TYPICAL AND ATYPICAL DEVELOPMENT OF MAGNITUDE PROCESSING

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Summary

of the Ph.D. Thesis

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Background

In this thesis my aim is to introduce and discuss the literature of numerical cognition, with an emphasis on *typical and atypical development of arithmetic abilities*. Based on some unresolved issues and hot debates in the literature, an event-related potential (ERP; extended with principal component analysis [PCA]) and behavioural study will investigate the cognitive factors behind the atypical development of numerical abilities. Magnitude representation, among several other abilities (spatial- and body representations, working memory, IQ, executive functions) will be tested (developmental dyscalculia, chapter III).

Another behavioural study will look into the debated nature of the co-development and interdependency of magnitude representation, memory and counting knowledge in kindergarten children (chapter IV).

Two further studies will explore the development of magnitude representation: the interaction of numerical and physical magnitudes will be tested in an ERP and behavioural experiment, considering the role of attentional and executive functioning as well (chapter V; extended with an adult PCA study: chapter VI); and the speed and automaticity of accessing numerical representations will also be examined in children, with ERP and behavioural measures (chapter VII).

The results will be discussed in light of the importance of considering a broader range of basic cognitive abilities in the research of numerical abilities. Basic skills like executive functioning, working memory, and inhibition of prepotent and incorrect responses seem to be highly relevant in both typical and atypical numerical development. In my opinion, arithmetic abilities are by far more complex than it could be explained by one single cognitive module. This supposed module, the *core analogue magnitude representation* may provide a good basis for the understanding of relative and approximate magnitudes, but this is yet far away from the problems children have to cope with in school. Rather, the *network* of co-developmental routes and interactions of several basic and specific abilities have to be considered and examined in more detail during the research of numerical development and developmental dyscalculia.

I. Magnitude representation – is it a module?

By most researchers in the field of numerical cognition, number representation is assumed to be domain specific, innate, neurally hardwired, and accessed in a fast and automatic fashion (for an overview, see Dehaene et al., 1998; or Cantlon et al., 2008). These attributes are exactly the proposed attributes of a cognitive module. In this chapter, I review the literature of magnitude representation in the light of cognitive modularity. For the organization of this chapter, I will use Coltheart's (1999) definition of cognitive module. Results of behavioural and neuro-cognitive, developmental and comparative studies will be introduced under the appropriate sections. Both pros and contras for the modular assumption of numerical processing are discussed. The empirical studies in the present thesis will build on some hypotheses, unresolved questions of this review chapter.

1. Properties of a cognitive module

The term *modularity* refers to the concept (or to the principle) that cognition can be split into a collection of small, independent and specialized subprocesses (Marr, 1982). These subprocesses, or *modules* are considered to be isolated from each other and supposed to be highly specialized to one task.

The concept of modularity is central to cognitive science. In his milestone book, Fodor (1983) further elaborated the attributes and properties of a cognitive module. However, although widely used, Fodor's definition of the cognitive module is mostly misinterpreted according to Coltheart (1999). Fodor's description of a cognitive module does not imply that the possession of one or the other property were a necessary condition for a system to be a module. Rather, according to Coltheart, neither of the following attributes is necessary or sufficient for the definition of a cognitive module; rather, these are only properties, and not crucial conditions of a cognitive module. These attributes, or properties, are the following:

(1) Domain specificity

(2) Innateness

(3) Informationally encapsulated

(4) Hardwired (specific neural networks are responsible for the function)

(5) Not assembled (from other cognitive subcomponents)

(6) Automatic, and

(7) Fast (in terms of processing and speed of access)

2. The most widely accepted neuro-cognitive model of magnitude representation: analogue magnitude representation

The most widely accepted cognitive model of number representation is the so-called 'triple code model' (Dehaene and Cohen, 1995; Dehaene et al., 1998). In this model, number representation is considered to function as an evolutionary inherited, highly specialized cognitive module. Other models of number representation (e.g. McCloskey, 1992; Campbell and Clark, 1988: complex coding model; Noel and Seron, 1992: preffered code model) are not explicitly claimed to be modular. However, these models could be also viewed as highly domain-specific and modular in practice. *Domain-specific*, because neither of these models are stated or assumed to be valid for other domains of cognition. For example, no one intends to explain language processing by a cognitive model of magnitude representation, or vice versa. And *modular*, because the content and function of these models are described as separate 'boxes of cognition'.

The 'triple code model' consists of three brain circuits which are responsible for the three different functions contributing to number representation. The first system is called the 'analogue magnitude representation' or the 'the core quantity system', hosted in the horizontal intraparietal sulcus (brain imaging (Dehaene and Cohen, 1997; Dehaene et al., 1999; Eger et al., 2003; Pinel et al., 2001; Simon et al., 2002; for a review, see Dehaene et al., 2003) and lesion studies (e.g. Cipolotti et al., 1991)). Approximation and comparison of numerical magnitudes are supported by this core quantity system. The *analogue magnitude representation* is complemented by two other systems, if the situation requires. The left gyrus angularis and the perisylvian areas host the verbal system which is responsible for calculations executed in verbal form (e.g. overlearnt multiplications, verbal problems). The verbal system also contributes to exact calculations (Spelke and Tsivkin, 2001). The bilateral posterior superior parietal areas play a role in the orientation of spatial attention, indispensable for instance in number comparison, subtraction, or during reading and writing numbers with more place values (Grossberg and Repin, 2003).

3. Magnitude representation – modul, or network?

As it has been discussed in chapter I, it is a commonly held view that the representation of magnitudes is a neuro-cognitive module (e.g. Dehaene and Cohen, 1995, 1997); it is *innate*, *domain specific*, *hardwired*, *informationally encapsulated* and the access to it is *fast* and *automatic*. It is supposed to be innate, as several studies with animals and human infants have concluded. Both animals and non-verbal infants are able to discriminate approximate magnitudes based on their numerosity, moreover, their discrimination abilities obey the same regularities (the ratio effect and Weber's law; e.g. Xu and Spelke, 2000; Cantlon and Brannon, 2007). The horizontal part of the intraparietal sulcus (IPS) has been found to be activated during magnitude- and number tasks, in several experiments – so forth the IPS is the proposed host for the representation of numerical magnitudes in the brain (Dehaene et al., 2003). Number representation was also found to be isolated from other representations: adults who suffered brain damage to the parietal cortex showed deficiencies in their numerical abilities, while their other high-level cognitive functions remained intact (Dehaene and Cohen, 1995). Fast and automatic access to the numerical representation has also been proved – the effect of numerical distance exerts its effect already at around 200 ms both in children and in adults (ERP studies; Grune et al., 1993; Dehaene, 1996; Szűcs, Soltész et al, 2007; chapter V and chapter VI).

However, there are of course studies which rather confute the modular nature of numerical cognition (see chapter I). In sum, after the review of the literature I would suggest to conclude that the supposedly modular magnitude representation is not straight away hand in hand with numerical abilities; there is rather a large and complex network of different abilities, including the analogue magnitude representation as well, which support the acquisition of counting and mathematics.

Regarding magnitude representation, it seems to be more like a general tool or measure for all kinds of perceptual and analogue magnitudes which are covariates of numbers among natural circumstances (e.g. sum surface area). This basic ability to discriminate continuous magnitudes may serve as a departure point for the understanding of concepts like ‘more’ and ‘less’, ‘add’ and ‘take away’, which are part of later arithmetics.

II. Developmental dyscalculia[1]

Having the modular theory as a departure point, pro and contra behavioural and brain imaging evidence are reviewed. Theories of domain-general deficits are also introduced. Second, a re-analysis of my previous ERP data (Soltész, 2004, Soltész et al., 2007) complemented with neuropsychological measurements and with a temporal principal component analysis is included (Soltész and Szűcs, 2009). Third, the present findings are discussed in light of the theories presuming the impairments of more general cognitive abilities behind developmental dyscalculia and mathematical learning deficits.

1. A combined event-related potential and neuropsychological investigation of developmental dyscalculia

Adolescents with developmental dyscalculia (DD) but with no other impairments were examined with neuropsychological tests and with event-related brain potentials (ERPs). A matched control group and an adult control group were tested as well. Behavioural and ERP markers of the magnitude representation were examined in a task where subjects decided whether visually presented Arabic digits were smaller or larger than 5. There was a normal behavioural numerical distance effect (better performance for digits closer to the reference number than for digits further away from it) in DD (see Figure 1).

[1] Published: Soltész et al. (2007), Neuroscience Letters, and Soltész and Szűcs, (2009), Cognitive Development

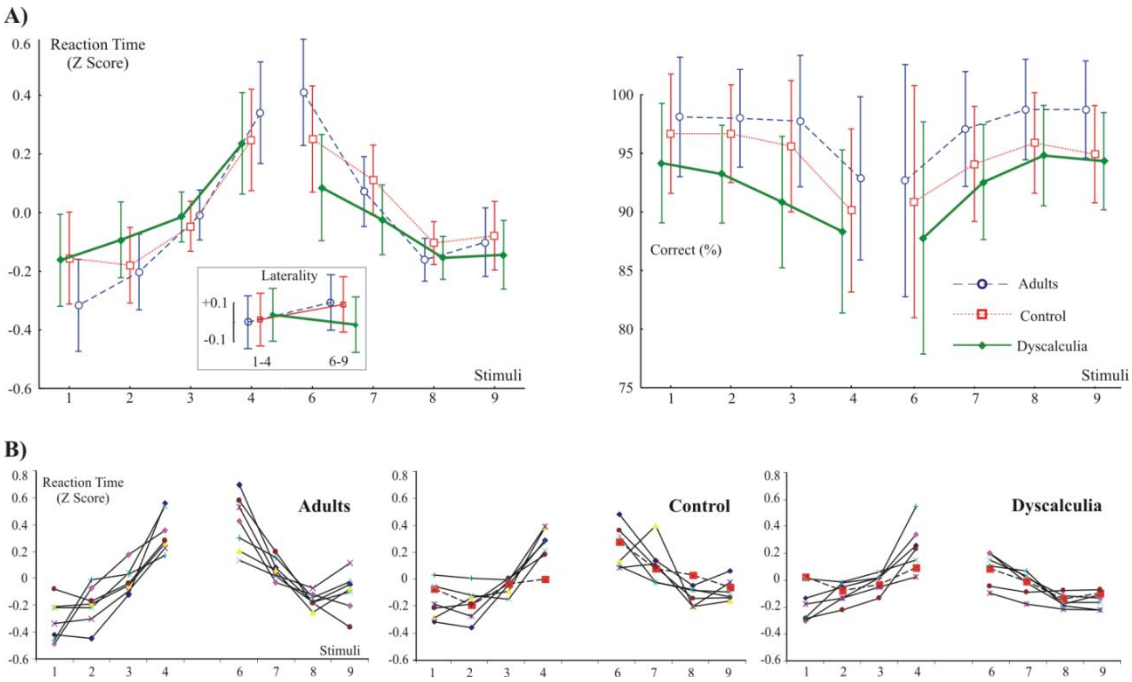

Figure 1: A: The Distance Effect in the normalised RTs (Z Scores) and in the proportion if corerct answers (%) in all 3 groups. Insertion: the Laterality Effect on the normalised RTs. B: The patterns of the individual Distance Effects Effect in the normalised RTs (Z Scores) in all 3 groups. Individual data marked by dotted line didn't reach significance.

This suggests that semantic magnitude relations depend on a phenomenologically (nearly) normal magnitude representation in DD, at least in the range of single-digit numbers. However, minor discrepancies between DD subjects and controls suggest that the perception of the magnitude of single digits may be slightly differed in DD. Early ERP distance effects were similar in DD and in control subjects. In contrast, between 400-440 ms there was a focused right-parietal ERP distance effect in controls, but not in DD (see Figure 2).

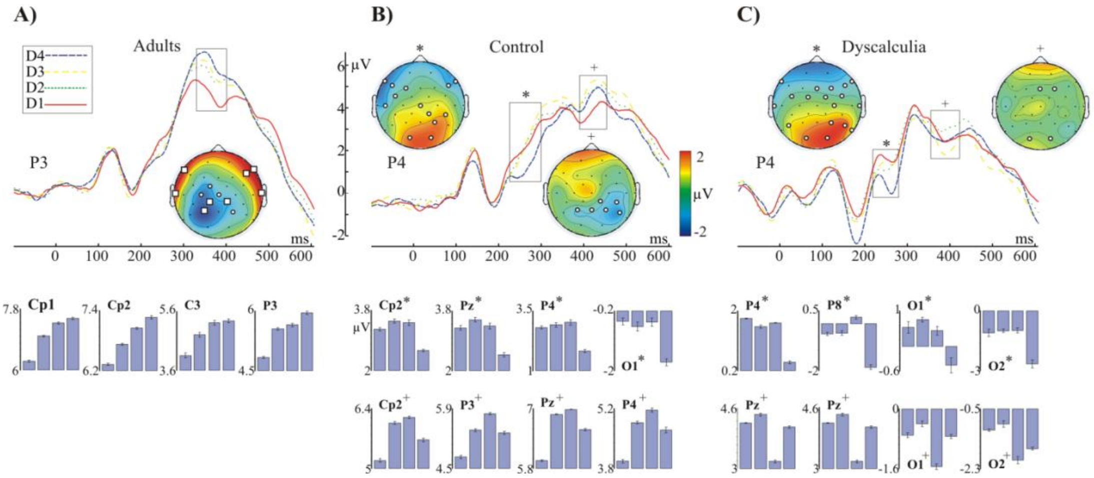

Figure 2: The raw waves and the topographies of the Distance Effect. Topographies were constructed from de difference between DS and DB. Electrodes with partial Distance Effect are marked by circles. Electrodes with fully graded DE are marked by squares. Point-to-point ANOVA was significant ($p<0.025$) over these time intervals: A: Adults: 300-400 ms. B: Control: * 240-300 ms and $^{+}$ 400-440 ms. C: Dyscalculia: * 210-300 ms and $^{+}$ 330-430 ms.

This suggests that early, more automatic processing of digits was similar in both groups, and between-group processing differences arose later, during more complex controlled processing. This view is supported by signs of decelerated executive functioning in developmental dyscalculia. Further, DD subjects did not differ from controls in general mental rotation and in body parts knowledge, but were markedly impaired in mental finger rotation, finger knowledge, and tactile performance.

2. An electro-physiological temporal principal component analysis of processing stages in number comparison and developmental dyscalculia

By a re-analysis of a previous event-related brain potential (ERP) data here my objective was to identify and compare cognitive processes in adolescents with DD and in matched control participants during one-digit number comparison. To this end temporal principal component analysis (tPCA) was performed on ERP data. First, tPCA has identified four major components explaining the 85.8% of the variance in number comparison. Second, the ERP correlate of the most frequently used marker of the so-called magnitude representation, the numerical distance effect, was intact in DD during all processing stages identified by PCA (Figure 3). Third, hemispheric differences in the first temporal component and group differences in the second temporal component suggest executive control differences between DD and controls.

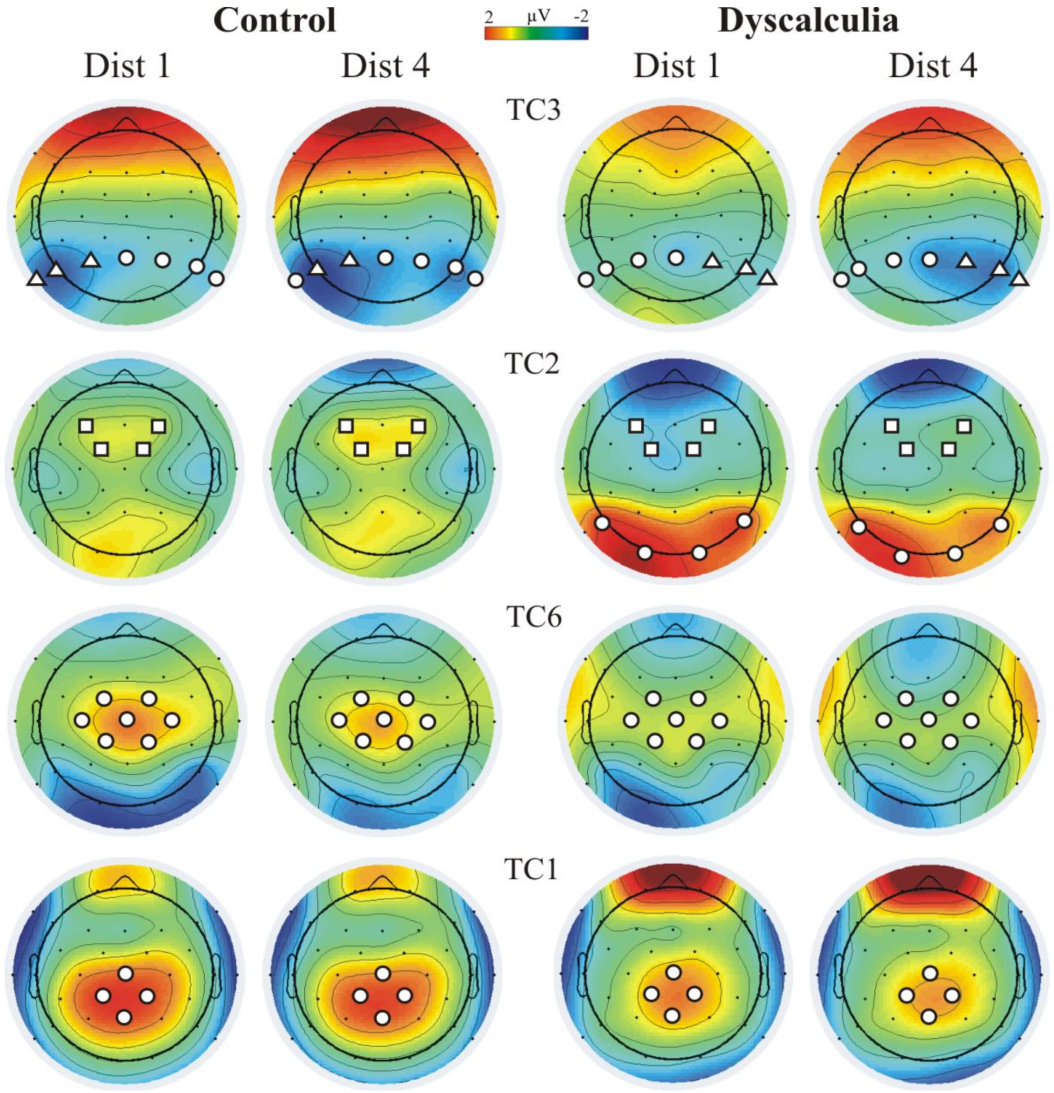

Figure 3: Component scores for TC3, TC2, TC6 and TC1. The represented values are in untits of microvolts. TC3: markers denote electrodes with significant DE. Triangle markers show the significant hemispheric differences. TC2: circle markers denote significant DEs. Square markers denote group differences in polarity, where DE was also significant. TC6. Markers denote significant DE. TC1: markers denote electrodes at wich DE was significant.

III. Magnitude representation in children – what counts?[2]

There is a debate in the developmental literature whether the analogue magnitude representation preempts and predicts counting (and later arithmetic) abilities (e.g. Halberda et al., 2008; Butterworth, 1992) or it is rather the other way around: learning to count helps children in the understanding of the abstract nature of numbers, and to understand that numbers are independent of other perceptual magnitudes (e.g. Brannon and van de Walle, 2001; Mix et al., 1999). May seem as a theoretical question, it is indeed highly practical and has considerable consequences on how counting and mathematics could and should be taught.

1. The co-development of magnitude discrimination and counting in preschool children

4-7-year-old kindergarten children participated in this study investigating the relationship between the development of the magnitude representation, knowledge of number symbols, counting, arithmetic fact retrieval, verbal skills, and numerical and verbal short term memory. The magnitude representation was tested by a non-symbolic numerical Stroop task. Performance on the discrimination task was compared to numerous verbal measures. 4-year-old children, who did not yet possess verbal numerical abilities at a ground level, were unable to discriminate number independently from task-irrelevant perceptual variables. In contrast, 5-7 year old children successfully discriminated number and their performance was compatible with the analogue magnitude representation theory. Number discrimination and verbal skills did not correlate at the level of the whole sample; however, verbal counting knowledge of a group of children with minimal counting knowledge correlated with number discrimination skills when quantities were hard to distinguish (ratio of 2:3). In agreement with the *verbal account* of numerical development, I conclude that verbal knowledge about numbers helps the understanding of the abstract nature of numbers and provides basis for the transition from approximate magnitudes to the recognition of exact and discrete numerosities.

[2] This chapter, in a somewhat different form, has been reviewed, revised and waiting for editorial decision at Behavioral and Brain Functions.

Sensitivity to irrelevant features of the task are affected by age and memory, suggesting more general cognitive abilities also play an important part in Stroop-like magnitude comparison.

IV. Interference between physical and numerical magnitudes: The speed and automaticity of number processing[3]

1. The interaction of physical size and numerical magnitude in children and in adults

In chapter V, the development and interactions of magnitude and number representation were examined in a numerical Stroop paradigm, where task-irrelevant physical size and task-relevant numerical size was manipulated in an orthogonal fashion. Behavioural and ERP results confirmed that grade 1-3 children represent numerical magnitudes in a similar manner to adults; *numerical distance* exerted its effects at around 170 ms after stimulus presentation in adults and at around 200 ms in children (Figure 4).

[3] These studies are submitted: Soltész et al, Developmental Neuropsychology and Soltész et al, Learning and Individual Differences

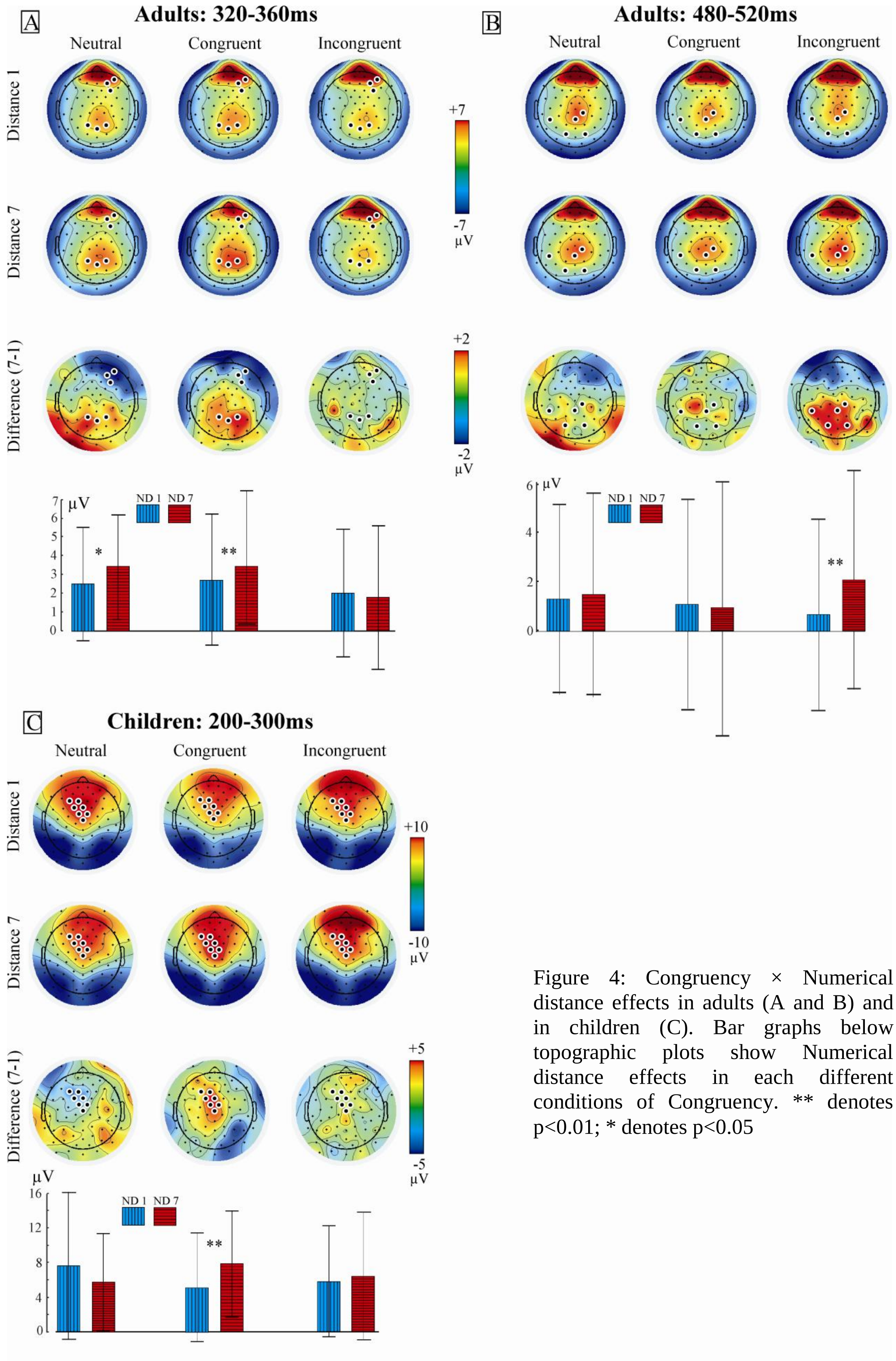

Figure 4: Congruency × Numerical distance effects in adults (A and B) and in children (C). Bar graphs below topographic plots show Numerical distance effects in each different conditions of Congruency. ** denotes p<0.01; * denotes p<0.05

This is in line with previous studies (e.g. Temple and Posner, 1998; Szűcs, Soltész et al., 2007) and suggests a *fast access* to the representation of numerical magnitudes. The slower and more error-prone responses of children are due to the stronger susceptibility to *interference* from irrelevant information, arising from the weaker executive and inhibition abilities. Stronger interference effects in children were found by both behavioural and ERP measures.

Furthermore, as an explorative methodological extension for this study, a spatiotemporal principal component analysis was performed on adults' data. PCA disentangled at least two separate *latent components* behind facilitation and interference effects in adults. This is an interesting and promising finding with regard to the complexity of Stroop tasks.

2. The automaticity and speed of numerical processing in children

The study presented in chapter VI was carried out in order to investigate the *speed* and *automaticity* of the access to numerical representations in young children. This is an interesting issue because a fast and accurate link between symbolic numerals (Arabic digits in the present case) and their referents, numerical magnitudes is inevitable for the learning of arithmetics. The efficiency of the matching of these symbols with their meanings in memory was found to be predictive for school performance during the earliest years of school (Holloway and Ansari, 2009) and was also found to be relevant in developmental dyscalculia (Rouselle and Noël, 2007).

Using the physical version of the numerical Stroop paradigm, it was found that grade 1 children already process the meaning of and relations between Arabic numerals *involuntarily*. Furthermore, numerical meaning not only interfered with, but also modulated physical judgements in function of the symbolic *numerical distance.* This finding leads to the conclusion that not only a crude evaluation of the relation of numerical magnitudes, but a refined comparison occurs in a fast and automatic fashion in children.

Interference from the irrelevant numerical information was in fact the strongest in the youngest group (grade 1) and weakened by age. This suggests that the *automatic* processing of numerical symbols is very fast and unavoidable and that, even being a little counterintuitive (and also contradicts to Piaget's theory), numerical magnitudes are just as salient for young children as physical/perceptual magnitudes are. The strong interference effects in grade 1 children also suggest that *inhibitory functions* are weaker in younger children and develop year by year.

In parallel with the decreasing interference across grades, the size of the ERP interference effect correlated with the size of the interference effect in behaviour in grade 1 (Figure 5). This correlation weakened and lost its significance with age. This finding may also reflect the emphasized role of attention and inhibitory functions at younger ages. Besides the development of inhibitory abilities, automatic number processing got also faster with age. In accord with this growing automaticity, the size of the numerical distance effect in ERP predicted behaviour.

As for a technical note at the end, measuring the size of experimental effects in ERP was proven to be promising for the linking of ERP signatures and behaviour; in the future, ERP measurements may be able to track and *predict* the development of cognitive abilities in children.

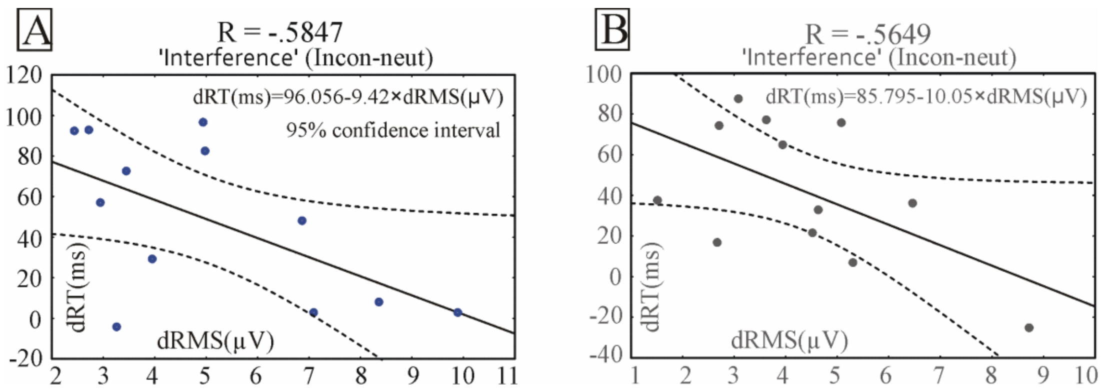

Figure 5: Correlation of 'interference' effects between ERPs and behaviour in Grade 1 (A) and in Grade 2 (B) (n.s.). X-axis: difference of RMS between incongruent and neutral conditions. Y-axis: difference of RT between incongruent and neutral conditions.

Conclusion

To sum up, I think it is oversimplifying to attribute all the relevance to the *analogue magnitude representation* in the (typical and atypical) development of numerical cognition. In fact, many researchers in the field of cognitive neuroscience disregard the importance of many other abilities necessary for numerical development. Basic skills like executive functioning, working memory, and inhibition of prepotent and incorrect responses seem to be highly relevant in both typical and atypical numerical development. In my opinion, arithmetic abilities are by far more complex than it could be explained by one single cognitive module. This supposed module, the *core analogue magnitude representation* may provide a good basis for the understanding of relative and approximate magnitudes, but this is yet far away from the problems children have to cope with in school. Rather, the *network* of co-developmental routes and interactions of several basic and specific abilities have to be considered and examined in more detail during the research of numerical development and developmental dyscalculia. *Cognitive neuroscience* and *educational research* have also to be moved closer to each other in this matter.

Related, first-authored publications

Soltész, F., & Szűcs, D. (2009). An electro-physiological temporal principal component analysis of processing stages of number comparison in developmental dyscalculia. Cognitive Development, 24(4), 473-485.

Soltész, F., Szűcs, D., Dékány, J., Márkus, A., & Csépe, V. (2007). A combined event-related potential and neuropsychological investigation of developmental dyscalculia. Neuroscience Letters, 417(2), 181-6.

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Soltész, F., Goswami, U., White, S., Szűcs, D. (submitted). Executive function effects on numerical development in children: Behavioural and ERP evidence from a numerical Stroop paradigm. Learning and Individual Differences.

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