused functional and not anatomical changes. Therefore, the trainings led to an increase in theta power. This assumption is borne out by the increased alpha power in both studies, showing increased automaticity of the applied strategies and less involvement of cortical resources. It might be because the training was not sufficient to move participants to the strategy change phase.

Klimesch (1999) reported more theta power in individuals with high calculation skills compared to individuals with low calculation skills (see also Núñez-Peña & Suárez-Pellicioni, 2012). According to the efficiency increase phase of the model, individuals with higher performance were able to do more compacted and fast procedural strategies, which led to increased theta power in this group, compared to individuals with lower performance. De Smedt et al. (2009) found greater theta power (increased theta ERS) and alpha power (decreased alpha ERD) in simple one-digit addition and subtraction problem-solving compared to larger problems (see also Grabner & De Smedt, 2011). These findings can be partially interpreted with our model. According to the model, a simple calculation is related to the strategy change phase, while the more complex calculation is related to the efficiency increase phase. Therefore, we would expect reduced theta power but increased alpha power in simple calculations. The inconsistent finding in the theta band can be attributed to the necessity of inhibition in retrieval strategies, which leads to an increase in theta power. Moreover, it has been shown that both adults and children solve very small problems by fast compacted procedural strategies (Barrouillet & Thevenot, 2013).

With respect to complexity, Gevins et al. (1997) found increased theta power in a frontal midline site and decreased alpha power in a parieto-central site with increased memory load in WM task. They interpreted the theta power increase as a result of increased engagement of sustained attention, and decreased alpha power as the result of increased involvement of cortical resources (see also Harmony et al., 1999). These explanations are in line with the efficiency increase phase of our model, which is associated with increased complexity of the task. In sum, although several studies support our theoretical model, there is still a substantial lack of knowledge about neurocognitive and neurophysiological changes over the course of arithmetic development and learning, particularly in children. Therefore, future studies are needed to enable the further development of our model.

FUTURE PERSPECTIVES

In the following, some suggestions are presented for future studies, which are also necessary to evaluate the proposed model of arithmetic development and learning. Moreover, some basic and methodological studies need to be conducted, which might be very helpful for the design of future experiments and interpretation of the findings.

1. It is concluded that brain activation networks underlying arithmetic processes differ between adults and children. However, this conclusion mostly comes from the findings of separate studies in adults and children, and from only a few studies which compared these groups directly (e.g., Kawashima et al., 2004), yet

sometimes showed controversial findings. Therefore, it is worthwhile to investigate these possible differences directly, which would help with future decisions such as how to develop interventions for children based on adults' findings. On the other hand, in the case of negligible differences, conducting studies in adults is much easier and more efficient than in children.

2. As mentioned previously, arithmetic development and learning has been defined as a strategy shift from effortful and slow procedural strategies to fast and compacted procedural strategies, and then to retrieval strategy. Item-based methods are the most common approach for investigating strategy use, in other words, obtaining verbal reports of the applied strategy after every single problem. However, verbal reports of strategy use have been criticized because they are such a limited way to investigate the real strategies (Kirk & Ashcraft, 2001; Russo, Johnson, & Stephens, 1989), and might not be more informative than EEG findings (Hinault & Lemaire, 2016). Therefore, it is suggested to study the strategy use during arithmetic processing by means of EEG, particularly in children, because it is so often that they really do not know how they solved the problems.
3. Most of the arithmetic learning studies in adults (for a review see Zamarian et al., 2009) and in children, including our studies, used multiplication problems. However, it has been shown that neural correlates of different arithmetic operations are not identical (e.g., Fehr et al., 2007). For instance, Prado et al. (2014) found that while a grade-related increase in multiplication proficiency leads to an activation increase in the left temporal cortex, subtraction proficiency leads to an activation increase in the right parietal cortex. Therefore, it is recommended for future studies to investigate other arithmetic operations as well. Moreover, it would be helpful to understand the adult-like brain activation patterns of different math skills, particularly arithmetic operations with different complexity levels. This information can be helpful for therapeutic planning, because then the therapist will be aware of the ideal time to plan each particular intervention.
4. Different domain-general cognitive factors are needed during arithmetic problem solving (Cragg & Gilmore, 2014). While several studies have already shown the

importance of WM (Menon, 2016), a recent study by Nemati et al. (2017) suggested that some other cognitive processes, namely planning and self-control, might overcome WM in arithmetic performance. Therefore, it seems to be essential to investigate more domain-general cognitive factors rather than only WM in future studies.

5. While most of the previous neuroimaging studies of arithmetic learning revealed an increased activation of the left AG in the post-training measure (Zamarian et al., 2009), a recent study by Bloechle et al. (2016) showed that the activation does not appear in a post- versus pre-training contrast. Furthermore, it has been shown that different paradigms might influence the strategy use and therefore, possibly the brain activation pattern (see also Hinault & Lemaire, 2016). For instance, behavioral studies (e.g., Campbell, 1987) showed different cognitive processes underlying production and verification paradigms. It seems that methodological differences might lead to different results, which can consequently bias any diagnostic and interventional decision based on neural findings in future. Therefore, it seems to be essential to take this issue into account, and consider it for any further comparison across studies. Moreover, to our best of knowledge, no neuroimaging study has investigated these differences in the field of numerical cognition.

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ACKNOWLEDGEMENTS

After an intensive period of over four years, I am writing this note of thanks as the finishing touch on my dissertation. It has been a period of intense learning for me, not only in the scientific arena, but also on a personal level. I would like to reflect on the people who have supported and helped me so much throughout this period.

I would first like to thank all children and their parents who volunteered to participate in my studies. Without their engagement and patience, none of the findings could have been made. I would particularly like to single out my supervisor, Hans-Christoph Nuerk, for all of the opportunities I was given to learn and conduct my research, and also for his great support and supervision. I want to thank Ann-Chrsitine Ehlis, Thomas Dresler, Christina Artemenko, and Andreas J. Fallgatter for their excellent cooperation and for all of their valuable feedback on my works. I would like to thank my colleagues for their wonderful collaboration, and also Andreas Schweizer, for his very kind technical support.

Last but not least, I would also like to thank my beloved Pari and my family for their wise counsel and sympathetic ear. You are always there for me. Finally, there are my friends. We were not only able to support each other by deliberating over our problems and findings, but also happily by talking about things other than just our papers.

CURRICULUM VITAE

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Education

11.2017-present	**Postdoctoral fellow**
	Diagnostic and Cognitive Neuropsychology, University of Tuebingen, Tuebingen, Germany
	LEAD Graduate School & Research Network, University of Tuebingen, Tuebingen, Germany
6.2013-10.2017	**PhD candidate of Neural and Behavioural Sciences**
	Diagnostic and Cognitive Neuropsychology, University of Tuebingen, Tuebingen, Germany
	Graduate Training Centre of Neuroscience/ International Max Planck Research School for Cognitive and Systems Neuroscience, Tuebingen, Germany
7.2012-2.2013	**Research assistant in Cognitive neuroscience**
	Institute of Medical Psychology and Behavioural Neurobiology, University of Tuebingen, Tuebingen, Germany
9.2011-7.2012	**Research assistant in Cognitive neuroscience**
	Department of psychology, University of Tabriz, Tabriz, Iran
9.2005-8.2008	**MSc in Occupational therapy**
	Faculty of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran
9.2001-7.2005	**BSc in Occupational therapy**
	Faculty of Rehabilitation, Iran University of Medical Sciences, Tehran, Iran
9.1996-8.2000	**High school diploma in Experimental sciences**
	Allameh Helli, Tehran, Iran

Research interests

Developmental cognitive neuroscience

Educational Neuroscience

Generalized magnitude system (number, space, time)

Grants and awards

2017 Excellent grade (summa cum laude) for the PhD dissertation

2017 EUR 200 travel prize from the Universitätsbund to participate in the 20th Conference of the European Society for Cognitive Psychology (ESCoP), September 3-6, 2017, Potsdam, Germany.

2016 EUR 200 travel prize from the Universitätsbund to participate in the 2016 Biennial Meeting of the Society for functional Near Infrared Spectroscopy, October 13-16, 2016, Paris, France.

2016 EUR 9875 via intramural funding of the excellence initiative of the German Research Foundation, University of Tuebingen (ZUK 63) for the Workshop "Domain-General and Domain-Specific Foundation of Numerical and Arithmetic Processing", Tuebingen, Germany, September 2016.

2016 EUR 200 travel prize from the Universitätsbund to participate in the 2016 Meeting of the EARLI SIG 22 "Neuroscience and Education", June 23-25, 2016, Amsterdam, the Netherlands.

2011 One of 4 accepted PhD students in national exam of Cognitive neuroscience in Iran.

2005 Ranked 3rd in national MSc entrance exam of Occupational therapy in Iran.

2005 Ranked 3rd in the four-year bachelor, Iran University of Medical Sciences.

Publication

Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A.J., Nuerk, H.-C.*, Ehlis, A.-C.* (under review). Oscillatory EEG changes during arithmetic learning in children. *BMC Neuroscience*. [*: equally contributed]

Soltanlou, M., Artemenko, C., Ehlis, A.-C., Huber, S., Fallgatter, A.J., Dresler, T.*, Nuerk, H.-C.* (revision submitted). Reduction but not shift in brain activation in arithmetic learning in children: A simultaneous fNIRS-EEG study. *Scientific Report.* [*: equally contributed]

Nemati, P., Schmid, J., **Soltanlou, M.,** Krimly, J.-T., Nuerk, H.-C., Gawrilow, C. (2017). Planning and self-control, but not working memory directly predicts multiplication performance in adults. *Journal of Numerical Cognition, 3(2)*. doi:10.5964/jnc.v3i2.61

Soltanlou, M., Artemenko, C., Dresler, T., Haeussinger, F.B., Fallgatter, A.J., Ehlis, A.-C.*, Nuerk, H.-C.* (2017). Increased arithmetic complexity is associated with domain-general but not domain-specific magnitude processing in children: A simultaneous fNIRS-EEG study. *Cognitive, Affective, & Behavioral Neuroscience.* doi: 10.3758/s13415-017-0508-x [*: equally contributed]

Nazari, M.A., Mirloo, M. M., Rezaei, M., **Soltanlou, M.** (2016). Emotional stimuli facilitate time perception in children with attention-deficit/hyperactivity disorder. *Journal of Neuropsychology*. doi: 10.1111/jnp.12111

Nazari, M.A.*, Caria, A., **Soltanlou, M.*** (2016). Time for action versus action in time: time estimation differs between motor preparation and execution. *Journal of Cognitive Psychology*. 1-8. doi: 10.1080/20445911.2016.1232724 [*: equally contributed]

Soltanlou, M., Pixner, S., Nuerk, H.-C. (2015). Contribution of working memory in multiplication fact network in children may shift from verbal to visuo-spatial: A longitudinal investigation. *Front. Psychol.*, 6: 1062. doi: 10.3389/fpsyg.2015.01062

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Nazari, M.A., **Soltanlou, M.,** Saeedi Dehaghani, S., Damya, S., Rastgar Hashemi, N., Mirloo, M. M. (2014). The effect of gender, valence and arousal of Persian emotional words on time perception. *Journal of Social Cognition*. 2(4): 62-73.

Nazari, M.A., Mirloo, M. M., **Soltanlou, M.,** Rezaei, M., Roshani, A., Asadzadeh, S. (2013). Design and development of the time discrimination threshold computerized task. *Advances in Cognitive Science.* 15(1): 67-76.

Soltanlou, M., Anbara, T., Taghi-Zadeh, G., Rahim-Zadeh Rahbar, S., Karimi, H. (2013). Assessing the relationship between cognitive deficits and functional balance in right adult stroke patients. *Urmia Medical Journal*. 24 (5): 295-301.

Salemi Khamene, A., Ghahari, S., **Soltanlou, M.**, Darabi, J. (2013). Effectiveness of pivotal response treatment on communicative and behavioral disorder of 8-12 years-old autistic boys. *J Gorgan Uni Med Sci.* 15(1): 6-11.

Soltanlou, M., Olyaei, G., Tehrani Dost, M., Abdolvahab, M., Bagheri, H., Faghihzadeh, S. (2009). Comparison of attentional set shifting in cerebral palsy children with normal in aged 7-12 years. *Modern Rehabilitation Journal*. 2 (3 & 4): 60-65.

Soltanlou, M., Olyaei, G., Tehrani Dost, M., Abdolvahab, M., Bagheri, H., Faghihzadeh, S. (2008). Comparison of spatial working memory and strategy use in cerebral palsy children with normal subjects with 7-12 years old. *Modern Rehabilitation Journal*. 2 (1): 9-14.

Book chapter

Soltanlou, M., Jung, S., Roesch, S., Ninaus, M., Brandelik, K., Heller, J., Grust, T., Nuerk, H.-C., & Moeller, K. (2017). Behavioral and neurocognitive evaluation of a web-platform for game-based learning of orthography and numeracy. In: Buder J., Hesse F. (eds) *Informational Environments* (pp. 149-176). Springer, Cham. doi: 10.1007/978-3-319-64274-1_7

Cipora, K., Schroeder, P., **Soltanlou, M.,** Nuerk, H.-C. (under review). More space, better math: is space a powerful tool or a cornerstone for understanding arithmetic?

Conference presentation

Soltanlou, M., Coldea, A., Artemenko, C., Dresler, T., Fallgatter, A.J., Ehlis, A.-C., Nuerk, H.-C. (2017). Neural representation of lexico-numerical processing in children: An fNIRS study. *Workshop on Linguistic and Cognitive influences on numerical cognition*. September 8-9, Tuebingen: Germany. [Poster]

Heubner, L., Schlenker, M.-L., **Soltanlou, M.,** Cipora, K., Göbel, S.M., Domahs, F., Lipowska, K., Haman, M., Nuerk, H.-C. (2017). Which factors affect response speed in a two-digit number parity judgment task: a cross-lingual study. Part III: Auditory presentation. *Workshop on Linguistic and Cognitive influences on numerical cognition*. September 8-9, Tuebingen: Germany. [Poster]

Schlenker, M.-L., Heubner, L., **Soltanlou, M.,** Cipora, K., Göbel, S.M., Domahs, F., Lipowska, K., Haman, M., Nuerk, H.-C. (2017). Which factors affect response speed in a two-digit number parity judgment task: a cross-lingual study. Part II: Number words. *Workshop* *on Linguistic and Cognitive influences on numerical cognition*. September 8-9, Tuebingen: Germany. [Poster]

Schlenker, M.-L., Heubner, L., **Soltanlou, M.,** Cipora, K., Göbel, S.M., Domahs, F., Lipowska, K., Haman, M., Nuerk, H.-C. (2017). Which factors affect response speed in a two-digit number parity judgment task: a cross-lingual study. Part I: Arabic notation. *Workshop on Linguistic and Cognitive influences on numerical cognition*. September 8-9, Tuebingen: Germany. [Poster]

Smaczny, S., **Soltanlou, M.,** Göbel, S.M., Nuerk, H.-C., Cipora, K. (2017). The parity congruency effect depends on the target: Evidence for automatic place-value processing. *Workshop on Linguistic and Cognitive influences on numerical cognition,* October 8-9, Tuebingen, Germany. [Poster]

Soltanlou, M., Coldea, A., Artemenko, C., Dresler, T., Fallgatter, A.J., Ehlis, A.-C., Nuerk, H.-C. (2017). Neural representation of lexico-numerical processing in children: An fNIRS study. *The 20th Conference of the European Society for Cognitive Psychology (ESCoP)*, September 3-6, Potsdam, Germany. [Poster]

Cipora, K., **Soltanlou, M.,** Reips, U.-D., Nuerk, H.-C. (2017). SNARC and MARC effects – Insights from large-scale online study. *The 17th Biennial EARLI Conference*. August 29-September 2, Tampere, Finland. [talk]

Soltanlou, M., Artemenko, C., Dresler, T., Ehlis, A.-C., Fallgatter, A.J., Nuerk, H.-C. (2017). Math anxiety impairs arithmetic learning in children. *European Workshop on Cognitive Neuropsychology*, January 22-27, Bressanone, Italy. [Short talk and Poster]

Cipora, K., Mihulowicz, U., **Soltanlou, M.,** Reips, U.-D., Nuerk, H.-C. (2017). The SNARC and MARC effects in individuals reporting attentional deficit disorders or learning disabilities. *European Workshop on Cognitive Neuropsychology*, January 22-27, Bressanone, Italy. [Short talk and Poster]

Soltanlou, M., Artemenko, C., Dresler, T., Ehlis, A.-C., Fallgatter, A.J., Nuerk, H.-C. (2016). The neural correlates of arithmetic complexity in children differ from those in adults: An fNIRS study. *The 2016 Biennial Meeting of the Society for functional Near Infrared Spectroscopy*, October 13-16, Paris, France. [Poster]

Cipora, K., **Soltanlou, M.,** Reips, U., Nuerk H.-C. (2016). SNARC and MARC over the Web - a large scale online study. *Workshop "Domain-General and Domain-Specific Foundations of Numerical and Arithmetic Processing"*, September 28-30, Tuebingen, Germany. [Poster]

Akbari, S., Leuthold, H., **Soltanlou, M.,** Sabourimoghddam, H., Babapour, J., Nuerk, H.-C. (2016). The effect of arrangement on enumeration speed and its early and sensory event related brain potentials. *Workshop "Domain-General and Domain-Specific Foundations of Numerical and Arithmetic Processing",* September 28-30, Tuebingen, Germany. [Poster]

Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A.J., Nuerk, H.-C., Ehlis, A.-C. (2016). Neurophysiological changes during arithmetic learning in children. *Workshop "Domain-General and Domain-Specific Foundations of Numerical and Arithmetic Processing"*, September 28-30, Tuebingen, Germany. [Poster]

Sitnikova, M., Artemenko, C., **Soltanlou, M.,** Bahnmueller, J., Dresler, T., Nuerk, H.-C. (2016). Parietal activation during approximate calculation tasks in left- and right-handed students assessed with functional near-infrared spectroscopy (fNIRS). Workshop "Domain-General and Domain-Specific Foundations of Numerical and Arithmetic Processing", September 28-30, Tuebingen, Germany. [Poster]

Nemati, P., Schmid, J., **Soltanlou, M.,** Krimly, J.-T., Nuerk, H.-C., Gawrilow, C. (2016). Contribution of domain-general factors in complex multiplication in adults: Role of planning and self-control. Workshop "Domain-General and Domain-Specific Foundations of Numerical and Arithmetic Processing", September 28-30, Tuebingen, Germany. [Poster]

Soltanlou, M., Artemenko, C., Dresler, T., Ehlis, A.-C., Fallgatter, A. J., Huber S., Nuerk, H.-C. (2016). Children learn arithmetic differently than adults: Evidence from simultaneous fNIRS-EEG study. *2016 Meeting of the EARLI SIG 22 "Neuroscience and Education",* June 23-25, Amsterdam, the Netherlands. [Poster]

Artemenko, C., **Soltanlou, M.,** Ehlis, A.-C., & Nuerk, H.-C., & Dresler, T. (2016). The neural correlates of mental arithmetic in children – A longitudinal fNIRS study. *2016 Meeting of the EARLI SIG 22 "Neuroscience and Education",* June 23-25, Amsterdam, the Netherlands. [Poster]

Soltanlou, M., Artemenko, C., Dresler, T., Ehlis, A.-C., Fallgatter, A. J., Nuerk, H.-C. (2015). The neural correlates of arithmetic in children: An fNIRS study. *4th basic and clinical neuroscience congress,* December 23-25, Tehran, Iran. [Talk]

Artemenko, C., **Soltanlou, M.,** Dresler, T., Ehlis, A.-C., Nuerk, H.-C. (2015). Multiplication in a natural setting – An fNIRS study in children. *Symposium "Neuroeducation of Number Processing"*, October 21-23, Hanover, Germany. [Poster]

Artemenko, C., **Soltanlou, M.,** Dresler, T., Ehlis, A.-C., Nuerk, H.-C. (2015). Neural correlates of the basic arithmetic operations in children – A longitudinal fNIRS study. *Symposium of the LEAD Graduate School "Learning, Educational Achievement, and Life Course Development",* October 14-16, Blaubeuren, Germany. [Poster]

Soltanlou, M., Artemenko, C., Huber, S., Dresler, T., Ehlis, A.-C., Fallgatter, A. J., Nuerk, H.-C. (2015). Learning via on-line learning game; Evidence from arithmetic learning in children. *9th Conference of the Media Psychology Division,* September 9-11, Tuebingen, Germany. [Talk]

Artemenko, C., **Soltanlou, M.,** Dresler, T., Ehlis, A.-C., Nuerk, H.-C. (2015). How high and low performers deal with task difficulty in two-digit mental arithmetic – Evidence from fNIRS. *Symposium of the LEAD Graduate School "Learning, Educational Achievement, and Life Course Development",* April 15-17, Bad Urach, Germany. [Poster]

Artemenko, C., **Soltanlou, M.,** Dresler, T., Ehlis, A.-C., Nuerk, H.-C. (2015). Do high and low math performers differ in the neural correlates of mental arithmetic? – A combined fNIRS-EEG study. *33rd European Workshop on Cognitive Neuropsychology,* January 25-30, Bressanone, Italy. [Short talk and Poster]

Soltanlou, M., Artemenko, C., Huber, S., Dresler, T., Ehlis, A.-C., Fallgatter, A. J., Nuerk, H.-C. (2015). Neurocognitive foundations of interactive arithmetic learning in children: Evidence from fNIRS. *33rd European Workshop on Cognitive Neuropsychology*, January 25-30, Bressanone, Italy. [Poster]

Artemenko, C., Dresler, T., **Soltanlou, M.,** Ehlis, A.-C., Nuerk, H.-C. (2014). The neural correlates of the carry effect in two-digit addition. *Workshop "Educational Neuroscience of Mathematics"*, October 3-4, Tuebingen, Germany. [Poster]

Soltanlou, M., Huber, S., Reips, U.-D., Nuerk, H.-C. (2014). Language Differences in Numerical Processing: Evidence from an On-line Experiment. *12th biannual conference of the German cognitive science society (KogWis 2014),* September 29- October 2, Tuebingen, Germany. [Talk]

Soltanlou, M., Pixner, S., Kaufmann, L., Nuerk, H.-C. (2014). On the development of the multiplication fact network in elementary school children. *2014 Meeting of the EARLI SIG 22 "Neuroscience and Education"*, June 12-14, Goettingen, Germany. [Poster]

Woitscheck, C., Dresler, T., **Soltanlou, M.,** Kaufmann, L., Pixner, S., Moeller, K., Ehlis, A.-C., Nuerk, H.-C. (2014). The borrowing effect in two-digit subtraction: Developmental aspects and neural correlates. *2014 Meeting of the EARLI SIG 22 "Neuroscience and Education"*, June 12-14, Goettingen, Germany. [Poster]

Woitscheck, C., **Soltanlou, M.,** Dresler, T., Ehlis, A.-C., Nuerk, H.-C. (2014). Neurofunctional Foundations of Arithmetic Processes. Symposium of the LEAD Graduate School – Learning, Educational Achievement, and Life Course Development, April 10-12, Freudenstadt, Germany. [Poster]

Soltanlou, M., Nazari, M. A., Nemati, P. (2012). Temporal decision making, *2nd CIN systems retreat*, September 10, Reutlingen, Germany. [Poster]

Soltanlou, M., Anbara, T., Taghizadeh, G., Rahimzadeh Rahbar,S., Karimi, H. (2011). Cognitive deficit is associated with functional balance in right adult stroke patients, *4th international conference of cognitive science*, May 10-12, Tehran, Iran. [Poster]

Soltanlou, M., Tehrani Dost, M., Olyaei, G.R., Abdolvahab, M., Bagheri, H., Faghihzadeh, S. (2009). Spatial planning in spastic diplegic cerebral palsy, *14th congress of Iranian occupational therapy*, November 10-11, Tehran, Iran. [Talk]

Soltanlou, M., Tehrani Dost, M. (2009). Executive dysfunction theory in autism, *14th congress of Iranian occupational therapy*, November 10-11, Tehran, Iran. [Talk]

Soltanlou, M., Anbara, T., Taghizadeh, G., Rahimzadeh Rahbar, S., Karimi, H. (2009). Cognitive deficit is associated with functional balance in right adult stroke patients, *14th congress of Iranian occupational therapy*, November 10-11, Tehran, Iran. [Talk]

Soltanlou, M., Tehrani Dost, M., Olyaei, G., Abdolvahab, M., Bagheri, H., Faghihzadeh, S. (2009). Executive dysfunctions in spastic bilateral cerebral palsy, *3rd international conference of cognitive sciences*, March 3-5, Tehran, Iran. [Poster]

Soltanlou, M., Tehrani Dost, M., Olyaei, G., Abdolvahab, M. (2008). Prefrontal cortex, *13th national congress of occupational therapy*, May 27-28, Tehran, Iran. [Poster]

Soltanlou, M. (2006). FM systems, *10th national congress of audiology*, November 20, Tehran, Iran. [Talk]

Soltanlou, M., Taghavi, S. (2004). Sensory integration theory in pervasive developmental disorders, *5th congress of occupational therapy*, May 25, Tehran, Iran. [Talk]

Workshop, Seminar, and Summer School

2nd Summer School on Internet-based Data Collection and Analysis in Decision Making 2017, University of Konstanz, September 11-15, Konstanz, Germany.

Head of organization team of Workshop on Linguistic and Cognitive influences on numerical cognition, University of Tuebingen, September 8-9, 2017, Tuebingen, Germany.

Head of organization team of Workshop on Domain-General and Domain-Specific Foundation of Numerical and Arithmetic Processing, University of Tuebingen, September 28-30, 2016, Tuebingen, Germany.

A member of organization team of Workshop on Neuroeducation of Number Processing, October 21-23, 2015, Hanover, Germany.

A member of organization team of Workshop on Educational Neuroscience of Mathematics, University of Tuebingen, October 3-4, 2014, Tuebingen, Germany.

A member of organization team of Workshop on Development of Numerical Processing and Language, University of Tuebingen, October 7-8, 2013, Tuebingen, Germany.

TIMELY Workshop “Temporal Processing Within and Across Senses”, University of Tuebingen, October 4-5, 2012, Tuebingen, Germany.

C++, *Academic center of education, culture and research*, November, 2011, Tehran, Iran.

Quantitative EEG: measurements and analyses, *Institute of Cognitive Science Study*, July 12-14, 2011, Tehran, Iran.

Human EEG: measurements and analyses in cognitive tasks, *4th international conference of cognitive science*, May 10-12, 2011, Tehran, Iran.

FSL training workshop for fMRI data analysis, *Research Centre for Science and Technology in Medicine*, February 21-22, 2010, Tehran, Iran.

MATLAB, *Hubbell premise wiring*, April, 2009, Tehran, Iran.

Color vision, *3rd international conference of cognitive science*, March 3-5, 2009, Tehran, Iran.

Basic of structural and functional neuroimaging studies in cognitive science, *3rd international conference of cognitive science*, March 3-5, 2009, Tehran, Iran.

Head of organization team, *5th scholar congress of occupational therapy*, May 25, 2004, Tehran, Iran.

Teaching experience

Summer term 2017	Language-related effects on number processing
Summer term 2017	Neural and behavioural correlates of learning disorders
Winter term 2017-18	Linguistic, cognitive, and affective determinants of number processing
Winter term 2017-18	Neural and behavioural correlates of learning disorders

Co-supervisor of student thesis

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Jennifer Them	Uni. of Tuebingen, BSc in cognitive science, Apr-Nov 2016
Annalena Kukofka	Uni. of Tuebingen, BSc in psychology, Apr-Sep 2015
Franziska Schumacher	Uni. of Tuebingen, BSc in psychology, Apr-Sep 2015
Anne Kathrin Buesemeyer	Uni. of Innsbruck, Internship in psychology, Jun-Sep 2015
Andra Coldea	Uni. of Glasgow, Internship in psychology, Jun-Sep 2015
Eva Herzog	Uni. of Tuebingen, MSc project in psychology, Oct 2014-Mar2015

Stefania Macchione	Uni. of Padua, MSc in clinical psychology, Apr-Sep 2014
Franziska Hegger	Uni. of Tuebingen, BSc in psychology, Apr-Sep 2014
Amanda Lillywhite	Uni. of Glasgow, Internship in psychology, Apr-Sep 2013

Professional memberships

2016-present	Member of society of functional near-infrared spectroscopy (sfNIRS)
2015-2016	Member of society for neuroscience (SfN)
2006-2011	Member of Iran medical council
2003-2011	Member of Iranian society for occupational therapy

Computer and imaging skills

Presentation software (Neurobehavioral system), Open Sesame, Psychopy, SPSS, R studio, JASP, jamovi, Brainstorm, EEGLab, Psytask, Online Survey, Microsoft office, MATLAB [Basic], SPM [Basic]

fNIRS (functional Near-Infrared Spectroscopy), EEG (Electroencephalography), Physiological measures (Skin Conductance, heart rate)

Career experiences

2015-present	Research assistant at Diagnostics and cognitive neuropsychology, University of Tuebingen, Tuebingen, Germany
2013-15	Research assistant at Knowledge Media Research Center (KMRC), Tuebingen, Germany
2012-13	Research assistant at Medical Psychology and Behavioural Neurobiology, University of Tuebingen, Tuebingen, Germany
2011-12	Research assistant at Cognitive Neuroscience Lab, University of Tabriz, Tabriz, Iran
2008-12	Supervisor of occupational therapy unit, Beautiful Mind Paediatric Rehabilitation Clinic, Tehran, Iran
2007-08	Therapist, EEG neurofeedback unit, psychiatric clinic, Tehran, Iran
2006-09	Supervisor of occupational therapy unit, Azadi Neuropsychiatry Hospital, Tehran, Iran

Language skills

Persian: Mother tongue

English: Fluent

German: Intermediate

Turkish: Basic

Arabic: Basic

References

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