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Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia

S. Rotzer[a,*], T. Loenneker[a,b], K. Kucian[a], E. Martin[b], P. Klaver[a,1], M. von Aster[a,c,1]

[a] MR-Center, University Children's Hospital, Steinwiesstrasse 75, CH-8032 Zurich, Switzerland
[b] Center for Integrative Human Physiology, University of Zurich, Switzerland
[c] Department of Child and Adolescent Psychiatry, German Red Cross Hospitals Westend, Berlin, Germany

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ABSTRACT

The underlying neural mechanisms of developmental dyscalculia (DD) are still far from being clearly understood. Even the behavioral processes that generate or influence this heterogeneous disorder are a matter of controversy. To date, the few studies examining functional brain activation in children with DD mainly focus on number and counting related tasks, whereas studies on more general cognitive domains that are involved in arithmetical development, such as working memory are virtually absent. There are several studies showing a close relationship between DD and spatial working memory [Camos, V. (2008). Low working memory capacity impedes both efficiency and learning of number transcoding in children. *Journal of Experimental Child Psychology*, *99*(1), 37–57; McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, *74*(3), 240–260; Rosselli, M., Matute, E., Pinto, N., & Ardila, A. (2006). Memory abilities in children with subtypes of dyscalculia. *Developmental Neuropsychology*, *30*(3), 801–818; Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development*, *60*(4), 973–980]. The relationship between these two mechanisms is still matter of debate, but this study follows the assumption that poor spatial working memory capacity may hinder the acquisition of spatial number representations in children with DD [Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin*, *114*(2), 345–362; von Aster, M., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, *49*(11), 868–873].

Using functional MRI the current study compares brain activity associated with spatial working memory processes in 8–10-year-old children with DD and normally achieving controls. Both groups showed significant spatial working memory related activity in a network including occipital and parietal regions. Children with DD showed weaker neural activation compared to the control group during a spatial working memory task in the right intraparietal sulcus (IPS), the right insula and the right inferior frontal lobe. Performance tests outside the scanner showed impaired working memory proficiency in children with DD. Bringing behavioral performance and neural activity together we found significant correlations of right IPS activity with performance on the verbal digit span forward and the spatial Corsi Block Tapping test.

Our findings demonstrate for the first time an involvement of spatial working memory processes in the neural underpinnings of DD. These poor spatial working memory processes may inhibit the formation of spatial number representations (mental numberline) as well as the storage and retrieval of arithmetical facts.

1. Introduction

Developmental dyscalculia (DD) is characterized by difficulties representing and manipulating numerical information nonverbally and visuo-spatially, in learning and remembering arithmetic facts and in executing arithmetic procedures. DD in children has a prevalence of 3–6% in the school aged population, what is comparable to dyslexia, and high rates of comorbidities, such as ADHD (Koumoula

* Corresponding author. Tel.: +41 44 266 78 27; fax: +41 44 266 71 53.
E-mail addresses: stephanie.rotzer@kispi.uzh.ch, stephanierotzer@gmx.ch (S. Rotzer).
[1] Shared last authors.

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et al., 2004; Shalev, Auerbach, Manor, & Gross-Tsur, 2000). Yet little is known about the underlying deficits. The question of whether this difficulty in learning mathematics is due to a single impairment of a basic number specific core competence ('number sense') or a combination of impairments in a more general cognitive system is still open (Butterworth, 2005; Mix & Sandhofer, 2007). One impediment to research on DD is the complexity of the numerical domain that includes verbal, visuo-spatial, memory, and executive functions (Ardila, Galeano, & Rosselli, 1998; Geary, Hamson, & Hoard, 2000; von Aster, 2000). This wide array of cognitive factors that could contribute to DD poses a special challenge to investigate this disorder.

Deficits in working memory systems have been argued to substantially contribute to specific deficits in building cognitive representations of number, the formation of concepts and procedures as well as arithmetic fact retrieval in children with DD (Geary, 1993; von Aster & Shalev, 2007). Working memory refers to the mental capacity responsible for the temporary processing and storage of information (Rosselli, Matute, Pinto, & Ardila, 2006). It requires both the simultaneous processing of incoming and the retrieval or manipulation of retained information (Siegel & Ryan, 1989). This capacity for information processing is limited, since higher demands on the former will negatively influence the access to the latter, and vice versa. Therefore, variation in this capacity is related to performance in any cognitive activity (Camos, 2008), including arithmetics.

Several studies investigated the role of working memory in typically achieving children and children with DD (Bull, Espy, & Wiebe, 2008; D'Amico & Guarnera, 2005; Geary et al., 2000; Geary & Hoard, 2001; McLean & Hitch, 1999; Rosselli et al., 2006; Siegel & Ryan, 1989). Van der Sluis, van der Leij, and de Jong (2005) showed that children with arithmetic disabilities performed worse on a task requiring the memorization of dynamic visual information—these results are consistent with other findings (McLean & Hitch, 1999), reporting lower performance of children with arithmetic disabilities on the Corsi Block Tapping task. Concerning the different aspects of working memory, children with poor arithmetic performance generally appear to have normal phonological working memory (McLean & Hitch, 1999; Siegel & Ryan, 1989), although their capacity of spatial working memory is impaired.

Spatial working memory is modulated by a broad network of regions including predominantly frontal and parietal regions. Children performing visuo-spatial working memory tasks show the same, but decreased activation pattern compared to adults, especially the dorsolateral prefrontal cortex is less recruited (Klingberg, Forssberg, & Westerberg, 2002; Kwon, Reiss, & Menon, 2002; Nelson et al., 2000; Scherf, Sweeney, & Luna, 2006).

To date, only a few studies have investigated children with DD by means of anatomical or functional brain functions. Kucian et al. (2006) showed that children with DD have weaker brain activation in the IPS and the middle and inferior frontal gyrus of both hemispheres for approximate calculation than typically achieving children. Evidence of parietal dysfunction in DD has also been reported by Price, Holloway, Räsänen, Vesterinen, and Ansari (2007). In a recent study investigating structural brain volume in children with and without DD Rotzer et al. (2008) found reduced grey matter volumes in frontal and parietal regions. Hence, the question arose whether these differences are related to specific number processes or whether they may be attributed to more domain general factors such as working memory and attention.

The current study aims, for the first time, to compare the functional neuroanatomy of children with and without DD while performing a spatial working memory task. We hypothesize that children with DD show weaker activation in brain areas related to spatial working memory, such as the frontal and parietal cortex, since children with DD seem to have impaired spatial working memory capacities that are modulated by frontal and parietal brain regions.

2. Methods

2.1. Participants

The study included 11 girls and 3 boys with the diagnosis of developmental dyscalculia and 12 age-matched controls with age appropriate calculation performance (ZAREKI-R; von Aster, Weinhold Zulauf, & Horn, 2006). None of the participants had neurological or psychiatric disorders. They were not on medication and had no exclusion criteria for MRI. Five children were not included—two children with DD refused scanning, another two children with DD and one control child showed less than 60% accuracy rate within the scanner task. The remaining group included 10 children with DD (8 female, 2 male; mean age, 10.4; SD, 1.2) and eleven controls (9 female, 2 male; mean age, 10.2; SD, 1.0). Parents gave informed consent and children received a voucher for their participation. The study was approved by the local ethics committee based on the World Medical Association's Declaration of Helsinki (WMA, 2002).

2.2. Behavioral testing

Behavioral evaluation was carried out during two sessions before scanning. Mental ability was measured with three verbal (Vocabulary, Arithmetic and Similarities) and two performance subtests (Picture Arrangement, Block Design) of the Wechsler Intelligence Scale for Children (HAWIK-III) (Tewes, Rossmann, & Schallberger, 2000), (population mean = 100, SD = 15). Handedness was examined through the Edinburgh Handedness Inventory (Oldfield, 1971). Numerical abilities were assessed using the Neuropsychological Test Battery for Number Processing and Calculation in Children (ZAREKI-R). This neuropsychological battery examines the progress of basic skills in calculation and arithmetic and identifies and characterizes the profile of mathematical abilities in children with dyscalculia. It is composed of 11 subtests, such as reverse counting, subtraction, number reading, dictating, visual estimation of quantities, digit span forward and backward. Criteria for developmental dyscalculia were met if a child's performance in the ZAREKI-R was 1.5 SD below average in three subtests or in the total score. Spatial working memory performance was measured with the Corsi Block Tapping test, a test assessing spatial working memory span. On a board with 9 cubes, the examiner taps the cubes in a given sequence. Subjects are required to repeat the cube sequences in the same order immediately after the examiner has finished. While the sequences gradually increase in length, the number of cubes last tapped on in two consequently correct sequences is defined as maximum span. Children were also tested on the Block Suppression test—this test is based on the Corsi Block Tapping test and requires the subject reproducing every 2nd block in a given sequence (Beblo, Macek, Brinkers, Hartje, & Klaver, 2004). This task requires children to suppress irrelevant spatial information actively.

2.3. Paradigm design

The scanner paradigm is an adaptation of the Corsi Block Tapping test (Klingberg et al., 2002). Participants were asked to remember the location of three red dots, which were presented sequentially in a 4×4 grid, each dot for 2333 ms. After a delay period of 1500 ms, a red circle appeared for 1500 ms and they had to press a button with their right index finger when the circle was in the same location as any of previously presented dots. If not, they had to press another button with their right middle finger. The control condition used the same stimuli as the working memory task, but with green dots. Children just had to watch the dots and to press a button when a green circle appeared. Three working memory trials (red dots) alternated with three control trials (green dots) for three times. The presentation order was counterbalanced across subjects. The time between conditions was jittered between 5000 and 15,000 ms. Subjects were carefully instructed about the experimental procedure and had to practice trial tasks, before entering the scanner.

2.4. Image acquisition

Brain images were acquired on a 3.0 T whole-body scanner (GE Medical Systems, Milwaukee, WI, USA) using a standard 8-channel head coil. Scan parameters were number of slices (NS): 36 (parallel to the AC-PC line); slice thickness (ST): 3.4 mm; matrix size (MS): 64×64; field of view (FOV): 220 mm $\times$ 220 mm; flip angle (FA): 45°; echo time (TE): 31 ms; repetition time (TR): 2100 ms. The task was presented via video goggles (MRI Audio/Video System, Resonance Technology, Inc., USA) using E-Prime software (Psychology Software Tools Inc.). Three-dimensional anatomical images of the entire brain were obtained by using a T1-weighted gradient echo pulse sequence (NS = 172, ST = 2.0 mm, TR = 9.988 ms, TE = 2.916 ms, FOV = 240 mm $\times$ 240 mm, FA: 20°, MS = 256×192).

2.5. Data analysis

2.5.1. Behavioral data

Two sample *t*-tests and non-parametric Mann–Whitney tests were used as planned comparisons to evaluate behavioral tests outside the scanner. Non-

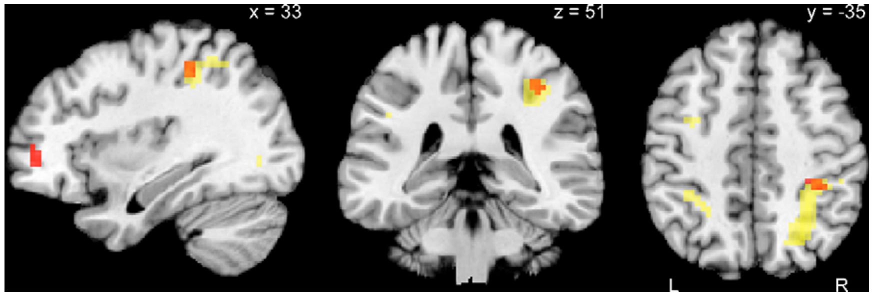

Fig. 1. Statistical maps overlaid onto a reference high resolution anatomical brain image (Colin27 brain, MNI Montreal). Displayed are the within-subject contrasts for control children (yellow, voxel level uncorrected $p < 0.0001$) and between-subject contrasts (red, control children > dyscalculic children, voxel level uncorrected $p < 0.001$) for the contrast between spatial working memory and the control task. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

parametric Mann–Whitney tests were used to evaluate mean response times (red and green circles) and accuracy rate of the scanner task. All statistical procedures were performed with the "Statistical Package for the Social Science 14.0" (SPSS 14.0).

2.5.2. Imaging data

Functional images were analyzed with statistical parametric mapping software (SPM5; http://www.fil.ion.ucl.ac.uk/spm/software/spm5). Brain volumes for each individual were spatially realigned and unwarped. No child had to be removed from the study because of movement artefacts (maximum movement of less than one image-pixel size). A mean functional image volume was constructed for each participant for each session from the realigned image volumes. These mean images were then segmented using an age-matched grey matter brain template (Cincinnati: http://www.irc.cchmc.org/software/pedbrain.php) and normalization parameters were estimated during the segmentation process. These normalization parameters were applied to the original functional brain images for spatial normalization on the children template. Normalized images were resliced to 3 mm^3 and smoothed with a 9 mm full width at half maximum isotorpic Gaussian kernel.

To generate statistical maps for each subject we modelled the expected hemodynamic response for the working memory and control task with a canonical hemodynamic response function, and its temporal and dispersion derivative. The functions were convolved by the event train of stimulus onsets of every dot to create covariates in a general linear model. Three scans were discarded to accommodate for T2 saturation. Parameter estimates for each covariate were obtained by maximum-likelihood estimation while using a temporal high-pass filter (cut-off 128 s) and modelling temporal autocorrelations as an AR(1) process. For group analysis, we conducted the SPM5 implemented standard whole brain second-level random effects analysis. First, we computed one sample *t*-tests for each group to reveal activations for spatial working memory (working memory > control task). Significant voxels are reported at a threshold of $p < 0.0001$, uncorrected. Second, to detect the effect of DD, we computed group comparisons with two sample *t*-tests between children with DD and control children. Significant activation differences between groups are identified at $p < 0.001$, uncorrected (Fig. 1).

Additionally, we conducted correlations between working memory related neural activity in the whole brain (working memory–control task) and performance tests outside the scanner. We performed non-independent correlation analyses with functional region of interests (ROI) to identify if any of the behavioral tests is associated with the fMRI group results. The following ROIs were based on the significant differences between cohorts (working memory > control task, $p < 0.001$): the right intraparietal sulcus (IPS) ($x = 36/y = -42/z = 51$), the right insula (45/−3/6) and right inferior frontal gyrus (33/42/0). ROI spheres of 8 mm radius were generated and analyses were performed using the MarsBar toolbox (http://marsbar.sourceforge.net/) in SPM5. For each participant percent BOLD signal change was extracted from unsmoothed voxels in each ROI, which was correlated with behavioral data of working memory tests and calculation tests. All data are reported in Montreal Neurological Institute (MNI) stereotactic space.

3. Results

3.1. Behavioral performance (outside the scanner)

Mean scores and standard deviations for tests are presented in Table 1. All subjects scored an intelligence quotient (IQ) of 97 or more on the HAWIK-III subtests. This means that all children were within the average range and there was no significant group difference in estimated total subtests IQ or performance IQ but there was a significant difference in verbal IQ. Analysis of the ZAREKI-R of children with DD showed significant different percentile ranges compared to normally achieving children at different subtests and the total score (see Table 1). Table 1 shows also lower performance of the children with DD compared to the control children in all working memory tasks (Corsi Block Tapping test, Block Suppression test and digit span forwards) except of digit span backwards.

3.2. Behavioral performance (inside the scanner)

Behavioral data during scan session demonstrated that both groups had equivalent performance on the working memory task regarding reaction time ($p > 0.42$) and accuracy rate ($p > 0.49$).

Table 1
Demographic and clinical characteristics.

	Dyscalculic group ($N = 10$)		Control group ($N = 11$)		Analysis
	(5/4/1)[a] Mean	SD	(9/2/0)[a] Mean	SD	*t*-Test
Age	10.4	1.2	10.2	1.0	$p > 0.5$
Total IQ	103.7	5.3	109.4	6.7	$p > 0.06$
Verbal IQ	103.2	8.6	110.7	7.2	$p < 0.05$
Performance IQ	104.8	6.9	107.5	8.8	$p > 0.4$
ZAREKI-R, "addition" (percentile rank (PR))	33.3	36.4	80.9	31.0	$p < 0.05$
ZAREKI-R, "number writing" (PR)	36.1	44.5	90.6	21.5	$p < 0.05$
ZAREKI-R, "subtraction" (PR)	9	17.0	70.0	30.8	$p < 0.001$
ZAREKI-R, "number comparison words" (PR)	37.6	43.9	75.6	32.5	$p < 0.05$
ZAREKI-R, total (PR)	17.6	29.3	69.1	21.9	$p < 0.01$
Corsi Block Tapping test	4.5	0.7	5.3	1.0	$p < 0.05$
Block Suppression test	1.9[b]	1.0	3.1	1.2	$p < 0.05$
Digit span forwards	4.4	0.70	5.3	0.79	$p < 0.05$
Digit span backwards	3.0	0.67	3.5	0.82	$p > 0.05$

[a] Handedness (*N*: right/ambidexter/left)
[b] $N = 8$.

Table 2
Regions of significant activation during spatial working memory task in control and dyscalculic children. Listed are peak voxels ($p_{uncorrected} < 0.0001$). (L = left, R = right).

Region of activation	MNI coordinates			*T* score voxel level	Number of voxels in cluster (k_E)
	x	*y*	*z*		
Control group					
R middle occipital gyrus	48	−78	−15	9.07	87
L middle occipital gyrus	−36	−90	9	6.85	36
	27	−60	57	10.19	125
L superior and intraparietal cortex	−27	−48	45	7.91	116
L inferior frontal gyrus	−33	36	6	7.37	37
R middle frontal gyrus	24	−6	66	8.36	22
L putamen	−27	9	0	6.39	59
L caudatus	−18	18	3	11.6	290
R cerebellum	24	−69	−33	8.92	110
L cerebellum	−18	−48	−27	10.28	172
L thalamus	−12	−24	15	9.57	373
Dyscalculic group					
R cuneus	33	−75	30	8.25	235
L cuneus	−24	−93	−6	12.84	439
R lingual gyrus	21	−102	−12	11.12	116
R inferior occipital gyrus	42	−90	−15	8.83	159
L middle occipital gyrus	−51	−72	0	8.22	129
L superior and intraparietal cortex	−21	−63	69	11.71	344
R precuneus	24	−57	45	8.64	120
L inferior parietal lobe	−45	−45	54	8.9	27
R thalamus	12	−24	12	9.78	104
L putamen	42	−90	−15	8.83	159

Table 3
Regions showing significantly greater activation in control compared to dyscalculic children. Listed are peak voxels ($p_{uncorrected} < 0.001$). (L = left, R = right).

Region of activation	MNI coordinates			*T* score voxel level	Number of voxels in cluster (k_E)
	x	*y*	*z*		
R inferior frontal gyrus	33	42	0	4.19	22
R intraparietal sulcus	36	−42	51	3.52	13
R insula	45	−3	6	3.44	21

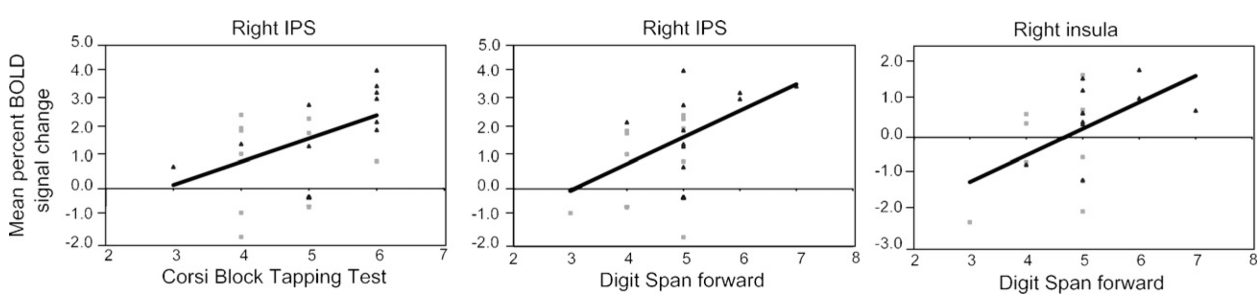

Fig. 2. Shows significant correlations between behavioral test results (Corsi Block Tapping test and the digit span forward) and mean percent BOLD signal change within regions of interest at the right IPS ($x = 36$, $y = -42$, $z = 51$) and the right insula ($x = 45$, $y = -3$, $z = 6$). (grey squares = dyscalculic children, dark triangles = control children).

3.3. fMRI results

In control children the working memory task elicited greater activation when compared with the control task in the following network: bilateral middle occipital, superior and intraparietal and cerebellar regions, but also the left inferior and the right middle frontal gyrus, the left thalamus and the basal ganglia (Table 2).

Children with DD, on the other hand, activated clusters in the right inferior occipital gyrus, the cuneus, the right precuneus and left superior, inferior and intraparietal cortex.

Three regions showed significantly greater activation for the working memory task in the control group compared with the dyscalculic group. Control children showed significantly enhanced activation in the right inferior frontal lobe, the right insula and in the right IPS. There were no regions that showed significantly greater activation in the dyscalculic group compared to the control group (Table 3, Fig. 1).

3.4. Whole brain level correlation analysis and non-independent ROI analyses

The whole brain level correlation with behavioral scores of spatial working memory provided no significant results at the statistical threshold that we used for all tests ($p < 0.001$ uncorrected). The non-independent correlation analyses revealed that the Corsi Block Tapping test ($p = 0.022$) and digit span forward ($p = 0.017$) significantly correlated with the ROI in the IPS. The latter test correlated also with the ROI of the right Insula ($p = 0.016$) (see Fig. 2). There were no other significant correlations with working memory tasks, calculation tests or the frontal ROI.

4. Discussion

Our study provides first evidence for significant changes in neural responses of underlying spatial working memory processes in dyscalculic children compared to normally achieving controls. Control children activated a broad network of bilateral middle occipital and bilateral superior and intraparietal areas during spatial working memory task. Moreover, they activated right middle and left inferior frontal areas, left thalamus and the cerebellum bilaterally. These findings are largely consistent with other studies (Smith & Jonides, 1999; Ungerleider & Haxby, 1994; Wager & Smith, 2003). In contrast to Klingberg et al. (2002), we found no activation in the superior frontal sulcus. This region has been found to exhibit sustained activity during the delay period when information is held in WM. An explanation for this discrepancy in results may lie in the difference between tasks. Klingberg and colleagues used both low and high load conditions, in which three, respectively five dots had to be held in WM. We discarded the high load condition, because we expected children with DD to exhibit problems with high working memory load and aimed to minimize inter-individual and group differences in behavioral performance during scanning.

Children with DD showed no activation clusters in frontal areas but additional clusters within the cuneus, bilaterally, and the right precuneus. Over all, activation clusters seem to be deviant from control children and may indicate a selective impairment of the dorsal stream. Nonetheless, the task was highly sensitive in terms of functional brain imaging. All children were performing above chance level (>60% correct answers) and showed comparable reaction times, indicating that differences in functional brain activation are related to task and not to task difficulty. Additionally, fMRI revealed significant activation patterns associated with cognitive performance outside the scanner.

Our results demonstrate reduced activation in working memory relevant brain areas, such as the right IPS, the right inferior frontal lobe and in the right insula in children with DD when compared to the control group. These activation differences are shown in relatively small clusters which might be caused by the small group size but they are in close relationship to spatial working memory processes (Bor, Duncan, & Owen, 2001; Klingberg, 2006; Smith, Jonides, & Koeppe, 1996).

Like in our VBM study (Rotzer et al., 2008), the right IPS plays a crucial role in the neural network of children with DD. Decreased activation in the right IPS of children with DD during a non-numerical spatial working memory task strongly argues for a central role of the right IPS in both working memory capacity and the acquisition of spatial number representations and arithmetic concepts. There is a recent study revealing atypical activation in the right intraparietal sulcus (Talairach coordinates: 33, −50, 52) during a non-symbolic, numerical magnitude processing task in children with DD (Price et al., 2007). The authors strengthen the hypothesis that DD is caused by ontogenetic disruption of the neural circuitry that supports fundamental representation of numerical magnitude. Our results might indicate that deficient spatial working memory lies at the core of difficulties in non-symbolic numerical magnitude processing.

In a recent study by McNab et al. (2008) a region including the right inferior frontal gyrus and the insula was identified to be associated with inhibition and working memory manipulations. The authors argue that such inhibition processes may play a role in resistance to distraction, which is linked to working memory or, alternatively, an involvement of working memory processes in inhibition tasks (Aron & Poldrack, 2005; Roberts, Hager, & Heron, 1994). Therefore, our results may indicate that children with DD have specific impairments in inhibiting irrelevant information. This is in accordance the clinical observation of frequently associated symptoms of inattentiveness and distractibility in children with DD (von Aster & Shalev, 2007).

Complementary to these differences in neural activation clusters children with DD show significant deficits in working memory tests. The performance in the Corsi Block Tapping test, the Block suppression test, the subtest 'subtraction' of the ZAREKI-R and the digit span forward was significantly lower in children with DD compared to normally achieving controls. These results are in line with findings from other studies (Schuchardt, Maehler, & Hasselhorn, 2008). Visuo-spatial short-term memory span was found to be a predictor specifically of math ability. Correlation and regression analyses revealed visual short-term and working memory to specifically predict math achievement at each time point (Bull et al., 2008; Schuchardt et al., 2008).

D'Amico and Guarnera (2005) examined children with a battery of working memory tests, and found that dyscalculic children showed a deficit in digit span forward, but only when the representation of numerical information was required, rather than the representation or rehearsal of verbal information. Our data are in line with these findings. Interestingly, in our study there are no differences between groups regarding the digit span backward, which is predominantly a measure of verbal working memory. Some studies have found impairments in this domain (D'Amico & Guarnera, 2005; Rosselli et al., 2006), whereas others suggest that children with DD do not appear to have a deficit in working memory for language-related tasks (McLean & Hitch, 1999; Schuchardt et al., 2008). Our results may be explained by the small group size of examined children and therefore additional research about the role of verbal working memory in children with DD is required.

In order to bring the findings from behavioral testing and functional MRI together we conducted correlation analyses on a whole brain level and based on functional ROIs. Whole brain analyses revealed no significant correlations, but significant results of our non-independent correlation analyses were found. These results have to be considered complementary to the results of the group contrast and interpreted carefully because of the small group size, which may contribute to the null result of the whole brain analysis, and significant ROI results, which were based a non-independent contrast between groups (Vul, Harris, Winkielman, & Pashler, 2009). Nevertheless, ROI analyses have the advantage compared to the whole brain analyses that they are based on independent voxel signals in unsmoothed data, which reduces the chance for a false positive result. Activation in the right IPS significantly correlated with the Corsi Block Tapping test and the digit span forward. Digit span forward is a measure of verbal short-term memory and the correlation between the performance on this test and the IPS is in good accordance with a recent study (Majerus et al., 2008) showing a relation between activation of the right IPS and short-term memory for order information. The correlation of the Corsi Block Tapping test performance and the IPS accentuates the close relationship between this region and the impaired spatial working memory capacity in children with DD. But as illustrated in Fig. 2 there are also children without DD with bad performance at the Corsi Block Tapping test showing decreased activation in the right IPS. The role of the IPS in calculation and in spatial working memory processes has been increasingly discussed in recent years and still remains a matter of debate (Ansari & Dhital, 2006; Cohen Kadosh et al., 2005; Dehaene, Bossini, & Giraux, 1993; Dehaene, Molko, Cohen, & Wilson, 2004; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Fias & Fischer, 2005; Knops, Nuerk, Fimm, Vohn, & Willmes, 2006; Nieder, 2004, 2005; Shuman & Kanwisher, 2004; Zago et al., 2001). A study in adults investigated the contributions of spatial working memory manipulation during the addition of numbers (Zago et al., 2008). They found that calculation and spatial manipulation share a common network at the right fronto-parietal hemisphere and that the anterior IPS is involved in tasks requiring magnitude processing with symbolic (numbers) and non-symbolic (locations) stimuli.

In our study we evaluated the neural underpinnings of spatial working memory in children with DD with a task similar to the Corsi

Block Tapping test. Given that this task has no obvious arithmetical or numerical content, the differences in cortical activity between children with DD and normally achieving children in the right IPS strongly supports the notion that a spatial working memory deficit significantly contributes to DD. Our data support the view, that poor spatial working memory capacity may hinder the acquisition of spatial number representations in children with DD (Geary, 1993; von Aster & Shalev, 2007).

Therefore, our results provide novel information about the influence of spatial working memory on the acquisition of arithmetic competencies and help to further improve the understanding of DD.

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