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Research report

An electrophysiological investigation of non-symbolic magnitude processing: Numerical distance effects in children with and without mathematical learning disabilities

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ABSTRACT

Introduction: The aim of the present study was to probe electrophysiological effects of non-symbolic numerical processing in 20 children with mathematical learning disabilities (mean age = 99.2 months) compared to a group of 20 typically developing matched controls (mean age = 98.4 months).

Methods: EEG data were obtained while children were tested with a standard non-symbolic numerical comparison paradigm that allowed us to investigate the effects of numerical distance manipulations for different set sizes, i.e., the classical subitizing, counting and estimation ranges. Effects of numerical distance manipulations on event-related potential (ERP) amplitudes as well as activation patterns of underlying current sources were analyzed.

Results: In typically developing children, the amplitudes of a late parietal positive-going ERP component showed systematic numerical distance effects that did not depend on set size. For the group of children with mathematical learning disabilities, ERP distance effects were found only for stimuli within the subitizing range. Current source density analysis of distance-related group effects suggested that areas in right inferior parietal regions are involved in the generation of the parietal ERP amplitude differences.

Conclusion: Our results suggest that right inferior parietal regions are recruited differentially by controls compared to children with mathematical learning disabilities in response to non-symbolic numerical magnitude processing tasks, but only for stimuli with set sizes that exceed the subitizing range.

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1. Introduction

With a prevalence rate of around 7% (Gross-Tsur et al., 1996; Shalev, 2007), learning disabilities in the domain of numerical processing and arithmetic (i.e., mathematical learning disabilities – MLDs) are about as common as disabilities related to the acquisition of written language. But compared to the large number of scientific studies on reading impairments, research on MLDs is still in its infancy. However, approaches to remediation that focus on the critical conceptual and procedural underpinnings of MLD (for a review see Butterworth et al., 2011) can only be developed on the basis of a thorough understanding of the neurocognitive mechanisms underlying typical and impaired numerical cognition. This clearly calls for developmental and cognitive neuroscience to increase research efforts on both, basic numerical and higher-level abilities related to typical and atypical numerical processing functions, and their specific developmental trajectories (Ansari and Karmiloff-Smith, 2002).

One well-established experimental procedure to tap into the basic representation systems that can be assumed to underlie higher-level functioning in the domain of number processing is *non-symbolic numerical magnitude comparison*, a task paradigm that allows for systematic manipulations of quantity differences, i.e., the *numerical distance*, between the to-be-compared sets of items such as dot arrays. Originally described by Moyer and Landauer (1967), the impact of numerical distance manipulations on behavioral measures was taken to reflect basic characteristics of quantity processing functions. The most widely accepted model for the observed systematic increases of response latencies and error rates related to decreasing numerical differences between choices is the assumption of more representational overlap between close compared to far numerical values (Dehaene and Changeux, 1993; for an alternative model that implies conflict primarily at output levels, see Van Opstal et al., 2008). The fact that numerical distance effects were demonstrated to be both, format-general and modality-independent (Barth et al., 2003), and demonstrated not only in humans, but also in other species (Brannon and Terrace, 2000), was taken as evidence that manipulations of numerical distance tap into a pre-verbal mental representation of magnitude, i.e., an approximate number system that is thought to constitute a crucial start-up mechanism for the acquisition of abstract numerical knowledge (Butterworth, 2010; Piazza, 2010).

However, in cognitive and developmental psychology there is a long-standing debate on the existence of *qualitative* as opposed to mere *quantitative* functional differences between the processing of small and large numerosities (Feigenson et al., 2004). The majority of empirical evidence in support of the hypothesis that stimulus arrays of up to four items are apprehended by a specific mechanism that is categorically different from enumeration of larger set sizes, comes from chronometric studies (Kaufman et al., 1949; Mandler and Shebo, 1982; but see Balakrishnan and Ashby, 1991). One focus of current research is to establish the role of attentional control in small number processing. Challenging Trick and Pylyshyn's (1994) description of subitizing as being the outcome of mid-level visuo-spatial indexing processes operating prior to the allocation of focal attention, a number of recent studies failed to confirm the assumed independence from attentional modulation as a property of the instantaneous and precise enumeration capacity for small set sizes (Burr et al., 2010; Poiese et al., 2008; Railo et al., 2008; Vetter et al., 2011; but see Piazza et al., 2003). The results of these studies rather suggest that the distinction of stimulus-driven versus goal-oriented attentional functions as elaborated in Corbetta and Shulman's (2002) model may better describe the existing data (Ansari et al., 2007). A second strand of research is not so much concerned with capacity limited cognitive resources, but with the nature of representational systems mediating quantity processing for small and large arrays of objects (Feigenson et al., 2004). In a recent review, Piazza (2010) distinguishes two functionally and neuroanatomically dissociable systems fundamental for quantification processes. Whereas a substantial body of research corroborates models that link estimation of large numerical quantities to the functioning of an analog magnitude processing system located in inferior parietal regions of both hemispheres (see Dehaene, 2009, for a recent review), much less is known of a putative second system underlying the rapid and accurate processing of small collections of items. This latter, the so-called object tracking system (Feigenson et al., 2002), is assumed to be crucial for establishing and tracing individual tokens of objects (see Carey, 2009, Chapter 3) and to be linked to the functioning of extra-striate visual areas (Sathian et al., 1999; but see Izard et al., 2008). The assumption of a functional separation of representation systems for small and precise versus large and approximate quantities was recently supported by Palomares et al. (2011), who showed processing of the object tracking systems to be restricted to small numerosities, while the parietal processing system was demonstrated to be involved in stimulus processing across the whole numerical range.

Apart from experimental demonstrations of the behavioral manifestations of numerical distance effect in adults (Dehaene et al., 1990) and children (Sekuler and Mierkiewicz, 1977), neuroimaging methods such as electroencephalography (EEG); (Dehaene, 1996; Temple and Posner, 1998) and functional magnetic resonance imaging (fMRI); (Pinel et al., 2001, 2004) were used to explore its neural basis. And just recently, eye movement measures were used to tap into levels of numerical processing related to the execution of magnitude comparisons (Merkley and Ansari, 2010).

In their seminal paper on atypical number development, Ansari and Karmiloff-Smith (2002) suggested that differences in behavioral and neural manifestations of numerical distance effects may serve as predictors of individual mathematical competencies and may allow for specific insights into the relationship between impairments of basic numerical functions and the development of so-called end-state representational systems. Consequently, a number of studies have addressed developmental changes of manifestations of the numerical distance effect. It was demonstrated that the impact of distance manipulations on behavioral measures generally *decreases* in the course of development (Duncan and McFarland, 1980; Holloway and Ansari, 2008; but see Reynvoet et al., 2009). Interestingly, on the level of neural functioning, an age-related *increase* of distance-related activation in relevant cortical regions such as the inferior parietal cortex was demonstrated for numerical magnitude comparisons on symbolic (Ansari et al., 2005) and non-symbolic (Ansari and Dhital, 2006) stimuli (for a review see Ansari, 2008). Regarding the relationship of numerical distance effects and individual numerical competencies, a number of studies using symbolic comparison tasks reported larger behavioral distance effects to be concomitant with lower mathematical achievement in children (De Smedt et al., 2009; Holloway and Ansari, 2009; Lonnemann et al., 2011; but see Landerl et al., 2009; Landerl and Kölle, 2009). These age- and achievement-related differences in numerical distance effects are either explained by noisier mappings between number symbols and their represented quantities in younger populations and in those with mathematical impairments (De Smedt et al., 2009; Holloway and Ansari, 2009; Rousselle and Noël, 2007) or, alternatively, by a lack of acuity at the level of numerical magnitude representations per se (Heine et al., 2010; Mazzocco et al., 2011; Piazza et al., 2010). For non-symbolic comparison paradigms, the data are less conclusive. In line with the findings on symbolic comparison tasks, Mussolin et al. (2010b) showed distance effects to correlate negatively with mathematical achievement in 10- to 11-year-old children. However, studies on somewhat younger children found no relationship between performance in non-symbolic numerical comparison tasks and measures of abstract mathematical abilities (De Smedt and Gilmore, 2011, 6:8-year-olds; Holloway and Ansari, 2009, 6- to 8-year-olds; Rousselle and Noël, 2007, 7-year-olds; Soltész et al., 2010, 4- to 7-year-olds). These latter findings are hard to reconcile with the common assumption that the processing of non-symbolic quantities, i.e., sets of objects, may serve as a precursor for higher-level numerical cognition (Barth et al., 2005, 5- to 6-year-olds; for a review see Ansari, 2008).

On the brain level, fMRI studies on developmental changes in neural correlates of number processing typically find a so-called *fronto-parietal activation shift* triggered by basic and higher-level numerical tasks (Ansari, 2008). The observed increase in activation in parietal regions in the course of individual development is taken as evidence for a functional specialization of the parietal cortex during ontogeny (Ansari and Dhital, 2006; Holloway and Ansari, 2010). The concomitant decreased involvement of prefrontal areas, on the other hand, is assumed to reflect a disengagement of domain-general processes related to executive control and working memory over developmental time (Ansari et al., 2005; Rivera et al., 2005). Neuroimaging studies on numerical distance effects in different mathematical achievement groups typically report higher distance-related activation differences in inferior parietal regions for controls compared to low achievers. For example, using a symbolic comparison task, Mussolin et al. (2010a) reported brain activation in bilateral inferior parietal regions to be modulated systematically by numerical distance manipulations only in controls, but not in children with MLDs. Using non-symbolic numerical comparison tasks, Price et al. (2007) showed larger distance-related activation differences in right-hemispheric inferior parietal regions in typically developing children compared to low math achievers. These results were confirmed by a recent meta-analysis of fMRI studies on typical and impaired numerical development. Based on the still relatively small number of published studies, a meta-analysis (Kaufmann et al., 2011) identified patterns of stronger activation in the right posterior parietal lobe in controls compared to low achievers in the mathematical domain. Children with MLDs seem to rely more on frontal brain areas and on more anterior parietal regions that were suggested to be related to immature finger-based number representations of quantities (Kaufmann et al., 2008). However, these results are challenged by an fMRI study on non-symbolic comparison that actually found stronger activation in bilateral inferior parietal areas in children with MLDs compared to their typically developing peers (Kaufmann et al., 2009), or by studies that reported no differential activation in inferior parietal cortex but in frontal and prefrontal areas (Kucian et al., 2011), occipital, as well as subcortical and cerebellar regions (Kovas et al., 2009). These latter findings, in particular, support the view that numerical processing involves an extensive brain network, including but not limited to inferior parietal areas. Overall, it is, thus, still an open question whether and how differences in inferior parietal activation levels are specifically related to differential numerical and mathematical abilities.

Apart from investigations into event-related potential (ERP) correlates of *early*, i.e., more automatized steps of numerical processing, electrophysiological studies typically focus on so-called *late parietal positivities* that are assumed to be reflections of quantity processing functions in adults, children or also in infants (Dehaene, 1996; Hyde and Spelke, 2011, 2012; Izard et al., 2008; Soltész et al., 2011; Szücs et al., 2007; Temple and Posner, 1998). For both, symbolic and non-symbolic comparison tasks, more positive-going amplitudes of the late parietal ERP components in response to large compared to small numerical distances were found in typical adult (Paulsen and Neville, 2008; Paulsen et al., 2010; Turconi et al., 2004), and in younger populations (Heine et al., 2011; Soltész et al., 2007; Temple and Posner, 1998). However, there are also reports of reversed amplitude effects under certain experimental conditions such as habituation paradigms (Hyde and Spelke, 2009) or task designs that involve comparisons with memorized numerical standards (Libertus et al., 2007). Interestingly, Soltész et al. (2007) found no distance-related effects for the late positive ERPs in a group of adolescents with impairments in the domain of mathematics, while age-matched typical achievers (TAs) showed a partially graded distance effect that was reminiscent of the fully graded distance effect demonstrated for an adult control group.

To sum up, the rather sparse and overall somewhat inconsistent data on neural signatures of basic numerical capacities in children suffering from MLDs obviously call for further studies into the neurocognitive correlates of typical and atypical magnitude processing. What is more, systematic investigations of processing signatures for stimuli tapping into different numerical ranges are required so as to gain insight into specific neurocognitive mechanisms related to the functioning of the two postulated core systems of number processing, i.e., the small number system and the approximate number system (Butterworth, 2010; Feigenson et al., 2004; Piazza, 2010). EEG, which offers an excellent temporal resolution, seems to be especially well-suited to track subtle individual differences in the time-course of numerical processing.

The aim of the present study was, thus, to probe distance-related electrophysiological effects in children with MLDs compared to a matched group of typically developing primary schoolers by analyzing ERPs and concomitant patterns of activation in underlying cerebral current sources. Our focus on children during their first years of schooling is motivated by the fact that it is typically at this point in development that critical deviations in basic numerical processing capacities become obvious in populations at risk for MLDs (Geary, 2004, 2010).

Following the general experimental procedures described in the literature, we investigated ERP and current density effects of numerical distance manipulations for non-symbolic stimuli in the subitizing range (i.e., arrays of up to four items, see Kaufman et al., 1949), the so-called counting range which spans arrays from four up to ten items (Piazza et al., 2003; Temple and Posner, 1998) and the estimation range (Ansari et al., 2007; Hyde and Spelke, 2009). Since canonicity of the displayed arrays of objects was shown to shift the cut-off point in behavioral performance measures, we added a fourth condition that involved arrays of canonical dot patterns (Mandler and Shebo, 1982, Exp. 4). While more recent studies on non-symbolic numerical processing typically focus on the comparison of small and large number processing (e.g., Ansari et al., 2007; Hyde and Spelke, 2009), we were also interested in distance effects for stimuli in the counting range, which were shown to also elicit late positive-going ERPs in typically developing children and in adults (Temple and Posner, 1998). Including not only non-canonical, but also canonical arrays of stimuli allows for further insight into the impact of familiarity of appearance on non-symbolic magnitude processing for stimuli within and just beyond the subitizing range and, thus, accommodates the discussion of whether subitizing may or may not be based primarily on a pattern-matching mechanism not specific to small numerosities (i.e., the pattern-matching hypothesis; Logan and Zbrodoff, 2003; Mandler and Shebo, 1982).

Choosing non-symbolic comparisons over symbolic tasks was mainly motivated by the fact that non-symbolic stimuli can be assumed to tap into the very basic processing functions proposed to underlie higher-level capacities (Piazza, 2010). Interestingly, Maloney et al. (2010) recently demonstrated that compared to symbolic variants of number comparisons in general, and particularly paradigms that involve comparisons of digits to a standard, non-symbolic magnitude comparisons have the highest reliability.

2. Materials and methods

2.1. Participants

The data from 40 second and third graders were used for the present EEG study on non-symbolic numerical comparison (i.e., 20 children with MLDs, 20 matched typically developing controls). Approval from the local research ethics committee was obtained prior to study enrollment, and all participants and their parents gave written informed consent.

The group of participants was selected from a pool of 1242 children from six public primary schools in Berlin based on their performance scores in several standardized tests, i.e., *mathematical achievement* [Heidelberger Rechentest 1-4 (HRT 1-4), Haffner et al., 2005], *intelligence* [Kognitiver Fähigkeitstest – Grundschulform (1-3, Heller and Geisler, 1983)] and *working memory capacity* [Working Memory Test Battery for Children (WMTB-C, Pickering and Gathercole, 2001)]. In a first step, children from the original pool were administered the *HRT 1-4* (Haffner et al., 2005). The *HRT 1-4* is a standardized math achievement test for grades 1–4 that comprises two subscales. The arithmetic subscale includes timed tests of arithmetic skills, e.g., addition, subtraction, multiplication, and division, whereas the second subscale consists of tests of visuo-spatial abilities, e.g., 2D-length estimation, estimation of set size. After the initial screening for mathematical achievement, a group of 382 children entered the second diagnostic phase. Children's general cognitive performance levels were determined using the *KFT 1-3*, a standardized intelligence test for primary school children (Heller and Geisler, 1983). After exclusion of children with IQs more than 1 standard deviation (SD) below the standard mean, working memory functions were assessed using the *WMTB-C*, a standardized test battery (Pickering and Gathercole, 2001). In a last step, screenings for possible attentional problems were carried out using the children's color trails test (CCTT), a standardized diagnostic tool (Llorente et al., 2003) and a short questionnaire for teachers (Conners, 1973). Additionally, performance in reading and spelling was measured by standardized tests, i.e., the *Salzburger Lese-Screening für die Klassenstufen 1-4* (*SLS 1-4*, Mayringer and Wimmer, 2003) and the spelling subtest of the Salzburger Lese- und Rechtschreibtest (SLRT), (Landerl et al., 1997). These final diagnostic testings guaranteed for both achievement groups that children with potential *attentional*, *reading* or *spelling* problems were excluded from the study (cut-off scores for all screenings: $\leq .8$ SD below the standard means).

Based on their performance on the arithmetic subscale of the math achievement test, children were assigned to one of two experimental groups, i.e., children with MLDs (math performance scores ≤ 1.65 SD below the standard mean, which corresponds to the fifth percentile as critical threshold, cf. Ramus et al., 2003; 10 girls; 9 2nd/11 3rd graders) and a group of typically performing children that were matched with respect to age, grade level, intelligence and working memory functions (TA; math performance scores $\geq .3$ SD below the standard mean; 11 girls; 9 2nd/11 3rd graders; see Table 1). We decided for a conservative cut-off criterion in order to assure that only children with MLD were included in the study (see Mazzocco et al., 2011, who distinguished between children with MLDs, i.e., diagnostic scores below the 10th percentile, and mathematical low achievers, i.e., scores between the 11th and 25th percentile). While children's math scores differed significantly between the two achievement groups (all $ps < .001$), the groups were matched with regard to age, intelligence and working memory capacity (all $ps > .300$; see Table 1).

2.2. Materials and procedure

EEG data were obtained while children performed a magnitude comparison task that involved four separate numerical conditions, i.e., different numerical ranges. The task required children to decide which of two sequentially displayed arrays

Table 1 – Relevant demographic and diagnostic variables.

Matching variable	Achievement group				F (1, 38)	p
	MLD (n = 20)		TA (n = 20)			
	M	(SD)	M	(SD)		
Age (months)	99.2	(9.0)	98.4	(6.4)	.43	.466
Intelligence[a]	53.05	(6.59)	54.30	(6.60)	.36	.553
Mathematics[b]						
Composite score	34.40	(3.60)	52.15	(4.84)	173.17	**.000**
Arithmetic operations	32.05	(2.87)	53.25	(8.94)	101.86	**.000**
Visuo-spatial abilities	41.95	(6.24)	52.50	(7.60)	22.99	**.000**
Working memory[c]						
Central executive	87.30	(11.86)	91.35	(12.53)	1.10	.300
Phonological loop	93.15	(13.87)	94.20	(14.40)	.06	.816
Visuo-spatial sketchpad	86.70	(19.41)	89.75	(19.45)	.25	.622

Note: MLD, children with mathematical learning disabilities; TA, typical achievers.
a KFT 1-3, mean standard score = 50, $SD = 10$.
b HRT 1-4, mean standard score = 50, $SD = 10$.
c WMTB-C, mean standard score = 100, $SD = 15$.

of dots was the numerically larger one (see Fig. 1). Each trial started with a fixation cross (600 msec), followed by the first array of dots (1000 msec), another fixation cross (600 msec), and the second dot array (1000 msec; interstimulus interval (ISI) = 3000 msec). Apart from two minor changes, the overall study design was adopted from the experimental procedure described by Ansari et al. (2007). However, in order to avoid errors caused by a mix-up of the temporal sequence of the displays within each trial, the dots were presented slightly to the left or right of the fixation cross. For each stimulus, both left–right and right–left sequences were generated and randomized so that the presentation of the two laterality combinations was balanced out. The children had to respond to the larger set size by pressing the button on the corresponding side of the response box. A third button had to be pressed for equal set sizes, which were included in order to prevent the children from drawing premature inferences about the second array in those cases where the first stimulus part was made up of the smallest or the largest set sizes for the respective experimental condition. A second modification concerned the timing of the response execution. In order to provide for sufficient artifact-free EEG segments, children were instructed to wait with the response execution until a cue appeared on the screen. These adjustments to the settings were introduced after two test runs with age-matched typically developing children who did not take part in the current study but were recruited in order to assess the suitability of the experimental settings for this specific age group.

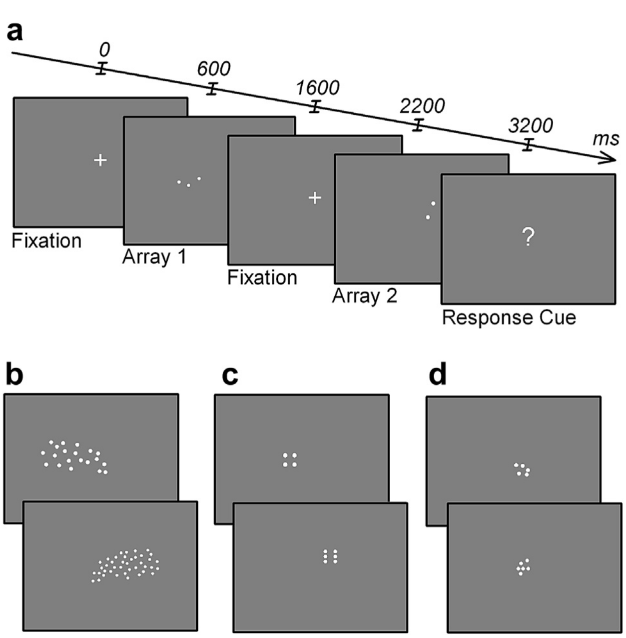

Fig. 1 – Experimental design with timing information and examples of stimuli for each block.

The experiment consisted of four experimental blocks separated by rest periods. Within each block, stimuli from only one of the four numerical conditions were presented in random order. Depending on the respective experimental condition, the stimuli consisted of arrays of either 1, 2, 3 and 4 (‘subitizing’ – SUB), 4, 5, 6 and 7 (‘small-number estimation’ – EST_S), or 10, 20, 30 and 40 (‘large-number estimation’ – EST_L) randomly distributed dots, or of 4, 5, 6 and 7 dots that were arranged into dice or domino patterns (‘canonical patterns’ – CAN).[1] It is important to note that even though arrays of 4, 5, 6 and 7 dots (EST_S, CAN) are instantiating the numerical range typically referred to as the ‘counting range’ in the literature (Piazza et al., 2003), the short stimulus presentation times used for the present experimental setting (i.e., 1000 msec) prevented counting processes to take place. Additionally, children were explicitly instructed to not count the dots, but try to find the correct solution by approximation.

For each condition, the dot arrays were assembled into pairs of 16 numerically different sets of dot arrays (e.g., 1-1, 1-2, 1-3, 1-4, 2-1, to 4-4 for the subitizing range). Numerical differences of two and three dots for the smaller numerical ranges (SUB, CAN, EST_S), and 20 and 30 dots for large-number estimation were considered large numerical distances, while a difference of one or 10 dots, respectively, was considered a small numerical distance. This resulted in six sets instantiating large distances and six sets instantiating small distances for each numerical condition.

In order to provide for equal numbers of EEG segments across the four conditions after the elimination of errors trials, the stimuli were presented either four or five times, depending on complexity (i.e., subitizing and canonical patterns: 64 trials; small-number and large-number estimation: 80 trials). Prior to each of the four or five presentation cycles within the blocks, the order of the stimuli was randomized. The overall duration of stimulus presentation was 24 min, divided into four blocks (SUB: 5 min, EST_L: 6 min, CAN: 5 min, EST_S: 6 min) with variable resting periods in between.

[1] The decision to introduce a set size of four items for both the subitizing and the small-number estimation conditions was motivated by two considerations: Firstly, the cut-off for the subitizing range actually falls somewhere between 3 and 4 items and varies interindividually. Secondly, since no canonical patterns exist for larger numerical values, the largest set size within the counting range had to be set at 7 – which, in turn, was included to provide for comparable stimulus arrays across the four conditions.

In order to minimize afterimages, the arrays of white dots were presented on a medium gray screen. Non-numerical variables that are continuous with numerical size were controlled within each of the four experimental conditions (see Piazza et al., 2004). Intensive parameters, i.e., individual dot size and spacing between the dots, are systematically related to extensive parameters, i.e., cumulative area of all dots and overall area covered by the dot configurations. Following Ansari et al. (2007), we held one of the extensive variables constant, i.e., the overall area of the dot configuration did not change within each of the experimental conditions (see also Libertus et al., 2007; Paulsen and Neville, 2008), and created combinations of dots arrays for all set sizes that were equated with respect to one of the intensive parameters (i.e., dot size and spacing between the dots). This means that within each single trial the arrays were equated along only one of the intensive continuous dimensions. However, within each experimental condition, the intensive variables were equated across the repetitions of set size combinations. Furthermore, the exact locations of the individual dot configurations (left/right from the fixation cross; upper/lower half of the screen) were balanced within the experimental conditions.

Following a standardized set of instructions, the children were asked to respond as quickly and accurately as possible as soon as the response cue appeared on the screen. Each of the experimental blocks was preceded by 10 practice trials, during which the children were invited to comment on their choice of button in order to make sure they fully understood the task. The children were seated in front of the computer screen (17" CRT display; distance: 60 cm) with their hands resting on the button box. During the experimental runs, the ambient light was dimmed.

2.3. *Acquisition and pre-processing of the EEG data*

Continuous EEG was recorded from 27 active electrodes (actiCAP system, Brain Products, Munich) placed according to the extended international 10–20 system. Horizontal and vertical eye movements were recorded unipolarly (i.e., sub- and supra-orbital, right and left outer cantheal sites). All electrodes were online referenced to the left mastoid lead. Electrode impedances were kept below 5 kΩ for the scalp electrodes, and below 10 kΩ for the electrooculogram. The recordings were amplified using a BrainAmp system (Brain Products, Munich). The sampling rate was 250 Hz.

The data were pre-processed using the BrainVision Analyzer software (Brain Products, Munich). In a first step, the EEG was filtered (bandwidth: .1–30 Hz, 24 dB/oct; and 50 Hz notch), and offline re-referenced to an average of the left and right mastoids. An independent component analysis was carried out on the filtered data to remove ocular artifacts from the EEG signal. An automatic rejection procedure (cut-off: $\pm 90\ \mu V$) was applied on the thus reconstructed EEG signal.

The continuous EEG signal was segmented into single trials (interval: −200–1000 msec), time locked to the onsets of the critical stimulus parts (i.e., the second dot array). After exclusion of all error trials, baseline corrected average ERPs were computed for each participant and stimulus category (baseline: 200–0 msec pre-stimulus).

2.4. *Data analysis*

Mean error rates and reaction times (RTs) were calculated for each participant and stimulus condition. Mean RTs were calculated on the basis of correct trials only. Tukey's (1977) fence method was applied to remove extreme outliers, i.e., the first quartile minus two times the interquartile range [i.e., Q1 − 2 (Q3 − Q1)] constitutes the lower and the third quartile plus two times the interquartile range [i.e., Q3 + 2 (Q3 − Q1)] the upper fence. Trials with RTs that exceeded this range were excluded from the analyses. After the elimination of outliers, an average of 98.4% of the correct trials entered the analyses. Mixed repeated-measures analyses of variance (ANOVAs) were performed on mean error rates and mean RTs with numerical condition (SUB, EST_L, CAN, EST_S) and numerical distance (small, large) as within-subject factors, and group (MLD, TA) as between-subjects factor. However, RT data should be treated with caution, because children were instructed to wait with their responses until the response cue was shown, i.e., children's response times may not actually reflect efficiency of numerical processing per se but domain general abilities related to cued response execution.

Based on visual inspection of grand average waveforms at posterior electrode sites that were shown to be modulated by numerical parameters in previous electrophysiological studies (Dehaene, 1996; Hyde and Spelke, 2009, 2011; Libertus et al., 2007; Temple and Posner, 1998), two time windows were selected for the ERP analysis. An early time window that comprises the parietal N1 component, i.e., the first negative-going component that follows the P1 (interval: 110–210 msec; early time window; Johannes et al., 1995), and a second time window that covers the large positive-going deflection at parietal electrode sites (interval: 280–600 msec; late time window). Statistical tests were focused only on relevant clusters of electrodes (cf. Luck, 2005, who suggests to 'analyze an ERP component only at sites where the component is actually present'; p. 254), i.e., left (P3, P7, CP5, O1) and right (P4, P8, CP6, O2) parieto-occipital recording sites which correspond to the effect sites typically referred to in the literature on number processing (Dehaene, 1996; Temple and Posner, 1998).

Following the procedure described by Hyde and Spelke (2012), who implemented a very similar design for an EEG study on numerical processing in healthy adults, peak latencies were used to decide whether separate or combined analyses of the ERP components for the different numerical conditions were warranted. Consistency in peak morphology across different experimental conditions indicates that activity in the respective time window can be explained by one single ERP component, which, in turn, suggests a joint analysis of that component across conditions. For this purpose, an automatic peak detection algorithm was applied to identify global maxima in the predefined time windows for the pooled bilateral parieto-occipital electrodes. Peak latency data were compared using repeated-measures ANOVAs with numerical condition as within-subject factor for each time window.

Experimental effects on both ERP components were tested by computing average amplitudes centered over critical intervals for each of the electrodes. The thus determined ERP data were subjected to mixed repeated-measures ANOVAs with numerical condition (for the early time window only), laterality (left, right), recording site (inferior parietal, IP; superior parietal, SP; central-parietal, CP; occipital, OC) and numerical distance (small, large) as within-subject factors, and group as between-subject factor. A number of follow-up analyses were carried out to gain further insights into the specific effects of relevant factors. The ERP waveforms were low-pass filtered offline with 10 Hz filter for presentation purposes only. All statistical analyses were performed on unfiltered data.

Across all types and levels of the statistical analysis, Greenhouse–Geisser corrected *p*- and epsilon-values (ε_{GG}) are reported when the assumption of sphericity was violated (see Luck, 2005). Bonferroni corrected post-hoc tests were carried out where appropriate, and corrected *p*-values are reported.

Standardized low-resolution brain electromagnetic tomography (sLORETA; Pascual-Marqui, 2002) was applied to estimate the underlying cortical generators of scalp effects. Significant differences in current source distributions were determined using statistical nonparametric mapping procedures (SnPM; Holmes et al., 1996) as implemented in sLORETA, i.e., randomization tests (5000 permutations) corrected for multiple comparisons. To gain insight into differences between the two achievement groups that were related to numerical distance manipulations, we used an independent groups design ([(A–A2) vs. (B–B2)]), with A and A2, and B and B2 paired, but (A,A2) independent of (B,B2); cf. Pascual-Marqui, 2003), where A and A2 refer to large and small numerical distances for the group of TAs, while B and B2 refer to the corresponding conditions for the group of children with MLD.

Table 2 – Mean error rates and RTs separated by achievement group and numerical condition.

Measure	Numerical distance			
	Small		Large	
	M	(*SD*)	*M*	(*SD*)
Children with MLDs				
Subitizing (a)				
Error rate (%)	8.91	(4.39)	3.75	(7.89)
RT (msec)	601	(202)	595	(268)
Large-number estimation (b)				
Error rate (%)	42.53	(10.29)	12.75	(6.83)
RT (msec)	700	(232)	651	(259)
Canonical patterns (c)				
Error rate (%)	11.86	(8.68)	6.09	(5.12)
RT (msec)	652	(277)	600	(322)
Small-number estimation (d)				
Error rate (%)	42.08	(12.12)	13.50	(14.20)
RT (msec)	742	(308)	627	(244)
TAs				
Subitizing (a)				
Error rate (%)	7.30	(6.08)	2.70	(4.08)
RT (msec)	524	(156)	543	(164)
Large-number estimation (b)				
Error rate (%)	36.63	(12.69)	4.31	(4.60)
RT (msec)	560	(235)	542	(174)
Canonical patterns (c)				
Error rate (%)	4.39	(10.39)	4.18	(7.14)
RT (msec)	527	(171)	508	(172)
Small-number estimation (d)				
Error rate (%)	33.13	(12.42)	6.23	(9.94)
RT (msec)	747	(330)	569	(195)

3. Results

3.1. *Behavioral data*

Children's responses were both slower and less accurate when the numerical distance was small (i.e., distance effect), or when the dot arrays were complex (i.e., small-number and large-number estimation). Overall, children with MLD performed worse than their typically developing peers. However, no specific interactions between group and the factors condition or distance were found (see Table 2).

3.1.1. *Error rates*

The analyses of error rates revealed main effects of numerical condition, $F(3, 114) = 112.34$, $p < .001$, $\varepsilon_{GG} = .74$, $\eta^2_p = .747$; distance, $F(1, 38) = 487.65$, $p < .001$, $\eta^2_p = .938$, and group; $F(1, 38) = 7.98$, $p = .007$, $\eta^2_p = .174$. Of the interactions only condition by distance was significant, $F(3, 114) = 118.05$, $p < .001$, $\eta^2_p = .756$ (all other *ps* $\geq .215$). Across both groups, accuracy differed depending on numerical condition (SUB: 5.66%, $SD = 4.99$; EST_L: 24.05%, $SD = 8.11$; CAN: 6.63%, $SD = 7.34$; EST_S: 23.73%, $SD = 11.82$; post-hoc comparisons: SUB *vs* EST_L, CAN *vs* EST_L, SUB *vs* EST_S, CAN *vs* EST_S: $ps < .001$; all other $ps > .999$) and distance (small: 23.35%, $SD = 7.85$; large: 6.69%, $SD = 5.80$). Furthermore, children with MLD committed more errors than TAs (MLD: 17.68%, $SD = 5.50$; TA: 12.36%, $SD = 6.40$). The interaction effect was caused by a much steeper distance-related decline in performance for small-number and large-number estimations compared to the other two conditions.

3.1.2. *RTs*

The analysis of RTs revealed significant effects of numerical condition, $F(3, 114) = 4.43$, $p = .006$, $\eta^2_p = .104$; distance, $F(1, 38) = 19.72$, $p < .001$, $\eta^2_p = .342$, and a condition by distance interaction, $F(3, 114) = 8.55$, $p < .001$, $\varepsilon_{GG} = .80$, $\eta^2_p = .184$ (all other *ps* $\geq .248$). Similarly to the accuracy data, children's RTs varied with condition (SUB: 566 msec, $SD = 197$; EST_L: 613 msec, $SD = 221$; CAN: 572 msec, $SD = 237$; EST_S: 671 msec, $SD = 258$; post-hoc comparisons: SUB *vs* EST_S, CAN *vs* EST_S: $ps < .045$; all other $ps > .462$) and numerical distance (small: 632 msec, $SD = 200$; large: 579 msec, $SD = 188$). However, while children with MLD were slower that TA, this difference in RTs was not significant (MLD: 646 msec, $SD = 222$; TA: 565 msec, $SD = 149$; $p = .184$).

3.2. *Electrophysiological data*

3.2.1. *Early time window, preliminary analysis*

A repeated-measures ANOVA on peak latencies for the pooled bilateral parieto-occipital electrodes with numerical condition as within-subject factor revealed no significant timing differences for the early ERP component, $F(3, 117) = 1.22$, $p < .305$,

$\eta^2_p = .030$ (SUB: 156 msec, $SD = 31$; EST_L: 162 msec, $SD = 24$; CAN: 159 msec, $SD = 27$; EST_S: 162 msec, $SD = 25$; post-hoc comparisons: all $ps > .769$). This consistency in peak latencies suggests that the negative-going activity in the early time window can be explained by a single ERP component (see Fig. 2), which suggests a joint analysis across all numerical conditions.

3.2.2. *Early time window, main analysis*

A repeated-measures ANOVA on mean amplitudes over the critical interval with numerical condition, laterality, recording site and distance as within-subject factors, and group as between-subjects factor revealed significant main effects of recording site, $F(3, 114) = 30.35$, $p < .001$, $\varepsilon_{GG} = .61$, $\eta^2_p = .444$ (IP: $-.51$ μV, $SD = 3.35$; SP: 3.16 μV, $SD = 4.30$; CP: .60 μV, $SD = 3.37$; OC: 4.06 μV, $SD = 4.75$; post-hoc comparisons: IP *vs* SP, IP *vs* OC, SP *vs* CP, CP *vs* OC: $ps < .001$; all other $ps > .125$), numerical condition, $F(3, 114) = 9.20$, $p < .001$, $\eta^2_p = .195$, and group, $F(1, 38) = 5.24$, $p = .028$, $\eta^2_p = .121$, as well as a significant two-way interaction of numerical condition and recording site, $F(9, 342) = 8.01$, $p < .001$, $\varepsilon_{GG} = .44$, $\eta^2_p = .174$. The main effect of numerical condition resulted from more negative-going amplitudes for the smaller numerical ranges compared to large-number estimation (SUB: 1.72 μV, $SD = 3.81$; EST_L: 3.44 μV, $SD = 4.10$; CAN: 1.12 μV, $SD = 4.08$; EST_S: 1.02 μV, $SD = 3.73$; post-hoc comparisons: EST_L *vs* SUB, EST_L *vs* CAN, EST_L *vs* EST_S: $ps < .042$; all other $ps > .999$). The main effect of group was due to larger N1-amplitudes for TAs in comparison to children with MLD (TA: .61 μV, $SD = 4.62$; MLD: 3.05 μV, $SD = 4.77$; see Fig. 3).

3.2.3. *Late time window, preliminary analysis*

A repeated-measures ANOVA on peak latencies revealed a significant effect of numerical condition, $F(3, 117) = 9.35$, $p < .001$, $\varepsilon_{GG} = .80$, $\eta^2_p = .193$. The first positive component following the N1 peaked approximately 50 msec later in response to dot arrays in the subitizing range compared to all other numerical conditions (SUB: 414 msec, $SD = 57$; EST_L: 361 msec, $SD = 62$; CAN: 356 msec, $SD = 62$; EST_S: 359 msec, $SD = 68$; post-hoc comparisons: SUB *vs* EST_L, SUB *vs* CAN, SUB *vs* EST_S: $ps < .001$; all other $ps > .999$). This peak delay is consistent with the findings from a recent study on adults (Hyde and Spelke, 2012), and, following Hyde and Spelke's approach, warranted separate analyses for the different numerical conditions.

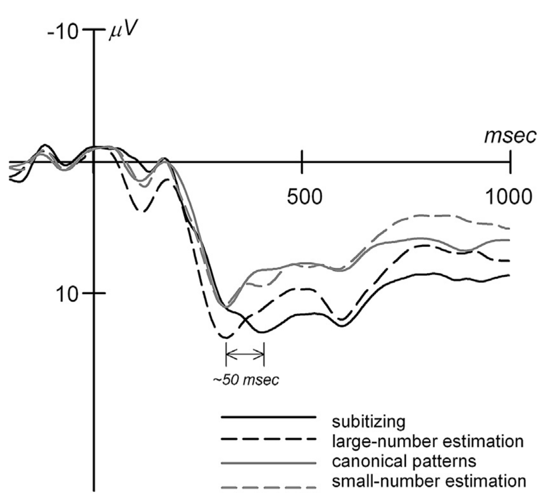

Fig. 2 – Stimulus-locked waveforms response to the different numerical conditions for the pooled bilateral parieto-occipital electrodes. The ERPs were averaged across groups and numerical distances.

3.2.4. *Late time window, main analysis*

Mean ERP amplitudes for the critical intervals were submitted to separate repeated-measures ANOVAs for each numerical condition with laterality, recording site and distance as within-subject factors, and group as between-subjects factor.

For the *subitizing* condition, the repeated-measures ANOVA revealed significant main effects of recording site, $F(3, 114) = 64.06$, $p < .001$, $\varepsilon_{GG} = .53$, $\eta^2_p = .628$ (IP: 12.00 μV, $SD = 4.47$; SP: 14.10 μV, $SD = 6.10$; CP: 6.46 μV, $SD = 4.64$; OC: 17.91 μV, $SD = 7.68$; post-hoc comparisons: all $ps < .007$), and numerical distance, $F(1, 38) = 7.19$, $p = .011$, $\eta^2_p = .159$ (small: 11.38 μV, $SD = 6.29$; large: 13.86 μV, $SD = 4.99$), as well as interactions of laterality by distance, $F(1, 38) = 14.06$, $p = .001$, $\eta^2_p = .270$, and laterality by recording site, $F(3, 114) = 3.29$, $p = .023$, $\varepsilon_{GG} = .67$, $\eta^2_p = .080$. For *large-number estimation*, a main effect of recording site, $F(3, 114) = 34.30$, $p < .001$, $\varepsilon_{GG} = .48$, $\eta^2_p = .474$ (IP: 11.08 μV, $SD = 4.35$; SP: 13.45 μV, $SD = 5.51$; CP: 5.67 μV, $SD = 4.70$; OC 14.43 μV, $SD = 8.31$; post-hoc comparisons: SP *vs* OC: $p > .999$; all other $ps < .006$), and interactions of laterality by distance, $F(1, 38) = 7.37$, $p = .010$, $\eta^2_p = .162$, laterality by recording site, $F(3, 114) = 6.74$, $p < .001$, $\varepsilon_{GG} = .55$, $\eta^2_p = .151$, and laterality by distance by group, $F(1, 38) = 5.88$, $p = .020$, $\eta^2_p = .134$, were found. For the *canonical patterns*, the analysis yielded a main effect of recording site, $F(3, 114) = 37.04$, $p < .001$, $\varepsilon_{GG} = .47$, $\eta^2_p = .494$ (IP: 8.31 μV, $SD = 4.00$; SP: 11.87 μV, $SD = 6.45$; CP: 5.61 μV, $SD = 5.78$; OC: 13.67 μV, $SD = 6.57$; post-hoc comparisons: SP *vs* OC: $p = .625$; all other $ps < .001$), and interactions of laterality by distance, $F(1, 38) = 5.87$, $p = .020$, $\eta^2_p = .134$, recording site by distance, $F(3, 114) = 4.88$, $p = .010$, $\varepsilon_{GG} = .66$, $\eta^2_p = .114$, and laterality by distance by group, $F(1, 38) = 9.83$, $p = .003$, $\eta^2_p = .206$. For *small-number estimation*, a main effect of recording site, $F(3, 114) = 41.29$, $p < .001$, $\varepsilon_{GG} = .58$, $\eta^2_p = .521$ (IP: 9.90 μV, $SD = 3.76$; SP: 10.12 μV, $SD = 5.15$; CP: 4.06 μV, $SD = 3.75$; OC: 13.35 μV, $SD = 7.32$; post-hoc comparisons: IP *vs* SP: $p > .999$; all other $ps < .014$), and interactions of laterality by distance, $F(1, 38) = 4.34$, $p = .044$, $\eta^2_p = .103$, laterality by recording site, $F(3, 114) = 6.43$, $p < .001$, $\varepsilon_{GG} = .68$, $\eta^2_p = .145$, and laterality by distance by group, $F(1, 38) = 4.31$, $p = .045$, $\eta^2_p = .102$, were found.

The significant interactions of laterality and distance for all numerical ranges can be attributed to the absence of numerical distance effects across all conditions for left in contrast to right posterior electrodes (see Fig. 3). Paired *t*-tests on pooled left parieto-occipital recording sites confirmed this observation [SUB: $t(39) = -.72$, $p = .479$; EST_L: $t(39) = -.75$, $p = .456$; CAN: $t(39) = .39$, $p = .696$; EST_S: $t(39) = -.53$, $p = .597$]. The follow-up analyses to further investigate the effects of distance manipulations for the two groups were, thus, carried out for pooled right-hemisphere electrodes only. Repeated-measures ANOVAs for each numerical condition with distance as within-subject factor and group as between-subjects factor revealed a main effect of distance, $F(1, 38) = 15.49$, $p < .001$, $\eta^2_p = .290$, for the subitizing condition, but no interaction. For large-number estimation, an effect of distance, $F(1,$

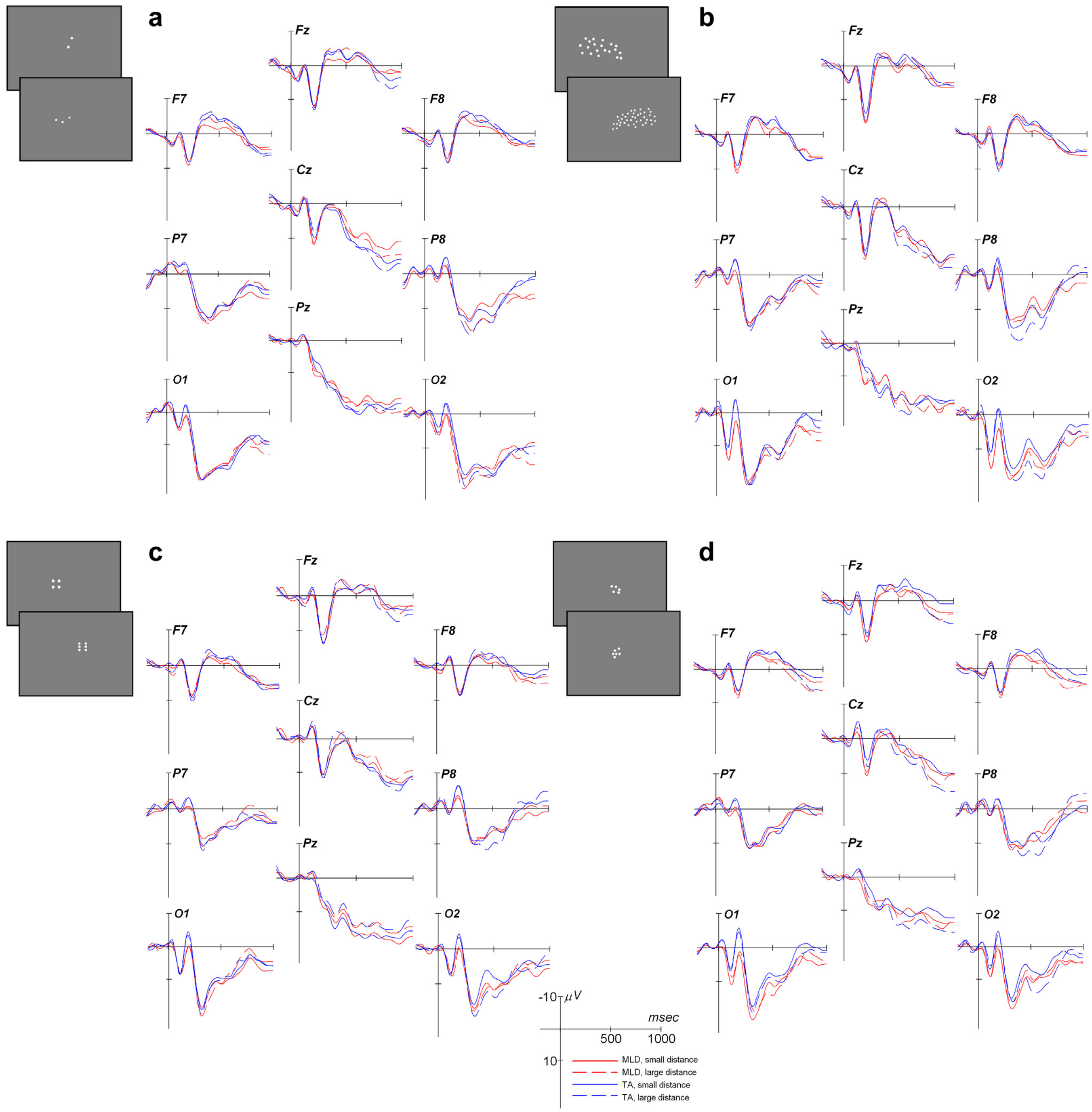

Fig. 3 – Stimulus-locked ERP waveforms at nine selected electrodes for both achievement groups (MLD: red; TA: blue). Large and small distances are plotted separately for each numerical condition, i.e., panels (a) subitizing, (b) large-number estimation, (c) canonical patterns and (d) small-number estimation. (MLD, children with mathematical learning disabilities; TA, typical achievers.)

38) = 7.04, $p = .012$, $\eta^2_p = .156$, and an interaction of distance by group, $F(1, 38) = 4.19$, $p = .048$, $\eta^2_p = .099$, were found. For the canonical patterns, distance and group interacted significantly, $F(1, 38) = 6.36$, $p = .016$, $\eta^2_p = .143$, while for small-number estimation the main effect of distance, $F(1, 38) = 8.76$, $p = .005$, $\eta^2_p = .187$, and a distance by group interaction, $F(1, 38) = 4.51$, $p = .040$, $\eta^2_p = .106$, were significant. This pattern of findings was followed up by paired t-tests that confirmed that for the group of MLD effects of numerical distance were present only for dot arrays in the subitizing range ($p = .009$), but absent for all other numerical conditions (all $ps \geq .438$), whereas TAs showed distance effects across the whole numerical range (all $ps \leq .015$; see Table 3).

To sum up the results of the analyses, the distance-related amplitude modulations of late positive-going components documented for the group of TAs are in line with previous ERP studies on numerical distance effects in children (Soltész et al., 2007; Temple and Posner, 1998). In contrast to the stable distance effects across the whole numerical range demonstrated for TA, the group of children with MLD showed

Table 3 – Results of the follow-up *t*-tests on mean ERP amplitudes (μV) of the late positive-going deflection at parietal electrode sites (interval: 280–600 msec; late time window) for the right-hemisphere posterior cluster of electrodes (P4, P8, CP6, O2) (statistically significant *p* values in boldface)

Measure	Numerical distance				$t(19)$	p
	Small		Large			
	M	(SD)	M	(SD)		
Children with MLDs						
Subitizing (a)						
R. Posterior cluster	10.56	(6.24)	14.81	(4.06)	−2.93	**.009**
Large-number estimation (b)						
R. Posterior cluster	10.92	(5.66)	11.44	(5.80)	−.48	.636
Canonical patterns (c)						
R. Posterior cluster	9.32	(4.32)	8.65	(5.65)	.55	.589
Small-number estimation (d)						
R. Posterior cluster	8.75	(4.60)	9.47	(4.57)	−.79	.438
TAs						
Subitizing (a)						
R. Posterior cluster	10.67	(6.81)	14.92	(7.15)	−2.66	**.015**
Large-number estimation (b)						
R. Posterior cluster	10.00	(7.02)	14.07	(5.47)	−3.02	**.007**
Canonical patterns (c)						
R. Posterior cluster	8.89	(4.87)	12.68	(7.21)	−2.96	**.008**
Small-number estimation (d)						
R. Posterior cluster	7.54	(6.19)	11.88	(6.60)	−2.99	**.007**

effects of distance manipulations only for stimuli in the subitizing range.

In a final step, sLORETA standardized current density estimations were performed on the late component to identify cortical current sources of differential effects of numerical distance on scalp voltage distributions for the two groups. Fig. 4 shows the results of the sLORETA computations. Significant distance-related current source density differences for the contrast TA versus MLD were established in several brain regions, i.e., inferior parietal (Brodman area (BA) 40), medial frontal (BA 24, BA 32) and occipital (BA 19) areas. Most notably, distance-related group differences were found in the right inferior parietal cortex for stimuli in the counting (CAN, EST_S) and large-number estimation (EST_L) ranges. Noticeable, however, is the absence of distance-related activation differences in inferior parietal areas between the two achievement groups for stimuli in the subitizing range (SUB). For small set sizes, differences were found only for a right occipital cluster of voxels. For non-canonical patterns in the counting range (EST_S), additional current density differences were found in the medial prefrontal cortex. It should be kept in mind, however, that in interpreting the results of sLORETA analyses, a good measure of caution is warranted with respect to the precision of current source localization in general. Nevertheless, there is convincing evidence for the validity and reliability of sLORETA solutions even for low-density EEG data (Anderer et al., 2003; Mulert et al., 2004; Vitacco et al., 2002).

4. Discussion

The present study was designed to investigate the electrophysiological indices of non-symbolic numerical processing in children with MLDs compared to typically developing children. A non-symbolic magnitude comparison task allowed us to determine the effects of distance manipulations for different numerical ranges, i.e., the subitizing, counting and estimation ranges. For the group of TAs, we found the amplitudes of late positive-going parietal ERP waveforms to be systematically affected by the magnitude of quantity differences between stimulus arrays. This is in line with previous ERP studies on numerical distance effects (Heine et al., 2011; Paulsen and Neville, 2008; Paulsen et al., 2010; Temple and Posner, 1998). The observed amplitude effects, i.e., more positive-going ERP waveforms for large compared to small distances, were more pronounced over right than over left parietal electrode sites, and detectable across all numerical ranges. Following Dehaene's (1996) early study on electrophysiological correlates of numerical distance processing, late posterior positivities are commonly assumed to be a reflection of current source activity primarily in inferior parietal regions (see e.g., Soltész et al., 2007; Temple and Posner, 1998). This interpretation of ERP patterns mirrors the fMRI literature on numerical comparisons (Fias et al., 2003; Holloway and Ansari, 2010; Kaufmann et al., 2011; Piazza et al., 2004). Positive deflections over parietal scalp sites are, thus, supposed to reflect the recruitment of domain-specific resources for the representation and manipulation of numerical quantities (Ansari, 2008; Brannon, 2006; Dehaene and Cohen, 1995; Dehaene et al., 2003; but see Shuman and Kanwisher, 2004).

On the behavioral level, children with MLD, even though performing less accurately than their typically developing peers, did not differ qualitatively from the TAs in that similar numerical distance effects were observed in both groups, i.e., no interactions effects were found. Our results confirm previous studies (Landerl et al., 2009; Landerl and Kölle, 2009), and corroborate Holloway and Ansari's (2009) assumption that behavioral measures of non-symbolic numerical comparison

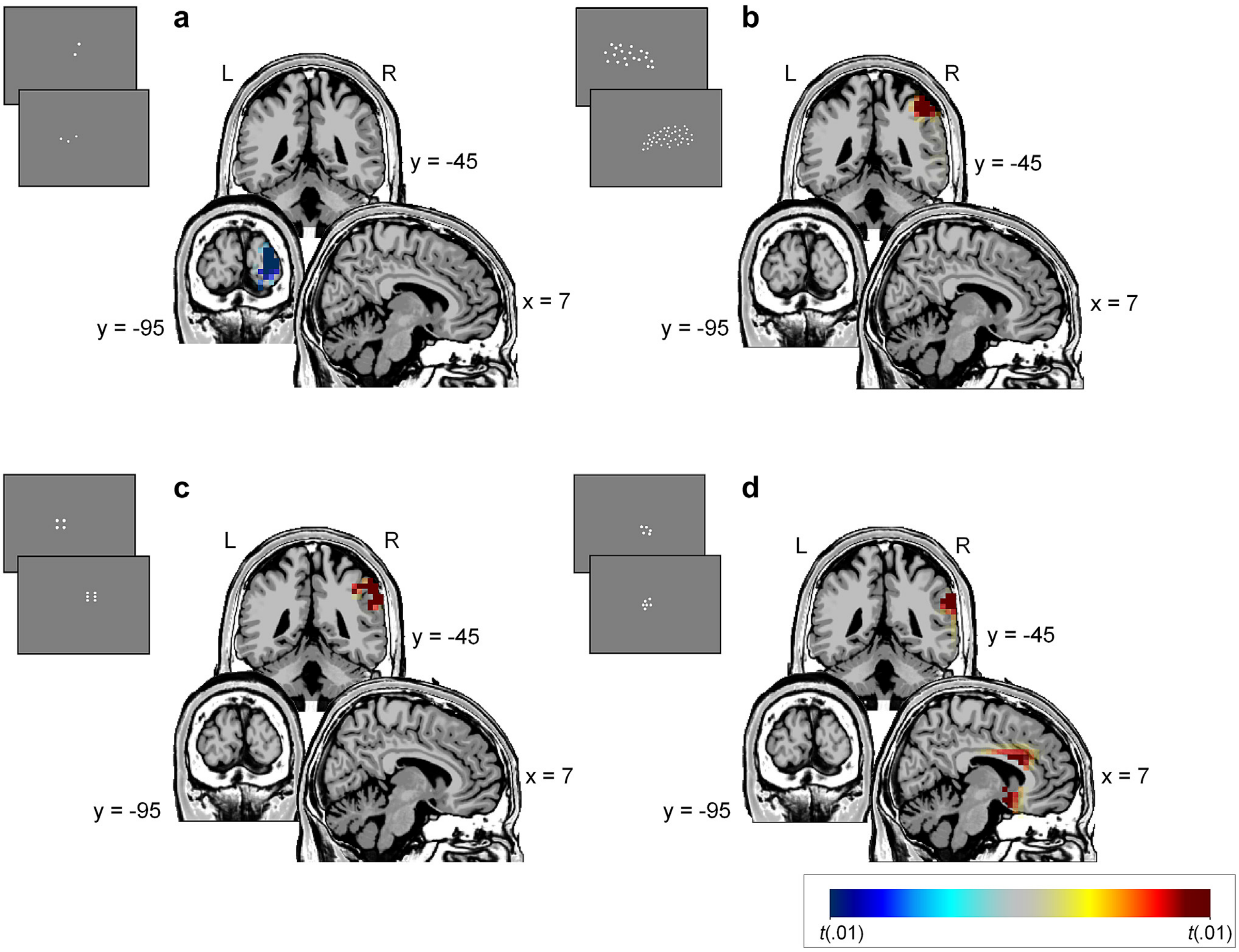

Fig. 4 – Differences in distance-related current source density between the two groups for the four numerical conditions as revealed by sLORETA analyses (Montreal Neurological Institute (MNI) coordinates for each slice are shown; L = left); R = right; panels (a) subitizing, (b) large-number estimation, (c) canonical patterns and (d) small-number estimation.

are not related to children's mathematical achievement before and during the first years of schooling (see also De Smedt and Gilmore, 2011; Rousselle and Noël, 2007; Soltész et al., 2010). It should be kept in mind, however, that the present RT data should be treated with caution since the children were instructed to wait with their responses until a cue was shown, i.e., the response times may be related primarily to domain general abilities such as cued response execution.

In contrast to the behavioral findings, the analysis of the electrophysiological data revealed clear differences between the two achievement groups. Different from the controls, we found no late parietal numerical distance effects for the group of children with mathematical disabilities for large arrays of dots, i.e., the counting and estimation ranges. This pattern of differential effects of numerical distance manipulations on neurophysiological measures in the absence of group differences on the level of behavioral performance confirms recent fMRI studies (Kaufmann et al., 2009; Kucian et al., 2011).

A previous ERP study on electrophysiological distance effects by Soltész et al. (2007) reported similar results for a group of dyscalculic adolescents compared to age-matched controls and adults. The authors demonstrated that while ERPs indicating early, i.e., more *automatic* processing steps were similar for all groups, correlates of later, i.e., more *controlled* stages of numerical information processing were less homogeneous. A graded late parietal numerical distance effect demonstrated for adults and controls was less specific in the group of dyscalculic adolescents. Applying principal component analysis to the same data set in order to disentangle the ERP-correlates of independent processing stages, Soltész and Szűcs (2009) related these group effects mainly to differences in executive functioning. However, while differential executive control capacities were previously demonstrated to be related to impaired numerical processing (cf. e.g., Bull et al., 1999; Passolunghi et al., 2007), Soltész and Szűcs (2009) rightly point out that domain-general deficits may be only one of a number of different explanatory factors for developmental dyscalculia. Given that for the present study the groups of children were matched with regard to working memory performance in general and, specifically, with respect to central executive abilities (Pickering and Gathercole, 2001), it does not seem likely that domain-general functions are at the core of the ERP differences found in the present study. It seems more plausible to relate our findings to children's number processing capacities per se, which were previously linked to ERP effects on right-parietal electrode sites (Szücs and Soltész, 2007; Szücs et al., 2007) that were shown to undergo systematic developmental changes (Soltész et al., 2011).

Current source density analysis of the distance-related group effects yielded areas in right inferior parietal regions to be involved, which is consistent with fMRI data on numerical magnitude comparison tasks (Chochon et al., 1999; Holloway et al., 2010). A number of studies have found right inferior parietal regions to be crucially related to format-independent numerical magnitude representations (Cappelletti et al., 2010; Dormal et al., 2010; Holloway and Ansari, 2010; Piazza et al., 2007). This was recently confirmed by a transcranial magnetic stimulation-study (TMS)-study (Dormal et al., 2012) that demonstrated right inferior parietal regions to play an essential functional role in non-symbolic numerical processing – a role that cannot be taken over by the left homolog areas. The authors propose that the right inferior parietal cortex may be the neural locus for approximate quantity representations, while left parietal regions are assumed to be complementary in that they provide resources for representations of exact magnitude.

Apart from these general findings, a meta-analysis on fMRI studies involving children reported activation in response to non-symbolic stimuli to be related to right inferior parietal regions mainly, while symbolic tasks typically yield more bilateral activation patterns (Kaufmann et al., 2011). Such a right-parietal dominance for non-symbolic magnitude processing functions was demonstrated in typically developing children as young as 4 years of age (Cantlon et al., 2006). The fMRI findings were corroborated by a study using near-infrared spectroscopy (Hyde et al., 2010). The very few studies on children with MLD reported reduced distance-related activation differences in right inferior parietal regions in low achievers compared to controls for non-symbolic comparisons (Price et al., 2007), and lateralization differences between achievement groups for symbolic comparisons (Mussolin et al., 2010a). Additionally, morphometric studies demonstrated generally lower gray-matter volumes in right inferior parietal regions in children with MLDs compared to typically developing controls (Rotzer et al., 2008; Rykhlevskaia et al., 2009). In light of these data from functional and structural imaging studies, the results of the sLORETA analysis point to a systematic relationship between a reduced involvement of right inferior parietal regions in numerical magnitude processing and levels of achievement in the domain of mathematics. Consequently, the present electrophysiological data complement the existing fMRI literature.

Interestingly, for dot arrays in the subitizing range, the ERPs did not differ between TAs and children with MLD, i.e., both groups showed similar distance effects. Furthermore, no group differences in current source density measures were found in parietal regions, but only in the right occipital cortex which can be assumed to be related to basic visual processing (Heine et al., 2011). This deviation of the EEG patterns for small set sizes from the general pattern found for larger arrays of dots is not completely unexpected. From a developmental perspective, it is primarily the analog magnitude processing system that is assumed to be a start-up tool for numerical processing (Barth et al., 2005; Piazza, 2010; for a review of comparative and developmental data see Nieder, 2005) and a possible locus of dysfunction in MLD (Mazzocco et al., 2011; but see Rousselle and Noël, 2007). In contrast to this well-established role of the approximate number system in numerical development, no conclusive evidence for an involvement of the object tracking system in higher-level numerical thinking in general, and in developmental disorders of numerical processing in particular exists. For example, a study by Piazza et al. (2011) showed that functional restrictions of the object tracking system are primarily related to visuo-spatial working memory capacity. Furthermore, data that confirm the assumption that subitizing deficits may be involved in the development of MLDs are sparse (Mandler and Shebo, 1982; Moeller et al., 2009; Schleifer and Landerl, 2011; Van Der Sluis et al., 2004; for a discussion, see Rubinsten and Henik, 2009). The current data do not support accounts that link subitizing deficits to impaired number processing, but rather support Piazza's (2010) account of an involvement of the analog magnitude processing system in the development of higher-level mathematical skills. The group-related activation differences in occipital areas can be assumed to reflect differential recruitment of domain-general visual processing resources instead of number-specific functions. On a more general level, the striking homogeneity of group-related ERP and current source density effects across the three conditions reflecting the classical counting and estimation ranges combined with the diverging EEG patterns for the subitizing condition suggests that numerosity of the stimulus arrays, rather than familiarity of appearance is the key factor underlying the distinction between small and large number processing. The results of the present study are, thus, hard to reconcile with subitizing accounts that focus mainly on visual aspects of non-symbolic stimuli such as the canonicity of dot arrangements (Logan and Zbrodoff, 2003; Mandler and Shebo, 1982). At least as far as *explicit* numerical comparisons are concerned, the electrophysiological results for the canonical pattern condition are suggestive of processing functions similar to those involved in small- and large number-estimations.

One final point should be mentioned, namely the amplitude effects in the early time window. In line with Dehaene's (1996) serial-stage model, we found no distance-related effects for the parietal N1 component. However, the amplitude differences between the two achievements groups were considerable. Posterior N1 components are generally assumed to be reflections of visuo-spatial attentional processing (Eimer, 1998). The more negative-going waveforms in the early time window may, thus, be related to a more effective allocation of visuo-spatial and/or attentional resources in the group of typically developing children compared to the children with MLD. Alternatively, as pointed out by Libertus et al. (2007), N1 effects may be related to differences in sensory processing (see also Turconi et al., 2004). It would be most interesting to conduct further studies in order to explore these effects in depth. Even though the two groups were matched with respect to general attentional and visuo-spatial working memory functions, more fine-grained diagnostic and experimental investigations into different levels of visuo-spatial and attentional processes in groups of children with and without MLDs should be carried out in the future.

5. Conclusion

To conclude, comparing the patterns of electrophysiological activity related to basic numerical processing of children with MLDs to those of typically developing children allowed for specific insights into the functional specifics of impaired number processing. Our results suggest that domain-specific systems in predominantly right inferior parietal regions are recruited differentially in the context of non-symbolic numerical magnitude processing in TAs compared to children with MLD. However, these functional differences were observed only for stimulus arrays with set sizes that exceeded the subitizing range.

On a more general level, the current study demonstrates that electrophysiological measures provide fine-grained insight into the complex neural reflections of quantity processing in children. EEG can thus be seen as a valuable tool for the investigation of the neuro-functional basis of typical and impaired behavioral performance in the domain of mathematics.

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