Working Memory Deficits in Children With Specific Learning Disorders

Kirsten Schuchardt

Claudia Maehler

University of Göttingen, Germany

Marcus Hasselhorn

German Institute for International Educational Research, Frankfurt, Germany

This article examines working memory functioning in children with specific developmental disorders of scholastic skills as defined by ICD-10. Ninety-seven second to fourth graders with a minimum IQ of 80 are compared using a 2×2 factorial (dyscalculia vs. no dyscalculia; dyslexia vs. no dyslexia) design. An extensive test battery assesses the three subcomponents of working memory described by Baddeley (1986): phonological loop, visual-spatial sketchpad, and central executive. Children with dyscalculia show deficits in visual-spatial memory; children with dyslexia show deficits in phonological and central executive functioning. When controlling for the influence of the phonological loop on the performance of the central executive, however, the effect is no longer significant. Although children with both reading and arithmetic disorders are consistently outperformed by all other groups, there is no significant interaction between the factors dyscalculia and dyslexia.

Keywords: learning disabilities; dyscalculia; dyslexia; working memory

Children with learning disabilities such as dyslexia or dyscalculia tend to experience significant difficulties in acquiring the core skills of reading, writing, and arithmetic from their very first days at school. Even when the instruction they receive is attuned to their special learning needs, these difficulties tend to persist or increase over the school career. Dyslexia is characterized by a specific and significant impairment in the development of reading skills (often accompanied by poor spelling); dyscalculia by a specific impairment in the acquisition of mathematical skills. There are numerous approaches to the definition and diagnosis of these learning disabilities. Internationally recognized criteria for their diagnosis are specified in the conventional classification systems: the *International Classification of Diseases* (ICD-10) published by the World Health Organization (2005), and the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, text revision* (DSM-IV-TR) published by the American Psychiatric Association (2000). According to these systems, learning disorders are present when individuals' abilities in the domains of reading, spelling, or arithmetic are substantially below their expected potential given their age, general intelligence, and education. In other words, there must be a considerable discrepancy between general intellectual ability and academic achievement. Although

there is an old and enduring controversy concerning the reliability of the discrepancy criterion (Francis et al., 2005; Siegel, 1989; Stanovich, 2005) the World Health Organization and American Psychiatric Association still adhere to these selection criteria. Cutoff points for the size of this critical discrepancy vary between 1 and 2 standard deviations of the psychometric norm distributions. Recent prevalence studies applying the ICD-10 criteria indicate that between 4% and 7% of children are affected by dyslexia (Lewis, Hitch, & Walker, 1994; Miles, Haslum, & Wheeler, 1998; Rutter et al., 2004; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). Hardly less extended prevalence rates (3% to 6%) are reported for dyscalculia (Fuchs et al., 2005; Lewis et al., 1994; Mazzocco & Myers, 2003).

Despite increasing research interest in learning disabilities, consensus has not yet been reached on the specific cognitive deficits that underlie different learning disorders. For a long time, dyslexia was considered to be caused by visual deficits; current deficits in phonological information processing are demonstrated to be responsible (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Causation of dyscalculia is much less clear. Deficiencies in the memory of basic facts, immature strategies, and a less developed number sense are taken into consideration (Geary, 2004).

In recent years, there has been particular interest in deficits in memory, especially working memory, which is responsible for the processing and short-term storage of information. Various models of working memory have been developed, and the model provided by Baddeley (1986) has proved a particularly useful theoretical tool in numerous studies on learning disabilities. The model distinguished between three components of working memory: The modality-free central executive is a kind of supervisory system that serves to control and regulate the cognitive processes occurring in its two limited-capacity slave systems, the phonological loop and the visual-spatial sketchpad. Further functions of the central executive that have since been identified by Baddeley (1996) include coordinating the slave systems, focusing and switching attention, and retrieving representations from long-term memory. The two slave systems perform modality-specific operations. Verbal and auditory information are stored temporarily and processed in the phonological loop. Two components of the phonological loop are distinguished: the phonological store and the subvocal rehearsal process. The visual-spatial sketchpad is concerned with remembering and processing visual and spatial information; it comprises a visual cache for static visual information and an inner scribe for dynamic spatial information (Logie, 1995; Pickering, Gathercole, Hall, & Lloyd, 2001).

Research has provided numerous indications that specific learning disabilities are associated with impairments in working memory (Alloway & Gathercole, 2006; Pickering, 2006a). It is undisputed that children with specific reading disabilities have deficits in phonological processing and storage (Pickering, 2006b; Swanson, 2006; Vellutino et al., 2004), and there is evidence to suggest that they also experience deficits in central executive functioning (Landerl, Bevan, & Butterworth, 2004; Palmer, 2000; Siegel & Ryan, 1989; Swanson, 1993, 1999). There are relatively few reports of impairments in the visual-spatial working memory of reading disabled children, however (Eden & Stein, 1995; Howes, Bigler, Burlingame, & Lawson, 2003; Kibby, Marks, Morgan, & Long, 2004; O'Shaughnessy & Swanson, 1998; Pickering, 2006b).

Empirical findings on children with specific arithmetic learning disabilities are also available for all three domains of working memory (Passolunghi, 2006). There is much evidence to suggest that not all components of working memory show the same kinds of deficits. The central executive seems to be particularly impaired (Geary, Brown, & Samaranayake, 1991; Geary, Hamson, & Hoard, 2000; Geary, Hoard, & Hamson, 1999; Hitch & McAuley, 1991; McLean & Hitch, 1999; Passolunghi

& Siegel, 2001; Siegel & Ryan, 1989; Swanson, 1993; Swanson & Sachse-Lee, 2001; Wilson & Swanson, 2001), but findings on the phonological loop are contradictory. Whereas Geary et al. (1991), Hitch and McAuley (1991), and Swanson and Sachse-Lee (2001) found children with specific arithmetic learning difficulties to show deficits in phonological working memory, no evidence of such impairment was found in the studies by Bull, Johnston, and Roy (1999), Geary et al. (2000), Geary et al. (1999), McLean and Hitch (1999), and Landerl et al. (2004). Thus, deficits in the phonological loop may not be a defining characteristic of children with arithmetic learning disabilities (Passolunghi, 2006). Recent studies (D'Amico & Guarnera, 2005; McLean & Hitch, 1999; Reuhkala, 2001; van der Sluis, van der Leij, & de Jong, 2005; also see Passolunghi, 2006) have reported visual-spatial deficits in children with specific arithmetic disability. However, Bull et al. (1999) and Geary et al. (2000) report arithmetic disabled children and their normally achieving peers to have comparable outcomes on measures of visual-spatial memory.

In sum, research findings on specific impairments of working memory are rather heterogeneous. Potential reasons for these mixed results include the limited comparability of the samples studied and differences in the selection criteria applied and in the instruments used. For example, classifications of learning disabled students differ across studies, with performance below the 25th or 35th percentile on a standardized test often being taken as the decisive criterion. Only few studies have taken into account intellectual ability or have specified a critical discrepancy between ability and achievement. It thus remains unclear whether the findings reported in previous research also apply to children with learning disorders as defined above. In addition, there are notable differences in the procedures used to diagnose learning disorders. Moreover, the various functions of working memory have as yet been operationalized by only a few, very different tasks, thus precluding differentiated analysis of individual components of working memory.

One reason for the heterogeneity of results regarding the precise nature of working memory deficits in children with specific learning disabilities might be the high rate of comorbidity of different learning disabilities. Numerous epidemiological studies have shown a comorbidity between dyscalculia and dyslexia (Badian, 1983; Gross-Tsur, Manor, & Shalev, 1996; Lewis et al., 1994; Ramaa & Gowramma, 2002; cf. Hasselhorn & Schuchardt, 2006). For example, Lewis et al. (1994) found that 2.3% of the children in their study had difficulties with both reading and arithmetic. Because most previous studies have examined the two disorders separately, little is yet known about

the deficits in cognitive functioning present in children with mixed disorders of scholastic skills. Broad deficits in cognitive functioning, and particularly in memory, are assumed. Studies comparing children with specific arithmetic or reading disabilities on one hand, with children with combined learning disabilities on the other, show that the latter group has particularly serious deficits in working memory functions (Geary et al., 1999, 2000; Siegel & Ryan, 1989; van der Sluis et al., 2005). A recent study has analyzed children classified as learning disabled in arithmetic, reading and spelling, or both, but who did not show a notable discrepancy between intellectual ability and achievement (Schuchardt, Kunze, Grube, & Hasselhorn, 2006). No evidence was found of an independent, characteristic pattern of deficits in working memory in the latter group. Similar findings were reported by van der Sluis et al. (2005). However, it remains unclear whether the same applies to children with clinically relevant learning difficulties in both domains.

The aim of the present study was to investigate the functioning of the three subcomponents of working memory in children who meet the ICD-10 criteria for clinically relevant learning disorders. Assessing children with specific learning disorders (i.e., dyslexia or dyscalculia) and children with mixed learning disabilities within a single study design makes it possible to compare the specific deficits in working memory underlying each disorder. Furthermore, using a comprehensive battery of working memory measures including various indicators of the three subcomponents makes it possible to explore whether there are specific deficits in individual components of working memory.

Method

Design

We used a two-factor mixed design: (a) presence or absence of dyscalculia and (b) presence or absence of dyslexia. To this end, we identified three groups of learning-disabled children based on the ICD-10 criteria for specific developmental disorders of scholastic skills: children with specific disorders of arithmetical skills (AD), children with specific reading disorders (RD), and children with mixed disorders of scholastic skills (AD + RD), and formed a control group (C) of normally achieving children matched for chronological age.

Participants

Ninety-seven second-grade to fourth-grade students (age 7-10 years) participated in the study. All children

were screened with standardized tests of intellectual ability, spelling, reading, and arithmetic. We used the full IQ scale from the German version of the Kaufman Assessment Battery for Children (Melchers & Preuß, 2001) to assess general intelligence. Mathematical skills were assessed using standardized German mathematical achievement tests for second, third, and fourth graders (Deutscher Mathematiktest für vierte Klassen [DEMAT 2+], Krajewski, Liehm, & Schneider, 2004; DEMAT 3+, Roick, Göllitz, & Hasselhorn, 2004; DEMAT 4, Göllitz, Roick, & Hasselhorn, 2006). These multicomponent tests include computation problems, word problems, and geometry problems. Spelling abilities were assessed by the Weingartener spelling tests for second and third graders (WRT 2+, Birkel, 1994a; WRT 3+, Birkel, 1994b) and the Westermann spelling test for fourth graders (WRT 4/5, Rathenow, 1980). In both of these standardized German achievement tests, children insert dictated words into given sentences. Reading speed abilities are classified on the basis of scores on two subtests of the Salzburger Lese- und Rechtschreibtest (Salzburg reading test; Landerl, Wimmer, & Moser, 1997): the word reading subtest "Textlesen" (short or long version depending on grade level) and the nonword reading subtest "Wortunähnliche Pseudowörter."

Only native German-speaking children were included in the study sample. The operational criteria for the learning disability subgroups were as follows: (a) $IQ \geq 80$, (b) below-average reading, spelling, and/or arithmetic scores ($T < 40$ [i.e., T -scores: mean of 50 and SD of 10] or percentile < 16), and (c) a critical discrepancy of 1.2 standard deviations between IQ and overall performance on the standardized tests of school achievement. We defined 17 children with T -scores lower than 40 (percentile < 16) in mathematics and T -scores higher than 40 (percentile ≥ 16) in reading and spelling as belonging to the AD group, and 30 children with T -scores lower than 40 (percentile < 16) in reading and spelling but higher than 40 (percentile ≥ 16) in mathematics as belonging to the RD group. Children with T -scores lower than 40 (percentile < 16) on both the reading and arithmetic tests were classified as belonging to the AD + RD group ($n = 20$). The control group ($n = 30$) showed average performance (percentile ≥ 16) on all achievement tests.

We recruited the three learning disability groups from the counseling center for children with learning disabilities at our department. Control group children were second and fourth graders from a public elementary school. None of the children in the study attended special schools.

Table 1 summarizes the four groups' descriptive statistics. On average, the AD and AD + RD groups performed significantly lower on the mathematics abilities test than did

Table 1
Descriptive Statistics

	AD			RD			AD + RD			C		
	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range
Age (months)	103.41	9.11	92 to 124	108.57	10.46	93 to 128	103.70	11.19	87 to 132	108.77	9.53	90 to 126
IQ	93.47	8.83	80 to 109	99.67	7.31	85 to 116	92.80	7.63	80 to 105	100.53	6.41	89 to 110
Spelling	46.81	8.55	41 to 61	33.13	4.83	21 to 39	32.10	6.63	20 to 39	50.97	6.41	41 to 61
Word reading	46.55 ^a	10.16	40 to 56	32.62	7.02	23 to 39	31.05	8.08	21 to 39	52.17	8.42	41 to 63
Nonword reading	48.00 ^a	11.37	41 to 61	33.48	8.06	20 to 39	35.21	11.38	23 to 39	49.04	8.71	41 to 59
Mathematics	30.35	4.46	22 to 39	48.00	8.19	40 to 61	30.90	5.51	15 to 38	50.43	5.59	41 to 60

Note: AD = children with specific disorders of arithmetical skills ($N = 17$, males = 5, females, 12); RD = children with specific reading disorders ($N = 30$, males = 18, females = 12); AD + RD = children with mixed disorders of scholastic skills ($N = 20$, males = 8, females = 12); C = normally achieving control children matched for chronological age ($N = 30$, males = 15, females = 15).

a. Salzburg Reading and Spelling Test data were missing for six participants.

the C and RD groups. At the same time, the RD and AD + RD groups scored significantly lower on spelling and reading tests than did the C and AD groups. Inspection of gender distribution patterns across learning disability groups showed that more AD (70%) and AD + RD (60%) children were female, whereas more RD children were male (60%). There were no differences in gender distribution between children with and without low math achievement, $\chi^2(1) = 2.87$, $p > .05$, and children with and without low achievement scores in reading and spelling, $\chi^2(1) = 0.53$, $p > .05$. Analysis of variance (ANOVA) revealed that the four experimental groups did not differ significantly in terms of age, $F(3, 93) = 1.94$, $\eta^2 = .06$, Mean Square Error = 102.36, $p > .05$. However, the AD and AD + RD groups were on average 5 months younger than the RD and C groups. The groups did differ significantly in terms of intelligence, $F(3, 93) = 6.91$, $\eta^2 = .18$, Mean Square Error = 54.75, $p < .05$. Post hoc comparisons showed that there was no difference in intelligence between the C and the RD group or between the AD and the AD + RD groups but that the AD and AD + RD groups scored significantly lower on intelligence than the other two groups did. We therefore included age and general intelligence as covariates in all subsequent analyses.

Working Memory Assessment

Working memory was assessed by a battery of 16 tasks: 7 phonological tasks (memory spans for digits, one-syllable and three-syllable words, one-syllable and three-syllable nonwords, and images; nonword repetition), 5 visual-spatial tasks (memory span for locations, matrix span simple and complex, corsi-block simple and complex), 4 central executive tasks (double span, backward spans for one-syllable words and digits, counting span). A detailed description of all tasks follows.

Phonological Loop

The digit span is the conventional measure used to assess phonological short-term capacity. A series of one to nine digits was presented acoustically at a rate of one digit per second, starting with two and continuing up to a maximum of eight digits. Participants had to repeat the digits immediately in the presented order. The one-syllable and three-syllable word span tasks and the one-syllable and three-syllable nonword span tasks were presented in the same manner as in the digit span measure. In the one-syllable and three-syllable word span tasks, familiar German nouns (e.g., *Stern* = star, *Fisch* = fish, *Erdbeere* = strawberry, *Briefkasten* = letterbox) were used; the one-syllable and three-syllable nonword span tasks are word-like nonwords (e.g., *fen*, *sim*, *bestrugeln*, *reseubelt*).

In the images span task, participants were presented a series of pictures of easily recognizable objects (e.g., sun, umbrella, door, car) on a computer screen and were asked to recall them in the order of presentation.

The German nonword repetition task administered was developed by Hasselhorn and Körner (1997). Children had to repeat 24 word-like nonwords of two, three, or four syllables immediately after their presentation. Nonwords of different lengths were presented auditorily in random order. The number of correctly repeated nonwords was taken as the score for this task.

Visual-Spatial Sketchpad

In the location span task, children were shown a series of green dots at different locations on a 3×3 matrix and asked to recall these locations in the correct order. Corsi-block tasks were used to assess the dynamic spatial component of visual-spatial memory. Nine red blocks are nailed in random positions on a gray board (23×27.5 cm.).

The experimenter taps a sequence of blocks at the rate of one per second. The child then attempts to reproduce the sequence of taps in the correct order. We used two variations of the corsi-block task: simple sequences involving short distances between blocks without path crossings and complex sequences involving long distances between blocks with path crossings.

A matrix span task was incorporated in the battery to measure the static component of visual-spatial working memory. This task assesses memory for random visual-spatial patterns of increasing complexity. Patterns of white and black boxes in a 4×4 matrix were presented on the computer, beginning with two black boxes and continuing up to a maximum of eight black boxes. Immediately after presentation, children were asked to reproduce the pattern in an empty matrix. Two variations of this task were also implemented: a simple matrix span with the black boxes arranged in simple patterns and a complex matrix span with the black boxes located at some distance from one another.

Central Executive

The same items and procedures were used for the backward digit and word span tasks as for the forward spans, the only difference being that participants were required to recall the sequences of items in reverse order. In addition, a double span task was implemented to assess the children's ability to coordinate the functioning of the phonological loop and the visual-spatial sketchpad. The same pictures as in the images span task were presented, but this time in different locations on a 3×3 matrix. Children had to recall simultaneously the pictures by verbally recoding the semantic content (phonological demand) and their location (visual-spatial demand) in the order of presentation. Thus, this task is properly viewed as a central executive task due to its coordinative requirements. The complex counting span task, a measure of storage and processing efficiency, was based on a task designed by Case, Kurland, and Goldberg (1982). A series of yellow circles (target items) and squares (distractor items) was presented in a random, computer-generated pattern. Children were instructed to count the number of circles. Subsequently, another map was presented and children again had to count the number of circles. Finally, the experimenter asked the child to recall the number of circles counted on each map. The number of maps presented per sequence was steadily increased up to a maximum of eight.

Stop criterion. We used the same stop criterion for all span tasks. The length of the sequences presented was increased gradually, beginning with a minimum of two

items and increasing to a maximum of eight items. There were four trials at each sequence length. If an error was made, the child was given a second attempt at an item of the same length. If a child succeeded on two successive trials of the same length, the task continued with the next span length. If a child failed on two successive trials of the same length, he or she was not presented with any further sequences of the same length but with a sequence one item shorter. The dependent measure for all span tasks was the longest sequence of items repeated in correct order. Children were credited an extra fourth point if they repeated a further sequence of the same length correctly (e.g., a score of 5.25 was awarded if two of four five-item sequences were recalled correctly, 5.5 if three of four sequences, and 5.75 if all four sequences were recalled correctly).

Procedure. Children with learning disabilities were administered standardized tests of spelling, reading, and arithmetic, intelligence, and working memory individually in two separate sessions. The DEMAT and WRT measures were administered to control group children in classroom learning groups. All other tests were administered individually within 3 weeks. Except for the corsi-block task, all working memory tasks were administered by computer. The order of presentation of the working memory tasks was the same for all children (images span, location span, double span, one-syllable word span, three-syllable word span, corsi-block simple, corsi-block complex, nonword repetition, backward word span, backward digit span, counting span, digit span, matrix span simple, matrix span complex, one-syllable nonword span, three-syllable nonword span).

Results

For all tests the alpha level was set at $p = .05$.

Table 2 presents means and standard deviations for all working memory measures by the four groups. Scores on the three components of working memory tasks were entered in multivariate analyses of variance (MANOVAs) with presence or absence of dyscalculia and dyslexia as fixed factors. IQ and chronological age were included as covariates in all subsequent analyses.

Phonological Loop

The scores on the seven tasks assessing phonological loop functioning were entered into a multivariate analysis of variance (MANOVA). The multivariate main effect for dyslexia, $F(7, 85) = 6.91$, $\eta^2 = .36$, $p < .001$, proved to be significant. The multivariate main effect for dyscalculia, $F(7, 85) < 1$, and the dyslexia by dyscalculia interaction were not significant, $F(7, 85) < 1$. Table 3 presents all univariate tests of phonological working memory. For the

Table 2
Working Memory Measures by Subgroup

	AD		RD		AD + RD		C	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Phonological loop								
Digit span	5.09	0.74	4.63	0.64	4.19	0.50	5.19	0.61
One-syllable word span	4.47	0.67	4.28	0.74	3.85	0.58	4.62	0.66
Three-syllable word span	3.67	0.47	3.64	0.47	3.24	0.46	3.86	0.43
One-syllable nonword span	3.85	0.58	3.47	0.89	3.19	0.96	4.27	0.50
Three-syllable nonword span	2.09	1.27	1.34	1.22	1.27	1.22	2.43	0.74
Images span	4.35	0.72	4.22	0.77	3.71	0.56	4.60	0.84
Nonword repetition	19.76	2.11	17.47	3.13	17.85	4.66	20.93	1.78
Visual-spatial sketchpad								
Location span	4.60	0.75	5.26	1.00	4.36	0.66	4.98	0.80
Corsi-block simple	5.43	0.98	5.68	1.34	4.94	1.10	5.78	1.36
Corsi-block complex	3.90	0.95	4.80	0.85	3.87	1.24	4.98	1.08
Matrix span simple	5.37	1.63	6.72	1.11	5.31	1.15	6.50	1.29
Matrix span complex	3.00	1.25	4.45	1.63	3.31	1.08	4.72	1.52
Central executive								
Backward digit span	3.71	0.56	3.45	0.66	3.10	0.86	3.90	0.68
Backward words span	3.46	0.57	3.58	0.56	3.19	0.31	3.82	0.63
Double span	3.76	0.79	3.78	0.76	3.31	0.55	4.04	0.72
Counting span	3.87	0.97	3.81	0.89	3.20	0.71	4.45	0.97

Note: AD = children with specific disorders of arithmetical skills; RD = children with specific reading disorders; AD + RD = children with mixed disorders of scholastic skills; C = normally achieving control children matched for chronological age.

dyslexia factor, univariate tests showed significant differences between groups on all phonological tasks.

Visual-Spatial Sketchpad

The scores on the five tasks assessing visual-spatial sketchpad were entered into a MANCOVA. The multivariate main effect for dyscalculia, $F(5, 87) = 4.31$, $\eta^2 = .20$, $p < .01$, proved significant. In contrast, the multivariate main effect for dyslexia, $F(5, 87) < 1$, and the Dyscalculia X Dyslexia interaction, $F(5, 87) = 1.44$, $\eta^2 = .08$, $p > .05$, were not significant. The univariate tests of visual-spatial sketchpad are presented in Table 4. For the dyscalculia factor, univariate tests of visual-spatial working memory tasks revealed significant differences between groups on all visual-spatial memory tasks with the exception of the corsi-block simple task.

Central Executive

Finally, the scores on the four tasks assessing central executive were entered into a MANCOVA. The multivariate main effect for dyscalculia, $F(4, 88) < 1$, was not significant. In contrast, the multivariate main effect for dyslexia, $F(4, 88) = 5.79$, $\eta^2 = .208$, $p < .000$, proved to be significant. The interaction of the two factors was not significant, $F(4, 88) < 1$. All univariate tests are

presented in Table 5. For the dyslexia factor, univariate tests showed significant differences between groups on all central executive memory tasks.

However, when we controlled for the influence of the phonological loop on the performance of the central executive, the differences in measures of central executive functioning between children with (RD and AD + RD) and without (AD and C) dyslexia were no longer significant. Specifically, when ANCOVAs (analyses of covariance) were used to control for performance on one-syllable word span forward in the word backward span task, $F(1, 91) = 1.53$, $\eta^2 = .02$, $p > .05$, for performance on images span in the double span task, $F(1, 91) = 1.22$, $\eta^2 = .01$, $p > .05$, for performance on digit span in the counting span task, $F(1, 91) = 1.21$, $\eta^2 = .01$, $p > .05$, and for performance on both digit span forward and nonword repetition in the word backward span task, $F(1, 91) = 3.65$, $\eta^2 = .04$, $p > .05$, no significant effects were found. Therefore, we conclude that the predominant working memory deficit in dyslexia is not in central executive but in phonological loop functioning.

In summary, children in the RD group and C group (without dyscalculia) outperformed children in the AD and AD + RD groups (with dyscalculia) on all measures of visual-spatial memory. At the same time, children in the AD group and C group (without dyslexia) outperformed children in the RD and AD + RD groups (with dyslexia) on all measures of phonological memory.

Table 3
MANCOVA Phonological Loop

	<i>F</i>	<i>p</i>	η^2
Dyscalculia			
Digit span	< 1	<i>ns</i>	—
One-syllable word span	< 1	<i>ns</i>	—
Three-syllable word span	2.60	<i>ns</i>	—
One-syllable nonword span	1.38	<i>ns</i>	—
Three-syllable nonword span	< 1	<i>ns</i>	—
Images span	< 1	<i>ns</i>	—
Nonword repetition	< 1	<i>ns</i>	—
Dyslexia			
Digit span	32.13	.000	.261
One-syllable word span	11.36	.001	.111
Three-syllable word span	12.27	.001	.119
One-syllable nonword span	21.27	.000	.189
Three-syllable nonword span	16.94	.000	.157
Images span	10.64	.002	.105
Nonword repetition	17.65	.000	.162
Dyscalculia X Dyslexia			
Digit span	1.92	<i>ns</i>	—
One-syllable word span	1.19	<i>ns</i>	—
Three-syllable word span	1.58	<i>ns</i>	—
One-syllable nonword span	< 1	<i>ns</i>	—
Three-syllable nonword span	< 1	<i>ns</i>	—
Images span	< 1	<i>ns</i>	—
Nonword repetition	1.48	<i>ns</i>	—

Table 4
MANCOVA Visual-Spatial Sketchpad

	<i>F</i>	<i>p</i>	η^2
Dyscalculia			
Location span	6.25	.014	.064
Corsi-block simple	2.48	<i>ns</i>	—
Corsi-block complex	13.06	.000	.125
Matrix span simple	8.42	.005	.085
Matrix span complex	12.96	.001	.125
Dyslexia			
Location span	< 1	<i>ns</i>	—
Corsi-block simple	1.25	<i>ns</i>	—
Corsi-block complex	< 1	<i>ns</i>	—
Matrix span simple	< 1	<i>ns</i>	—
Matrix span complex	< 1	<i>ns</i>	—
Dyscalculia X Dyslexia			
Location span	2.68	<i>ns</i>	—
Corsi-block simple	< 1	<i>ns</i>	—
Corsi-block complex	< 1	<i>ns</i>	—
Matrix span simple	< 1	<i>ns</i>	—
Matrix span complex	< 1	<i>ns</i>	—

Discussion

The aim of the present study was to analyze the role of the different components of working memory in various learning disabilities defined according to ICD-10. To this

Table 5
MANCOVA Central Executive

	<i>F</i>	<i>p</i>	η^2
Dyscalculia			
Backward digit span	< 1	<i>ns</i>	—
Backward words span	2.52	<i>ns</i>	—
Double span	< 1	<i>ns</i>	—
Counting span	1.35	<i>ns</i>	—
Dyslexia			
Backward digit span	13.95	.000	.133
Backward words span	5.17	.025	.054
Double span	5.53	.021	.057
Counting span	13.07	.000	.126
Dyscalculia X Dyslexia			
Backward digit span	< 1	<i>ns</i>	—
Backward words span	< 1	<i>ns</i>	—
Double span	< 1	<i>ns</i>	—
Counting span	< 1	<i>ns</i>	—

end, a broad battery of working memory measures was used to assess phonological, visual-spatial, and central executive functioning in children with specific disorders of arithmetical skills, specific reading disorders, and mixed disorders of scholastic skills, and in a control group of normally achieving peers.

Altogether, results confirm the value of using a comprehensive battery of measures to assess the cognitive memory deficits of children with clinically relevant learning disorders. Whereas previous findings have been mixed, the presented direct comparison of different learning disabilities within a single study design provides broad support for distinct patterns of working memory deficits. For example, independent of differences in age and IQ, children with specific reading disorders were found to have marked impairments in the phonological loop, scoring significantly lower than their peers without reading disorders on all seven phonological working memory tasks. This result replicates findings from numerous empirical studies that have reported phonological deficits in children with dyslexia (e.g., Gathercole, Alloway, Willis, & Adams, 2006; Helland & Asbjørnsen, 2004; Kibby et al., 2004; Siegel & Linder, 1984). Children with specific reading disorders also exhibited poor performance in tasks testing central executive functioning. Because all of the tasks selected to assess central executive functioning drew on the phonological loop, however, it was important to control its influence on performance in central executive tasks. It is interesting that the significant differences in all measures disappeared when phonological working memory scores were partialled out, indicating that the most relevant working memory deficit in children with specific reading

disorders is the phonological impairment rather than deficits in central executive functioning. Because performances on all tasks involving the phonological subsystem are impaired, it seems reasonable to assume an isolated but massive impairment of this subsystem.

The consistently good results of children with reading and spelling disorders on visual-spatial working memory tasks attest to the unimpaired functioning of the visual-spatial sketchpad in this population. This result is in line with the findings of Gould and Glencross (1990) and Kibby et al. (2004), who also found the visual-spatial slave system to function unimpaired in children with dyslexia. Based on these findings, it seems rather unlikely that visual processing and storage is impaired in children with developmental dyslexia.

A characteristic pattern of deficits was also found for children with specific disorders of arithmetic skills, namely, a specific impairment in the functioning of the visual-spatial sketchpad. Children with arithmetic learning disorders scored markedly lower than their peers without such disorders on the visual-spatial working memory tasks. It was only in the simple version of the corsi-block task that the difference in performance did not reach statistical significance. Overall, all children performed higher on the simple task versions (corsi-block simple, matrix span simple) than on the complex task versions (corsi-block complex, matrix span complex). However, children with and without arithmetic learning disorders did not differ in terms of the magnitude of this difference: In both groups, it was approximately two sequence lengths for the simple and complex matrix span tasks and just under one sequence length for the corsi-block tasks. Thus, variation in the degree of complexity of these tasks does not help to explain the specific pattern of impairment in visual-spatial memory exhibited by children with arithmetic learning disorders. With regard to the theoretical distinction between a more static visual cache and a more dynamic inner scribe component of the visual-spatial sketchpad (Pickering et al., 2001), it seems appropriate to pursue the question of whether the working memory deficiencies in children with dyscalculia are more prone to one or the other component. Because the performance of children with specific arithmetic disorders was, overall, much lower on the indicators measuring the dynamic component (location span, corsi-block complex) and the matrix span tasks measuring the static component, broad impairments in the visual-spatial sketchpad can be assumed. However, this conclusion contradicts the hypotheses of several researchers who assume the storage of dynamic spatial information—rather than the entire visual-spatial sketchpad—to be impaired (McLean & Hitch, 1999; also see Passolunghi, 2006) in students with specific arithmetic learning disabilities.

We did not find children with specific arithmetical disorders to show any impairment in phonological working memory. This finding is in line with the results of several other studies (Geary et al., 1999, 2000; McLean & Hitch, 1999).

It is surprising that in contrast to previous findings (Geary et al., 1991, 1999, 2000; Hitch & McAuley, 1991; McLean & Hitch, 1999; Passolunghi & Siegel, 2001; Siegel & Ryan, 1989; Swanson, 1993; Swanson & Sachse-Lee, 2001; Wilson & Swanson, 2001), we did not find evidence for impairments in the central executive functioning of children with specific arithmetic disorders. This discrepancy may be attributable to differences in the classification of arithmetic learning disorders. Whereas only children with average intellectual abilities were included in the present study, children with lower levels of intellectual ability were also classified as having specific arithmetic learning difficulties in studies such as those by Geary et al. (2000) and Geary et al. (1999) and McLean and Hitch (1999). In addition, many previous studies with children with arithmetic disorders did not explicitly control for reading and spelling achievement. Therefore, the possibility that some comorbid disabled (dyslexia and dyscalculia) children might be responsible for the reported poor central executive task performance cannot be ruled out. Another point that warrants mention is that the studies differ in their measures of central executive working memory. The measures of backward span, double span, and counting span administered in the present study assess the coordination of processing and storing information. Thus, the possibility that the weak arithmetic skills measured are attributable to deficits in other specific subfunctions such as selective attention or retrieval from long-term memory cannot be excluded.

Children with impairments in just one domain clearly outperformed children with combined arithmetic and reading disorders on almost all tasks administered in the present study. The interaction between the factors dyscalculia and dyslexia was not significant, however. In other words, the present findings do not suggest independent patterns of deficits in these children (cf. Schuchardt et al., 2006; van der Sluis et al., 2005). Rather, the results indicate that these children exhibit both deficits (i.e., those found for specific disorders of arithmetic skills and for specific disorders of reading and writing, but to a greater extent).

To conclude, comparison of children with different learning disorders revealed marked differences in working memory functioning. It is therefore important for future research to apply strict criteria to distinguish between children with specific disorders of arithmetical skills, children with specific disorders of reading and writing, and children with mixed disorders of scholastic skills,

because these three subgroups show differential deficits in cognitive functioning.

Although a number of implications might be warranted from our finding that specific learning disorders are associated with distinct deficits in working memory functioning, one of them seems to be of utmost practical importance from our point of view. If deficiencies in children's phonological loop are an important precursor of dyslexia, and if deficiencies in children's visual-spatial sketchpad are a precursor of dyscalculia, one might use this knowledge for an early identification of children at risk a long time before they meet the ICD-10 criteria of learning disorders at about the age of 8 years or so. One advantage of such an early identification of children with a risk for specific learning disorders would be the opportunity to apply focused prevention programs to them, which might reduce the severeness of the adumbrated learning disorder.

References

- Alloway, T. P., & Gathercole, S. E. (2006). *Working memory and neurodevelopmental disorders*. Hove, UK: Psychology Press.
- American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed, text revision). Washington, DC: Author.
- Baddeley, A. D. (1986). *Working memory*. Oxford, UK: Oxford University Press.
- Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, 49, 5-28.
- Badian, N. A. (1983). Arithmetic and nonverbal learning. In H. R. Myklebust (Ed.), *Progress in learning disabilities* (Vol. 5, pp. 253-264). New York: Grune & Stratton.
- Birkel, P. (1994a). *Weingartener Grundwortschatz Rechtschreib-Test für zweite und dritte Klassen (WRT 2+)* [Weingarten basic vocabulary spelling test for second and third grades (WRT 2+)]. Göttingen, Germany: Hogrefe.
- Birkel, P. (1994b). *Weingartener Grundwortschatz Rechtschreib-Test für dritte und vierte Klassen (WRT 3+)* [Weingarten basic vocabulary spelling test for third and fourth grades (WRT 3+)]. Göttingen, Germany: Hogrefe.
- Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology*, 15, 421-442.
- Case, R. D., Kurland, M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386-404.
- D'Amico, A., & Guarnera, M. (2005). Exploring working memory in children with low arithmetical achievement. *Learning and Individual Differences*, 15, 189-202.
- Eden, G. F., & Stein, J. F. (1995). Verbal and visual problems in reading disability. *Journal of Learning Disabilities*, 28, 272-290.
- Francis, D. J., Fletcher, J. M., Stuebing, K. K., Lyon, G. R., Shaywitz, F. A., & Shaywitz, S. E. (2005). Psychometric approaches to the identification of LD: IQ and achievement scores are not sufficient. *Journal of Learning Disabilities*, 38, 98-108.
- Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., & Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *Journal of Educational Psychology*, 97, 493-513.
- Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A. M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology*, 93, 265-281.
- Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities*, 37, 4-15.
- Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental Psychology*, 27, 787-797.
- Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology*, 77, 236-263.
- Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology*, 74, 213-239.
- Görlitz, D., Roick, T., & Hasselhorn, M. (2006). *Deutscher Mathematiktest für vierte Klassen (DEMAT 4)* [German mathematics test for fourth grades (DEMAT 4)]. Göttingen, Germany: Beltz.
- Gould, J. H., & Glencross, D. J. (1990). Do children with a specific reading disability have a general serial-ordering deficit? *Neuropsychologia*, 28, 271-278.
- Gross-Tsur, V., Manor, O., & Shalev, R. S. (1996). Developmental dyscalculia: Prevalence and demographic features. *Developmental Medicine and Child Neurology*, 38, 25-33.
- Hasselhorn, M., & Körner, K. (1997). *Nachsprechen von Kunstwörtern: Zum Zusammenhang zwischen Arbeitsgedächtnis und syntaktischen Sprachleistungen bei Sechs- und Achtjährigen* [Repeating nonwords: The relationship between working memory and syntactic competence in six- and eight-year-olds]. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, 29, 212-224.
- Hasselhorn, M., & Schuchardt, K. (2006). Lernstörungen: Eine kritische Skizze zur Epidemiologie [Learning disabilities: A critical sketch on epidemiology]. *Kindheit und Entwicklung*, 15, 208-215.
- Helland, T., & Asbjørnsen, A. (2004). Digit span in dyslexia: Variations according to language comprehension and mathematics skills. *Journal of Clinical and Experimental Neuropsychology*, 26, 31-43.
- Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. *British Journal of Psychology*, 82, 375-386.
- Howes, N. L., Bigler, E. D., Burlingame, G. M., & Lawson, J. S. (2003). Memory performance of children with dyslexia. *Journal of Learning Disabilities*, 36, 230-246.
- Kibby, M., Marks, W., Morgan, S., & Long, C. (2004). Specific impairment in developmental reading disabilities: A working memory approach. *Journal of Learning Disabilities*, 37, 349-363.
- Krajewski, K., Liehm, S., & Schneider, W. (2004). *Deutscher Mathematiktest für zweite Klassen (DEMAT 2+)* [German mathematics test for second grades (DEMAT 2+)]. Göttingen, Germany: Beltz.
- Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students. *Cognition*, 93, 99-125.
- Landerl, K., Wimmer, H., & Moser, E. (1997). *Salzburger Lese- und Rechtschreibtest (SLT)* [Salzburg reading and spelling test (SLT)]. Bern, Switzerland: Huber.
- Lewis, C., Hitch, G. J., & Walker, P. (1994). The prevalence of specific arithmetic difficulties and specific reading difficulties in 9- to 10-year-old boys and girls. *Journal of Child Psychology and Psychiatry*, 35, 283-292.

- Logie, R. H. (1995). *Visual-spatial working memory*. Hove, UK: Lawrence Erlbaum.
- Mazzocco, M. M., & Myers, G. F. (2003). Complexities in identifying and defining mathematics learning disability in the primary school-age years. *Annals of Dyslexia*, 53, 218-253.
- McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, 74, 240-260.
- Melchers, P., & Preuß, U. (2001). *Assessment Battery for Children (K-ABC), German version* (5th ed.). Göttingen, Germany: Hogrefe.
- Miles, T. R., Haslum, M. N., & Wheeler, T. J. (1998). Gender ratio in dyslexia. *Annals of Dyslexia*, 48, 27-55.
- O'Shaughnessy, T., & Swanson, H. L. (1998). Do immediate memory deficits in students with learning disabilities in reading reflect a developmental lag or deficit? A selective meta-analysis of the literature. *Learning Disability Quarterly*, 21, 123-148.
- Palmer, S. (2000). Phonological recoding deficit in working memory of dyslexic teenagers. *Journal of Research in Reading*, 23, 28-40.
- Passolunghi, M. C. (2006). Working memory and arithmetic learning disability. In T. P. Alloway & S. E. Gathercole (Eds.), *Working memory and neurodevelopmental disorders* (pp. 113-138). Hove, UK: Psychology Press.
- Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with specific arithmetic learning disabilities. *Journal of Experimental Child Psychology*, 80, 44-57.
- Pickering, S. J. (Ed.). (2006a). *Working memory and education*. San Diego, CA: Academic Press.
- Pickering, S. J. (2006b). Working memory in dyslexia. In T. P. Alloway & S. E. Gathercole (Eds.), *Working memory and neurodevelopmental disorders* (pp. 7-40). Hove, UK: Psychology Press.
- Pickering, S. J., Gathercole, S. E., Hall, M., & Lloyd, S. A. (2001). Development of memory for pattern and path: Further evidence for the fractionation of visuo-spatial memory. *The Quarterly Journal of Experimental Psychology*, 54, 397-420.
- Ramaa, S., & Gowramma, I. P. (2002). A systematic procedure for identifying and classifying children with dyscalculia among primary school children in India. *Dyslexia*, 8, 67-85.
- Rathenow, P. (1980). *Westermann Rechtschreibtest 4/5 (WRT 4/5)*. Braunschweig, Germany: Westermann.
- Reuhkala, M. (2001). Mathematical skills in ninth-graders: Relationship with visuospatial abilities and working memory. *Educational Psychology*, 21, 387-398.
- Roick, T., Göllitz, D., & Hasselhorn, M. (2004). *Deutscher Mathematiktest für dritte Klassen (DEMAT 3+)* [German mathematics test for third grades (DEMAT 3+)]. Göttingen, Germany: Beltz.
- Rutter, M., Caspi, A., Fergusson, D., Horwood, L. J., Goodman, R., Maughan, B., et al. (2004). Gender differences in developmental reading disability: New findings from four epidemiological studies. *Journal of the American Medical Association*, 291, 2007-2012.
- Schuchardt, K., Kunze, J., Grube, D., & Hasselhorn, M. (2006). Arbeitsgedächtnisdefizite bei Kindern mit schwachen Rechen- und Schriftsprachleistungen [Working memory deficits in children with low mathematics and verbal performance]. *Zeitschrift für Pädagogische Psychologie*, 20, 261-268.
- Shaywitz, S. E., Escobar, M. D., Shaywitz, B. A., Fletcher, J. M., & Makuch, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *New England Journal of Medicine*, 326, 145-150.
- Siegel, L. S. (1989). Why we do not need intelligence test scores in the definition and analyses of learning disabilities. *Journal of Learning Disabilities*, 22, 514-515.
- Siegel, L. S., & Linder, B. A. (1984). Short-term memory processes in children with reading and arithmetic disabilities. *Developmental Psychology*, 20, 200-207.
- Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development*, 60, 973-980.
- Stanovich, K. E. (2005). The future of a mistake: Will discrepancy measurement continue to make the learning disabilities field a pseudoscience? *Learning Disability Quarterly*, 28, 103-106.
- Swanson, H. L. (1993). Working memory in learning disability subgroups. *Journal of Experimental Child Psychology*, 56, 87-114.
- Swanson, H. L. (1999). Reading comprehension and working memory in learning-disabled readers: Is the phonological loop more important than the executive system? *Journal of Experimental Child Psychology*, 72, 1-31.
- Swanson, H. L. (2006). Working memory and reading disabilities: Both phonological and executive processing deficits are important. In T. P. Alloway & S. E. Gathercole (Eds.), *Working memory and neurodevelopmental disorders* (pp. 59-88). Hove, UK: Psychology Press.
- Swanson, H. L., & Sachse-Lee, C. (2001). A subgroup analysis of working memory in children with reading disabilities: Domain-general or domain-specific deficiency? *Journal of Learning Disabilities*, 34, 249-263.
- van der Sluis, S., van der Leij, A., & de Jong, P. F. (2005). Working memory in Dutch children with reading- and arithmetic-related LD. *Journal of Learning Disabilities*, 38, 207-221.
- Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades. *Journal of Child Psychology and Psychiatry*, 45, 2-40.
- Wilson, K. M., & Swanson, H. L. (2001). Are mathematics disabilities due to a domain-general or a domain-specific working memory deficit? *Journal of Learning Disabilities*, 34, 237-248.
- World Health Organization. (2005). *ICD: Classification of mental and behavioural disorders: Clinical descriptions and diagnostic guidelines* (10th rev. ed.). Geneva, Switzerland: Author.

Kirsten Schuchardt is a postgraduate student at the University of Göttingen in developmental and educational psychology. Her research focuses on working memory functioning in children with learning disabilities.

Claudia Maehler, PhD, is a member of the scientific staff at the University of Göttingen in developmental and educational psychology. She is interested in learning disabilities, working memory, and naive theories in children's thinking.

Marcus Hasselhorn, PhD, is a full professor of psychology and head of the Center for Education and Development at the German Institute of International Educational Research in Frankfurt am Main, Germany. He is also a member of the psychology departments at the University of Göttingen and at the University of Frankfurt. His current interests include learning disorders, intellectual disabilities, working memory functioning, and cognitive development across the life span.