

available at www.sciencedirect.comwww.elsevier.com/locate/brainres**BRAIN
RESEARCH****Research Report****Oscillatory EEG correlates of an implicit activation of multiplication facts in the number bisection task****Korbinian Moeller^{a,c,*}, Guilherme Wood^{b,c}, Michael Doppelmayr^{b,c}, Hans-Christoph Nuerk^{a,c}**^a*Institute of Psychology, Eberhard Karls University, Tuebingen, Germany*^b*Department of Psychology, Paris Lodron University Salzburg, Austria*^c*Center for Neurocognitive Research, University of Salzburg, Austria*

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ABSTRACT

Neuroimaging evidence points towards the left inferior parietal cortex to be crucial for the representation and retrieval of multiplication facts. However, to date studies allowing a functional interpretation of neuroimaging data are still scarce. In the current study we aimed at evaluating the functional involvement of left inferior parietal cortex areas in the implicit retrieval of multiplication fact knowledge in a number bisection task by examining event-related desynchronization (ERD) in the upper alpha band. Upper alpha ERD is generally agreed to be modulated by processes of memory retrieval. It was observed that upper alpha ERD decreased for multiplicative triplets (e.g. 3_6_9) but not for non-multiplicative (e.g. 2_5_8) triplets at left parietal electrodes but increased at left prefrontal electrodes. These results are interpreted to suggest that after multiplicativity has been recognized further magnitude evaluations in the left hemisphere may be abated by prefrontal processes of executive control.

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1. Introduction

Living at the beginning of the 21st century requires being numerate. Being able to differentiate the numerical size of 4 from that of 7 and to reflect about this conscious experience together with the ability of counting makes such mental representations of numbers exclusively human (Nieder, 2005). At least such a basic “number sense” (cf. Dehaene, 1997) is inevitable in everyday life. In fact, Bynner and Parsons (1997) found poor numeracy to hinder educational as well as job opportunities more severely than poor literacy.

However, although number magnitude and parity are the most salient numerical properties (e.g., Shepard et al., 1975), the human understanding of numbers is not limited to the

conscious experience of such attributes alone. Several other specific characteristics of the mental representation of numbers have been observed to determine performance in numerical tasks. For instance, it was found that different cognitive solution strategies employed in the same basic arithmetical task are driven by numerical features of the problem at hand (e.g., Klein et al., 2009; LeFevre et al., 1996). In particular, an exact whole-calculation strategy was distinguished from an approximate-calculation strategy in an arithmetic inequality verification task (El Yagoubi et al., 2003). Moreover, the fact that e.g., addition problems requiring a carry operation are generally more difficult than problems not requiring a carry (e.g., Deschuyteneer et al., 2005; Kong et al., 2005) indicates a crucial involvement of the place-value

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base-10 structure of the Arabic number system (see also Domahs et al., 2006, 2007; Verguts and Fias, 2005 for place-value effects in multiplication). However, not only influences of external attributes such as the place-value structure were observed. Also structural attributes of the mental representation of specific numerical knowledge, such as the multiplication facts, have been shown to affect performance in mental arithmetic (e.g., a dominance of table-related errors, e.g., Campbell and Graham, 1985; Domahs et al., 2007; Lochy et al., 2000; Verguts and Fias, 2005) as well as in more basic numeric tasks such as the Number Bisection Task (NBT; Nuerk et al., 2002).

1.1. Multiplication fact knowledge in the NBT

Although originally assumed to exclusively assess the magnitude representation of numbers (cf. Dehaene and Cohen, 1997), performance in the NBT reflects an interplay of different numerical representations including number magnitude but also parity and base-10 information as well as multiplication fact knowledge (Nuerk et al., 2002). In the verification version of the NBT participants are asked to classify a number triplet to be either correctly bisected or not by evaluating whether the central number of a triplet also is the arithmetic mean of the two outer numbers (e.g., 3_5_7) or not (e.g., 2_5_7). Nuerk et al. (2002) observed that among correctly bisected triplets those part of a multiplication table (e.g., 21_24_27) were associated with shorter latencies and fewer errors as compared to triplets that were multiplicatively unrelated (e.g., 22_26_29). Thus, recognition of a triplet being correctly bisected was easier for multiplicative related triplets than for unrelated triplets (see also Delazer et al., 2006; Korvorst et al., 2007; Moeller et al., 2009; Wood et al., 2008). Following the most prominent model of number processing, the so-called Triple Code Model (Dehaene and Cohen, 1995, 1997; see also Dehaene et al., 2003), above dissociation is due to a difference in the use of representational codes. On the one hand, the actual status of the central number in a non-multiplicative triplet (e.g., 22_26_29) has to be evaluated via magnitude manipulations involving calculation procedures. On the other hand, multiplication tables are supposed to be represented as verbally stored and accessed arithmetic facts (Dehaene et al., 2003, for a review). Thus, in a multiplicative related triplet (e.g., 21_24_27) time-consuming calculation procedures can be bypassed by activating and retrieving the corresponding multiplication table which in turn facilitates performance in the NBT. This interpretation is illustrated best by the single case study of Delazer et al. (2006) investigating spared numerical abilities in a case of posterior cortical atrophy. While patient HR did not show any effects related to number magnitude in a verification version of the NBT, he nevertheless exhibited standard multiplicativity effect. This suggested that multiplication fact knowledge and number magnitude are represented distinctly.

Only recently Wood et al. (2008) examined the neural correlates of multiplicativity in the NBT. The authors observed that relative to multiplicative triplets, non-multiplicative triplets elicited stronger activation within a fronto-parietal network involving large portions of the dorsolateral prefrontal cortex as well as the intraparietal sulcus, bilaterally. This activation pattern is in line with earlier results associating the

intraparietal cortex with magnitude manipulations and calculation procedures (see Dehaene et al., 2003 for a review), while prefrontal cortex areas have been linked to instrumental and attentional aspects of mental calculation (Ansari et al., 2006; Kong et al., 2005). For multiplicative triplets a very different pattern of activation was observed: specific activation of the left angular gyrus as well as the left superior frontal gyrus. While activation within the left angular gyrus has previously been associated with the retrieval of multiplication facts (Delazer et al., 2003; Lee, 2000; see Dehaene et al., 2003, for a review), neural activity within the left superior frontal gyrus has been attributed to the monitoring of different sources of relevant information (Brass and von Cramon, 2004). Since magnitude-based computations represent the default strategy for solving the NBT, a lack of activation in intraparietal cortex areas for multiplicative triplets may imply that such magnitude-based computations might be reduced after multiplicative relatedness of the three numbers constituting a triplet is recognized. On a broader level, these findings may suggest some kind of interplay between the left angular gyrus and the intraparietal cortex to be vital for an efficient use of multiplicativity information in the NBT (see also Grabner et al., 2009, for retrieval-related contributions of the left angular gyrus in arithmetic problem solving).

Taken together the study of Wood et al. (2008) pointed to a fronto-parietal network subserving the required magnitude manipulations in the NBT. Within this network number magnitude representation is mainly associated with the intraparietal sulcus, bilaterally, whereas instrumental and attentional aspects of mental calculation were correlated with prefrontal cortex areas. On the other hand, multiplicativity was mainly associated with activation in the left angular gyrus (Wood et al., 2008).

However, unfortunately brain activation patterns as identified by fMRI do mainly provide information about the localisation of brain areas involved or not involved in performing a certain task. As the temporal resolution of the bold signal is not very high little is still known about the time course of frontal and parietal processing and their interactions. At this point the electroencephalography (EEG) is of interest. (i) It allows for a better evaluation of temporal aspects. (ii) It is widely agreed that especially alpha oscillation is modulated by memory retrieval processes: alpha desynchronizes and its power decreases with increasing retrieval demands, hence, Event-related Desynchronization (ERD) reflects power modulations in the EEG (see Klimesch, 1999; Klimesch et al., 2005 for reviews). Therefore, EEG data and in particular the evaluation of ERD of the upper alpha band may provide converging evidence for an elaborate functional interpretation of neural activation in prefrontal and parietal cortex in numerical cognition. Additionally, even the less accurate temporal resolution of ERD as compared to event-related potentials can offer first evidence regarding the cycle of prefrontal and parietal processing in numerical cognition. In a previous study, Harmony et al. (1999) observed decreased power of the upper alpha band at left parietal electrodes in mental calculation (see also Earle, 1985). The authors interpreted this finding as indicating access to and retrieval from long-term memory representations of procedural rules associated with specific computations as well as of arithmetic facts. Moreover, many studies investigating electrophysiological correlates of mental multiplication

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