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Working Memory in Children With Learning Disabilities in Reading Versus Spelling: Searching for Overlapping and Specific Cognitive Factors

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Abstract

In transparent orthographies like German, isolated learning disabilities in either reading or spelling are common and occur as often as a combined reading and spelling disability. However, most issues surrounding the cognitive causes of these isolated or combined literacy difficulties are yet unresolved. Recently, working memory dysfunctions have been demonstrated to be promising in explaining the emergence of literacy difficulties. Thus, we applied a 2 (reading disability: yes vs. no) × 2 (spelling disability: yes vs. no) factorial design to examine distinct and overlapping working memory profiles associated with learning disabilities in reading versus spelling. Working memory was assessed in 204 third graders, and multivariate analyses of variance were conducted for each working memory component. Children with spelling disability suffered from more pronounced phonological loop impairments than those with reading disability. In contrast, domain-general central-executive dysfunctions were solely associated with reading disability, but not with spelling disability. Concerning the visuospatial sketchpad, no impairments were found. In sum, children with reading disability and those with spelling disability seem to be characterized by different working memory profiles. Thus, it is important to take both reading and spelling into account when investigating cognitive factors of literacy difficulties in transparent orthographies.

Keywords

working memory, reading, spelling, learning disabilities, transparent orthographies

Approximately 14% of elementary school children in Germany exhibit severe difficulties when learning to read and spell despite adequate schooling and normal intelligence (Fischbach et al., 2013). Stimulated by the tremendous importance of reading and spelling skills in our everyday life, in the past five decades many research activities were addressed to the cognitive causes of those literacy difficulties (see Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, most of this research has been conducted in English-speaking countries, thereby predominantly including children acquiring the opaque orthography English (Miles, 2000; Share, 2008). Opaque orthographies are characterized by irregular grapheme-to-phoneme correspondences, which result in various mappings between letters and sounds. Yet, in contrast to English, most of the world's languages are far more transparent in terms of their grapheme-to-phoneme relations and thus show a high degree of one-to-one mappings (e.g., German, Greek, and Hungarian). Given these differences between orthographies, the question came up as to what extent the English findings can be generalized to other orthographies (Aro & Wimmer, 2003; Goswami, Ziegler, Dalton, & Schneider, 2001; Smythe et al., 2008; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). This caution stems from the striking finding of cross-language studies that the manifestation of literacy difficulties is not universal but depends on the special characteristics of the orthography within which the difficulties occur (Landerl, Wimmer, & Frith, 1997; Vellutino et al., 2004). Consequently, research has shifted from a general to a more sophisticated approach to

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investigate learning disabilities in literacy. The present article follows this reorientation in the field by addressing a special feature and common phenomenon found in transparent orthographies, namely the dissociation between reading and spelling skills in the manifestation of literacy difficulties.

Reading and Spelling in Transparent Orthographies

In contrast to English, where reading and spelling skills are highly correlated with each other (r = .68–.86; see Ehri, 2000), the respective correlations are only moderate in transparent orthographies. For German orthography, for instance, this correlation is only around r = .56 (e.g., Moll & Landerl, 2009), thereby indicating that the developmental trajectories of these two literacy skills are more independent than in opaque orthographies. Indeed, isolated learning disabilities in either reading or spelling among German school children are at least as prevalent as a combined reading and spelling disability (Fischbach et al., 2013; Landerl & Moll, 2010). Thus, in transparent orthographies poor readers are not necessarily also poor spellers and vice versa. This phenomenon arises because orthographic regularity is only true for grapheme-to-phoneme correspondence (relevant in reading), but not for phoneme-to-grapheme correspondence (relevant in spelling). For example, reading the grapheme *ee* leads to the distinct German sound /e:/. In contrast, when transcribing the phoneme /e:/ various graphemes, and thus different spellings can be realized (e.g., *ee* like in S*ee* [lake], *eh* like in Z*eh* [toe], *e* like in *E*ber [boar]). As a consequence, from a phonological processing perspective, learning to spell German is more demanding than learning to read German.

The Working Memory Model by Baddeley (1986)

Mechanisms and limitations of phonological processing are captured in working memory approaches. According to Baddeley (1986) working memory consists of an attentional control system called the *central executive* and two domain-specific subsidiary systems of limited capacity, the *visuospatial sketchpad* and the *phonological loop*. The visuospatial sketchpad is responsible for the passive and temporary storage of visuospatial information. This is accomplished via two specialized subprocesses: Whereas visuostatic information (e.g., shape, color) is maintained in a visual store called the *visual cache*, spatial-dynamic information (e.g., movement) triggers spatial rehearsal attributed to the *inner scribe* (Logie, 1995). Correspondingly, the phonological loop is in charge of maintaining phonological information and is subdivided into a *phonological store* and an *articulatory rehearsal process*: Speech-based information receives direct access to the store, where it is retained passively for approximately 2 s on average (Baddeley, 2012) before it decays. Yet memory decay can be prevented by the rehearsal process, which initiates a subvocal repetition of the memory trace and thereby strengthens its representation within the phonological store. The domain-general central executive regulates complex cognitive processing and is thus involved in attentionally demanding tasks that require both the simultaneous storage and processing of information (Baddeley, 1996). Given that the central executive is modality free (Baddeley, 2012), complex processing not only involves the central executive but places additional storage demands on one or both subsidiary systems.

Working Memory in Children With Learning Disabilities in Reading Versus Spelling

So far, few studies have addressed the question of whether or not reading disabilities come along with other working memory profiles than do spelling disabilities in transparent orthographies. In contrast, a lot of studies have applied operational criteria that confound both factors by either including only children with a combined reading and spelling disability or by only unsystematically including children with severe difficulties in reading and/or spelling. Nevertheless, it is evident from these studies that children with literacy difficulties show severe impairments in the central executive and the phonological loop (de Weerdt, Desoete, & Roeyers, 2013; Maehler & Schuchardt, 2011; Marx, Weber, & Schneider, 2001; Porpodas, 1999; Schuchardt, Maehler, & Hasselhorn, 2008; Steinbrink & Klatte, 2008), but not in the visuospatial sketchpad (e.g., Maehler & Schuchardt, 2011; Schuchardt et al., 2008). Although these studies demonstrate that literacy difficulties are indeed associated with specific working memory limitations, they do not provide any information regarding the question whether other working memory limitations are responsible for the spelling problems of the children as opposed to their reading problems. To resolve this issue a 2 (reading disability: yes vs. no) × 2 (spelling disability: yes vs. no) factorial design seems to be helpful, in disentangling the two literacy factors by systematically incorporating children with learning disabilities in reading and/or spelling, respectively. Studies with such a design are scarce, and to our knowledge the few existing ones have only focused on the phonological loop. In two studies, Wimmer and his colleagues observed reduced nonword repetition skills in poor spellers, but average skills in poor readers (Wimmer & Mayringer, 2002; Wimmer & Schurz, 2010). Since nonword repetition is considered to reflect the efficiency of the phonological store (Baddeley, Gathercole, & Papagno, 1998; Hasselhorn, Grube, & Mähler, 2000), this might be taken as the first evidence that learning disabilities in spelling are associated with a reduced accuracy of phonological representation within the store, whereas learning disabilities in reading are not.

Two studies addressed the rehearsal process of the phonological loop. Whereas Hasselhorn, Schuchardt, and Mähler (2010) found a reduced word length effect on memory span (i.e., memory span decreases systematically with word length) in children with reading disability as opposed to children with spelling disability, there were no differences between these groups in an articulation rate task in the Wimmer and Mayringer (2002) study. These different results may be accounted for by the fact that—despite being conventional measures of the articulatory rehearsal process—both measures tap somewhat different aspects: Whereas the word length effect is supposed to indicate how easily and automated subvocal rehearsal is initiated, articulation rate is considered to reflect the maximum speed of the subvocal rehearsal process (Hasselhorn et al., 2000; Jarrold, Baddeley, & Phillips, 1999). Thus, poor reading skills but not poor spelling skills seem to be accompanied by a delayed initiation of subvocal rehearsal mechanisms. However, after being initiated, the overall speed of this process seems to be comparable across groups. Overall, these first results suggest that the phonological loop is differentially impaired in children with learning disabilities in reading versus spelling. However, the reported studies have focused only on specific subprocesses of the phonological loop instead of investigating its overall capacity as well. Therefore, one aim of the present study is to replicate and broaden these findings by using a comprehensive phonological loop assessment within the same sample.

Another issue not addressed in previous research is how the visuospatial sketchpad and the central executive are related to isolated as compared to combined learning disabilities in reading and spelling. Regarding the visuospatial sketchpad, one would not expect to find differential effects between reading disability on one hand and spelling disability on the other hand, since impairments in the sketchpad have not been reported in studies with poor readers (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009; van der Sluis, van der Leij, & de Jong, 2005) or in studies with poor spellers (Schuchardt, Kunze, Grube, & Hasselhorn, 2006). However, the central executive might play a crucial role in differentiating these learning disabilities. Some evidence that poor reading but not poor spelling in transparent orthographies might be accompanied by central-executive dysfunctions can be found in studies using an incomplete 2 (reading disability: yes vs. no) × 2 (spelling disability: yes vs. no) factorial design, in which only one of the two literacy factors is realized: Studies that selected children with literacy difficulties solely on the basis of poor spelling skills suggest that the central executive is not a major source of working memory deficits in these children. For example, Schuchardt et al. (2006) reported reduced performance in children with spelling disability only in a counting span task, but not in two backward span measures. Likewise, Tiffin-Richards, Hasselhorn, Woerner, Rothenberger, and Banaschewski (2007) found lower performance in poor spellers in only one of their two central-executive tasks. In contrast, studies that used poor reading skills as the critical criterion for diagnosing literacy difficulties usually reported extensive central-executive deficits: Compared to typically reading children, these impairments were found for backward span (Landerl et al., 2009) as well as for more complex measures such as counting span and reading span (de Jong, 1998).

A central issue of debate is related to the question whether central-executive impairments are domain-general or domain-specific. According to the *phonological processing limitation hypothesis* (Liberman & Shankweiler, 1985; Shankweiler & Crain, 1986), low phonological processing abilities impede higher-order cognitive processing. Difficulties experienced in central-executive tasks are thus considered to result from deficits in the phonological loop. Due to these deficits, children with literacy difficulties do have a handicap with phonological storage demands required in performing most executive tasks. This in turn results in a reduced overall performance, although the coordination functions of the central executive itself are fully intact. In contrast, the *domain-general hypothesis* (e.g., Swanson, 1999; Swanson & Ashbaker, 2000) proposes that children with literacy difficulties exhibit executive deficits irrespective and independent of their phonological loop impairments. Validating these two hypotheses requires statistical procedures controlling for the impact of phonological loop differences on tasks which assess central-executive functioning with phonological material. Of interest, de Jong (1998) addressed this issue in his study and found evidence for the domain-general hypothesis in transparent orthographies: The poor readers' deficit in the executive tasks remained statistically significant when controlling for their phonological loop impairments.

Hypotheses

To address some of these unresolved issues, the present study was designed to explore whether specific working memory profiles can be identified that allow differentiating between learning disabilities in reading and those in spelling, in transparent orthographies. Based on the theoretical considerations mentioned above, the following hypotheses were derived: First, poor spelling as well as poor reading skills are accompanied by phonological loop impairments. However, since in transparent orthographies learning to spell is phonologically more demanding than learning to read, poor spelling skills should be accompanied by broader phonological loop impairments than poor reading skills. Second, neither reading disability nor spelling disability should be associated with deficits in the visuospatial sketchpad. Third, dysfunctions in the central executive are

Table 1. Descriptive Characteristics as a Function of Group.

Characteristic	CG (n = 52; 28 Males)		RD Only (n = 44; 25 Males)		SD Only (n = 46; 36 Males)		RD+SD (n = 52; 35 Males)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (in months)	110.06	4.49	109.09	4.38	111.57	4.89	111.12	5.71
Nonverbal IQ	103.13	8.74	101.91	11.77	102.61	12.17	100.04	10.97
Reading	52.79	5.24	35.23	3.09	49.37	4.90	34.96	3.34
Spelling	50.15	4.80	45.57	3.81	36.04	2.84	34.52	3.24
Mathematics	53.33	4.92	51.59	5.73	53.37	6.28	51.96	6.70

Note. CG = control group; RD only = children with isolated reading disability; RD+SD = children with combined reading and spelling disability; SD only = children with isolated spelling disability.

expected only for reading disability, not for spelling disability. These central executive deficits should be due to a domain-general limitation as claimed by Swanson (1999).

Method

Participants

Based on standardized reading and spelling scores, 204 third graders were allocated to one of the four groups in a 2 (reading disability: yes vs. no) × 2 (spelling disability: yes vs. no) factorial design. Children were assigned to the reading disability (RD) only group when they (a) had below average reading scores of $T < 40$, equivalent to percentile < 16 (T-scores: mean of 50 and SD of 10), (b) had at least average spelling skills of $T \geq 40$, and (c) showed an intraindividual discrepancy between their reading and spelling skills of at least 5 T-points. Correspondingly, children were assigned to the spelling disability (SD) only group when they (a) exhibited below average spelling skills of $T < 40$, (b) exhibited at least average reading skills of $T \geq 40$, and (c) showed an intraindividual discrepancy between their reading and spelling skills of at least *5* T-points. To be included in the RD+SD group, children had to score below average ($T < 40$) in both reading and spelling. In contrast, children were classified into the control group (CG) when both their reading and spelling skills were at least average with $T \geq 40$. All children were normally achieving in mathematics ($T \geq 40$) and showed at least average intelligence (IQ ≥ 85). The achievement cutoff-score used in the present study (i.e., a reading and/or spelling score of at least one *SD* below the mean) is less rigorous than the one proposed in the *ICD-10 Diagnostic Criteria for Research* (World Health Organization [WHO], 1993), where a literacy score of at least 2 *SD*s below the mean is used to diagnose a learning disorder. The rationale for using the 16th percentile as cutoff score in the present study was to match with the diagnostic guidelines recommended for (Schulte-Körne, Deimel, & Remschmidt, 2001) and most frequently used (Hasselhorn, Mähler, & Grube, 2008; Klicpera, Schabmann, & Gasteiger-Klicpera, 2010) by psychologist and psychiatrics in German clinical practice. In doing so, our sample best represented the subpopulation of German school children commonly referred to as having learning disabilities. Also not in accordance with the ICD-10, an IQ–achievement discrepancy criterion was not applied to the definition of learning disabilities, due to its low validity: There is no empirical evidence that children with IQ–achievement discrepancy differ from poor learners without discrepancy on cognitive factors (e.g., Jiménez, Siegel, & López, 2003; Maehler & Schuchardt, 2011; Stuebing et al., 2002).

Children treated with psychostimulant drugs such as methylphenidate were excluded from further analyses, which was true for 10 children with literacy difficulties. Thus, the final sample consisted of 44 children with RD only, 46 children with SD only, 52 children with both RD and SD, and 52 normally achieving children. Table 1 shows children's descriptive characteristics as a function of group. A preliminary set of analyses of variance (ANOVAs) was done to check whether the four groups differed in terms of demographic and cognitive factors. For these and the following statistical procedures the alpha level was set at p = .05, if not otherwise specified. Effect sizes are reported using partial eta-square (η_p^2) classified by Cohen (1988) as small (.01–.05), medium (.06–.13), and large (≥ .14) effect. No statistically significant differences between groups were found for nonverbal intelligence, $F(3, 190) < 1$, $MSE = 119.20$; mathematical skills, $F(3, 103.45) = 1.20$, $MSE = 35.31$; and chronological age, $F(3, 190) = 2.34$, $MSE = 24.17$. However, as expected due to sampling procedures, groups differed significantly in reading skills, $F(3, 103.28) = 230.42$, $MSE = 18.22$, $p < .001$, $\eta_p^2 = .79$, as indicated by the Welch test correcting for variance inhomogeneity. Post hoc comparisons (Games–Howell correction) indicated that the CG and the SD only group outperformed the RD only and the RD+SD group. Likewise, there were statistically significant group differences with regard to spelling, $F(3, 103.77) = 184.06$, $MSE = 14.18$, $p < .001$, $\eta_p^2 = .76$, as indicated by the Welch test. Post hoc comparisons (Games–Howell correction) revealed that the CG and the RD only group outperformed the SD only and the RD+SD group. In addition, the CG reached slightly better spelling scores than the RD only group. There was an over-representation of boys in the groups with learning disabilities (RD only 57%, SD only 78%, RD+SD 67%). This is in line with epidemiological studies showing that learning disabilities in literacy are generally more frequent in boys than in girls (e.g., Fischbach et al., 2013). Still, the sex distribution was similar across groups, $\chi^2(3) = 7.61$, $p > .05$.

Tasks and Materials

Classification measures. To obtain an estimate of general cognitive ability, children completed the German version of the *Culture Fair Intelligence Test 1* (CFT 1; Cattell, Weiß, & Osterland, 1997). The CFT 1 is a nonverbal measure of perceptual speed and inductive reasoning assessing fluid intelligence. Reading skills were assessed with the *ELFE 1–6* (Lenhard & Schneider, 2006), a German reading comprehension speed test. A reading test covering reading speed and reading comprehension was used rather than a reading accuracy test, as reading accuracy is usually high in transparent orthographies (Landerl, 2001; Landerl et al., 1997), and consequently does not differentiate sufficiently between good and poor readers. To assess spelling achievement, the *WRT 2+* (Birkel, 2007), a German spelling test for second and third graders, was administered. This test requires children to spell 43 dictated words embedded in short sentences. To control for co-occurring learning disabilities in mathematics, children completed the *DEMAT 2+* (Krajewski, Liehm, & Schneider, 2004), a curricular valid test of basic arithmetic, magnitude, and geometry.

Working memory. Eleven subtests from the computerized *Working Memory Test Battery for Children Aged Five to Twelve Years* (AGTB 5–12; Hasselhorn et al., 2012) were administered. The AGTB 5–12 is a German standardized tool assessing working memory skills according to Baddeley's (1986) multicomponent model. Construct validity of the AGTB 5–12 was confirmed in a large study with 1,669 children (Michalczyk, Malstädt, Worgt, Könen, & Hasselhorn, 2013). Using confirmatory factor analyses, the authors found that a three-component model with separate latent factors for the phonological loop, the visuospatial sketchpad and the central executive yielded good fit indices for each age group (e.g., comparative fit index = .966–.980, root mean square error of approximation = .031–.045). Moreover, this three-factor model provided a better fit to the data than alternative models tested (e.g., one-factor model, four-factor model). Retest reliability of the AGTB 5–12 is established for two age cohorts (5- to 8-year-olds: $n = 145$; 9- to 12-year-olds: $n = 100$; Hasselhorn et al., 2012): Retest reliability over a 2-week interval was .85 to .89 for the phonological loop, .66 to .67 for the visuospatial sketchpad, and .78 to .85 for the central executive. These reliability scores are comparable to those reported for the *Automated Working Memory Assessment* (Alloway, 2007) and the *Working Memory Test Battery for Children* (Pickering & Gathercole, 2001). Internal consistency for the working memory measures as provided in the AGTB 5–12 manual is high, with values ranging from .92 to .99 (except for nonword repetition, whose internal consistency is .74).

Of the 11 subtests administered, 9 are span measures with an adaptive testing procedure. They consist of 10 trials, which are divided into five testing blocks with two trials each. The first testing block starts with a two-item sequence (for backward span tasks) or a three-item sequence (for forward span tasks), and sequence length is adjusted after each response: If the child recalls the presented trial correctly, the sequence length of the consecutive trial increases by one item. If, however, the child's recall is incorrect, the sequence length of the next trial decreases by one item. In the remaining four testing blocks sequence length is adjusted more conservatively as follows: If the child recalls both trials of the testing block correctly, the span length of the next block increases by one item. If the child recalls both trials incorrectly, the span length decreases by one item. If recall is incorrect for only one of the two trials, the span length remains the same. The calculation of the span score is based on the mean performance in the last four testing blocks, whereby a correct response is scored the span length equivalent. A false response is assigned the span length decreased by one item.

Phonological loop. Five subtests of the *Working Memory Test Battery* were administered to assess the functioning of the phonological loop. In *digit span*, increasing sequences of different digits are presented auditory at the rate of one digit every 1.5 s. The children's task is to repeat the sequence orally in the same serial order as presented. Digit span assesses the overall capacity of the phonological loop since both phonological storage and subvocal rehearsal are involved (e.g., Hasselhorn et al., 2000).

Similarly, *word span* requires the serial repetition of increasing sequences of words, which are presented auditory at the rate of one word every 1.5 s. Word sequences are constructed out of nine phonologically dissimilar, but familiar German nouns. To investigate the word length effect, there are two versions of the task—one using monosyllabic and one using trisyllabic words—resulting in separate span scores for short and long words, respectively.

In *nonword repetition*, children are asked to repeat nonwords (e.g., *limparett*) immediately after their auditory presentation. The task consists of 24 nonwords, which are constructed according to German linguistic rules. An oral repetition that includes all phonetic elements of the nonword is scored as accurate and the total number of correct repetitions serves as dependent variable. Nonword repetition is used as an indicator for the phonological store.

The *articulation rate* task assesses the speed of subvocal rehearsal. Children repeat a given triplet of nouns as quickly as possible, 10 times in a row. The triplet contains monosyllabic nouns and it is ensured in advance that the children are familiar with the words. The time needed to articulate each triplet is recorded and the four shortest triplets are transformed into a measure of mean articulation rate (in syllables per seconds). There are two trials of the task using different word triplets. Articulation rate is averaged across both trials.

Visuospatial sketchpad. The static component of the sketchpad (i.e., the visual cache) was assessed with a *pattern span task*: A pattern composed of two to eight black squares is presented on the screen within a four by four matrix. The pattern is then replaced by an empty matrix, on which the children have to tap the squares that had been blackened beforehand. The presentation time of the pattern increases linear to its complexity by 1,200 ms per black square.

In *corsi span*, nine white squares are distributed randomly on a gray screen. A smiley appears in one of these squares for 950 ms and then lights up in another square after an interstimulus interval of 50 ms. At the end of each trial, the children have to touch the squares where the smiley emerged, in correct serial order. Due to its sequential presentation format, the corsi span task captures the inner scribe of the sketchpad (e.g., Logie, 1995).

Central executive. To assess children's central executive functioning, four subtests of the *Working Memory Test Battery* were used. Two of these subtests were backward span tasks. The *digit span backward* and the *word span backward* are identical to the forward condition used to assess phonological loop capacity except that the children are instructed to recall the sequences in reverse order. Backward recall is considered to tap central-executive functioning, because reversing the stimulus order during recall increases processing load in children's working memory (Gathercole, 1998; Savage, Lavers, & Pillay, 2007, for a review). Also, these tasks are more strongly related to other complex span tasks than to simple forward spans (Alloway, Gathercole, & Pickering, 2006). In addition, two complex span measures were administered. In *counting span*, blue squares and dots of varying number are distributed randomly on a white screen. Having counted aloud all the dots, the children press a button to start the presentation of the next image. At the end of a trial, children are asked to recall the number of dots in correct serial order. In *object span*, an increasing number of objects (e.g., candle, cheese) is presented one by one on the screen and children are instructed to classify whether the presented object is eatable or not. Subsequently, children are asked to recall orally all the objects in correct serial order.

Procedure

The children were recruited via a screening on school achievement that took place in elementary schools in and around four German cities (i.e., Bremen, Frankfurt, Hildesheim, and Oldenburg). All children of the CG and most children with learning disabilities (95%) were screened in groups at their school in two 1.5-hr lessons. The remaining children with learning disabilities were recruited by means of a counseling center for learning difficulties. In the main assessment period, the *Working Memory Test Battery* and further cognitive measures were administered. Trained research staff tested the children individually in a quiet room at their school or at the university's lab. Testing was split over 2 days and lasted up to 90 min each, 45 min for working memory assessment. The children's consent as well as parental consent was obtained for all children prior to testing.

Results

Table 2 displays means and standard deviations for all working memory tasks as a function of group. To investigate distinct and overlapping working memory profiles associated with learning disabilities in reading versus spelling, separate two-way independent multivariate analyses of variance (MANOVAs) were conducted for each working memory component with RD (yes vs. no) and SD (yes vs. no) as fixed factors.

For phonological loop measures, the multivariate main effect of RD, $F(5, 184) = 4.47$, $p = .001$, $\eta_p^2 = .11$, as well as the multivariate main effect of SD, $F(5, 184) = 3.58$, $p = .004$, $\eta_p^2 = .09$, were statistically significant, whereas the interaction between the two factors did not reach significance, $F(5, 184) = 1.59$. For the factor RD, the subsequent analyses at the univariate level (ANOVAs) showed that the main effect found in the MANOVA was merely due to a significant difference on the digit span task, with poor readers recalling fewer digits in correct serial order than good readers, $F(1, 188) = 16.27$, $MSE = 0.28$, $p < .001$, $\eta_p^2 = .08$. On all other phonological loop tasks, no significant differences emerged between poor and good readers, 1-syllabic word span: $F(1, 188) = 3.70$, $MSE = 0.38$; 3-syllabic word span: $F(1, 188) = 2.85$, $MSE = 0.14$; nonword repetition: $F(1, 188) < 1$, $MSE = 12.91$; articulation rate: $F(1, 188) < 1$, $MSE = 0.26$. For the spelling factor, the subsequent ANOVAs revealed that good spellers outperformed poor spellers on all phonological loop tasks except the articulation rate task, in which no significant differences between groups emerged, digit span: $F(1, 188) = 14.39$, $MSE = 0.28$, $p < .001$, $\eta_p^2 = .07$; 1-syllabic word span: $F(1, 188) = 5.66$,

Table 2. Means and Standard Deviations for Working Memory Measures as a Function of Group.

	CG		RD Only		SD Only		RD+SD	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Phonological loop								
Digit span	4.60	0.58	4.16	0.47	4.18	0.54	4.00	0.51
1-syllabic word span	3.90	0.69	3.78	0.58	3.74	0.58	3.51	0.60
3-syllabic word span	3.09	0.43	3.01[a]	0.38	2.94	0.37	2.82	0.33
Nonword repetition	17.54	3.74	17.57	3.04	16.02	2.95	16.42	4.30
Articulation rate	3.24	0.52	3.09[a]	0.48	3.15	0.51	3.17	0.53
Visuospatial sketchpad								
Pattern span	4.72	1.16	4.47	0.99	4.61	1.13	4.69	1.20
Corsi span	4.18	0.71	4.28	0.69	4.21	0.61	4.20	0.59
Central executive								
Backward digit span	3.30	0.67	2.95	0.54	3.08	0.49	2.93	0.51
Backward word span	3.08	0.52	2.72[a]	0.45	2.80	0.44	2.71	0.42
Counting span	3.28	0.74	3.00[a]	0.69	3.06	0.88	2.83	0.66
Object Span	3.08	0.81	2.89[b]	0.68	2.83	0.79	2.81	0.62

Note. CG = control group; RD only = children with reading disability; RD+SD = children with reading and spelling disability; SD only = children with spelling disability.
[a]Data were missing for one participant. [b]Data were missing for three participants.

MSE = 0.38, p = .018, η_p^2 = .03; 3-syllabic word span: F(1, 188) = 9.57, MSE = 0.14, p = .002, η_p^2 = .05; nonword repetition: F(1, 188) = 6.55, MSE = 12.91, p = .011, η_p^2 = .03; articulation rate: F(1, 188) < 1, MSE = 0.26. Since children with SD showed reduced word spans for monosyllabic as well as for trisyllabic words, we investigated further whether they also exhibited a reduced word length effect when compared to good spellers. Therefore, we performed a 2 (SD: yes vs. no) × 2 (word length: 1-syllabic vs. 3-syllabic) factorial ANOVA with repeated measurement on the word length factor. This analysis revealed a significant main effect of SD, F(1, 191) = 10.69, MSE = 0.39, p = .001, η_p^2 = .05, as well as for word length, F(1, 191) = 399.07, MSE = 0.14, p < .001, η_p^2 = .68, with span performance being better for monosyllabic than for trisyllabic words. However, the interaction term was nonsignificant (SD × word length), F(1, 191) < 1, MSE = 0.14. This indicates that the magnitude of the word length effect did not differ between good and poor spellers.

For the visuospatial sketchpad, we had hypothesized that neither RD nor SD would be accompanied with a reduced efficiency in the temporary storage of visuospatial information. Thus, in this particular case, the null hypothesis was assumed to be preserved instead of being rejected. We therefore set the alpha level on .10 instead of using the conventional level of .05 (Bortz & Schuster, 2010). This increases statistical power and thus reduces the probability that the null hypothesis might erroneously be accepted, although it is false (Type II error). Even under this modified alpha level neither the multivariate main effects of RD, F(2, 189) < 1, p = .690, and SD, F(2, 189) < 1, p = .861, nor the interaction term, F(2, 189) = 1.05, p = .353, reached significance level.

In the MANOVA performed on the central-executive measures neither the multivariate main effect of SD, F(4, 184) = 1.68, nor the reading by spelling interaction, F(4, 184) = 1.06, appeared to be significant. However, the multivariate main effect of RD, F(4, 184) = 4.35, p = .002, η_p^2 = .09, was significant. The subsequent ANOVAs showed that good readers outperformed poor readers on all central-executive tasks, except the object span task, where no significant differences between groups emerged, backward digit span: F(1, 187) = 9.38, MSE = 0.31, p = .003, η_p^2 = .05; backward word span: F(1, 187) = 11.21, MSE = 0.21, p = .001, η_p^2 = .06; counting span: F(1, 187) = 5.47, MSE = 0.56, p = .020, η_p^2 = .03; object span: F(1, 187) < 1, MSE = 0.53. In a further step, it was investigated whether the lower level of central executive functioning in poor readers was reducible to their contemporaneous impairments in the phonological loop. Thus, all phonological loop tasks were z-transformed and then combined into a composite score. This composite was then entered as covariate in a one-way multivariate analysis of covariance (MANCOVA) with RD (yes vs. no) as fixed factor and backward digit span, backward word span, and counting span as dependent variables. Although the covariate was significantly related to the performance on the central-executive tasks, F(3, 187) = 18.40, p < .001, η_p^2 = .23, the multivariate effect of RD remained statistically significant in this analysis, F(3, 187) = 4.08, p = .008, η_p^2 = .06. This result is in line with Swanson's domain-general hypothesis indicating that children with RD have central-executive deficits that exist independently of their phonological loop impairment. The MANCOVA was followed up with separate ANCOVAs, which showed different patterns for the two backward span tasks on one hand and the counting span task on the other hand: In backward digit span, the effect of RD remained statistically significant, $F(1, 189) = 6.86$, $MSE = 0.30$, $p = .010$, $\eta_p^2 = .04$, having controlled for phonological loop functioning, $F(1, 189) = 14.23$, $MSE = 0.30$, $p < .001$, $\eta_p^2 = .07$. Likewise, the effect of RD remained statistically significant in backward word span, $F(1, 189) = 7.29$, $MSE = 0.19$, $p = .008$, $\eta_p^2 = .04$, when phonological loop functioning was controlled for, $F(1, 189) = 33.96$, $MSE = 0.19$, $p < .001$, $\eta_p^2 = .15$. In contrast, in the ANCOVA performed on counting span, the effect of RD was no longer statistically significant at $p = .05$, $F(1, 189) = 2.97$, $MSE = 0.50$, when the covariate was entered in the analysis, $F(1, 189) = 24.34$, $MSE = 0.50$, $p < .001$, $\eta_p^2 = .11$.

Discussion

Since reading and spelling are often considered related academic skills, most working memory studies in transparent orthographies have not sufficiently separated between these two literacy skills (e.g., de Weerdt et al., 2013; Maehler & Schuchardt, 2011; Porpodas, 1999). Thus, most issues surrounding working memory limitations that lead to isolated versus combined learning disabilities in reading and spelling are unresolved. However, the present study applied a 2 (reading disability: yes vs. no) × 2 (spelling disability: yes vs. no) factorial design to examine distinct and overlapping working memory profiles associated with learning disabilities in reading versus spelling.

Concerning phonological loop functioning, we expected SD to be accompanied with more diversified impairments than RD. Concordantly, children with age-adequate spelling scores outperformed poor spellers in four out of five phonological loop measures, whereas children with a learning disability in reading reached unremarkable levels in all but one task. According to Cohen's (1988) classification, the correspondent effects sizes were in the small to medium range ($\eta_p^2 = .03$ to $.07$). This result is compatible with the view that spelling in transparent orthographies is phonologically more demanding than reading, since phoneme-to-grapheme correspondences (relevant in spelling) are far less consistent than grapheme-to-phoneme correspondences (relevant in reading). But which particular components of the phonological loop are deficient in children with SD? The results presented here are in line with those reported by Wimmer (Wimmer & Mayringer, 2002; Wimmer & Schurz, 2010), who demonstrated that SD is associated with a reduced efficiency of the storage component of the phonological loop as indicated by low nonword repetition scores. The importance of phonological storage for spelling skills seems plausible since in spelling all phonemes of a word have to be segmented and identified correctly, so that the corresponding graphemes can be derived. It is evident that children may experience severe difficulties in these segmentation demands, when they have specific impairments in retaining spoken language accurately within the phonological store.

Regarding the subvocal rehearsal process, our results rather indicate that this particular component of the phonological loop is well functioning in children with SD: The automated initiation of subvocal rehearsal (assessed with the word length effect) as well as the maximum speed of this process (assessed with articulation rate) revealed themselves as unaffected. Whereas the former result replicates findings by Hasselhorn et al. (2010), the latter corresponds with Wimmer and Mayringer (2002). Yet the present research extends these former studies in also applying phonological measures such as digit span and word span, which are commonly considered to assess the overall functional capacity of the phonological loop, because they require both phonological storage and rehearsal: Children with SD had significantly lower levels of memory span for digits, as well as for monosyllabic and trisyllabic words. Overall, this pattern of results might be taken as evidence that SD in transparent orthographies is associated with impairments in the phonological storage component, but not in the subvocal rehearsal process.

A noticeable result with regard to the phonological loop profile of children with RD is that deficits in phonological tasks emerged only in digit span. Our results of an intact phonological storage (assessed with nonword repetition) and unimpaired speed of subvocal rehearsal (assessed with articulation rate) are compatible with those by Wimmer and colleagues (Wimmer & Mayringer, 2002; Wimmer & Schurz, 2010) and suggest that in German orthography the phonological loop is not a critical cognitive source of severe reading problems.

Our hypothesis that the visuospatial sketchpad is well functioning in children with RD and/or SD was corroborated by the data, also when applying a more liberal alpha level of .10 to reduce Type II error. Although to our knowledge this is the first study that investigated how visuospatial storage relates to isolated and combined literacy difficulties, this result is compatible with those of previous studies in transparent orthographies focusing on only one of the two literacy factors. For example, both Landerl et al. (2009) and van der Sluis et al. (2005) found visuospatial memory functions to be fully intact in children with RD. Likewise, Schuchardt et al. (2006) found no evidence that the visuospatial sketchpad is malfunctioning in children with SD.

Concerning central-executive functioning, our hypothesis was also confirmed by the present data. Only poor reading skills, but not poor spelling skills were associated with deficits in the correspondent tasks with effect sizes in the small to medium range (η_p^2 = .03 to .06). Although, to the best of our knowledge, no other study has examined central-executive functioning with contrasting poor readers and poor spellers so far, the present results correspond to a number of studies in the field. In line with Schuchardt et al. (2006) and Tiffin-Richards et al. (2007), who selected children with literacy difficulties solely on the basis of poor spelling skills, our results support the view that the central executive is not a source of major deficit in children with SD. In contrast, studies that used poor reading skills as single operational criteria for diagnosing literacy difficulties like de Jong (1998) and Landerl et al. (2009) found central-executive deficits to be associated with RD, which is in correspondence with the present results. In our study, these deficits were evident for backward span tasks (viz., for digits and words) as well as for counting span, but not for object span. Since counting span and object span are very similar in demands (i.e., both require the concurrent storage and processing of information), it is not clear why poor readers were outperformed by good readers in only one of the two complex span measures. It is very unlikely, for example, that poor performance in counting span is due to lower counting speed in the poor readers' group, since presence of dyscalculia was an exclusion criterion in the present study. A more likely explanation is that the children might have used different strategies when performing these two tasks: Despite their visual presentation format, both tasks are considered to assess the central executive phonologically based rather than visually based. Since elementary school children and adults have been shown to recode visually presented objects phonologically (e.g., Gathercole, 1998), children *without* RD are likely to adopt a phonologically based encoding strategy when performing these tasks. In contrast, children *with* RD might have relied more on visual strategies to support storage. In object span, where the task is to remember the presented objects, such visual encoding strategies are likely to be effective and should therefore result in rather high span scores. In contrast, in counting span a pure visually based encoding strategy seems more error-prone, because the children's task is to remember the number of dots rather than their particular location within the array. Consequently, even children with poor phonological skills are unlikely to adopt a visual encoding strategy in counting span, or even if they do, it is unlikely that this will lead to a right response. This explanation fits well with a study conducted by McNeil and Johnston (2004) showing that children with poor reading skills adopt a visual rather than a phonological encoding strategy for images, as long as items are easily captured in a visual way. Yet future studies should investigate this issue further (e.g., by asking children which strategies they adopt when performing these tasks).

Also of particular interest was whether the poor readers' deficits found in the executive tasks are best explained by the phonological processing limitation hypothesis (e.g., Shankweiler & Crain, 1986) or by the domain-general hypothesis (e.g., Swanson, 1999). We therefore reran the analysis on central-executive tasks and included phonological loop functioning as covariate in the MANOVA: Although phonological loop functioning contributed significantly to executive span performance, the overall effect of the central executive remained statistically significant in this analysis. This result corroborates the domain-general hypothesis suggesting that children with RD suffer from central-executive deficits over and above their phonological loop impairments. This also corresponds with de Jong (1998), who also found evidence for the domain-general hypothesis in poor readers acquiring a transparent orthography. Yet somewhat surprisingly, results in our study were slightly inconsistent when looking at the subsequent ANCOVAs. Whereas in both backward spans the executive deficit remained statistically significant when phonological loop functioning was controlled for, this was not the case in counting span. Differences in tasks demands might have led to this result: Although the presentation rates of the to-be-remembered items are timed and automatic in backward span, this is not the case in counting span, where a self-pacing procedure is used to start the next item presentation. It is thus possible that switching between encoding and retrieval strategies challenges the central executive to a higher degree in backward span, since less processing time is provided between the items. This explanation seems plausible since self-pacing has been shown to decrease executive demands in complex memory tasks, resulting more in a measure of immediate storage (see Conway et al., 2005; St. Clair-Thompson & Sykes, 2010).

The design used in the present study also allows drawing conclusions on the combined RD+SD group: Although children with combined literacy difficulties had generally lower working memory scores than children with isolated disabilities, none of the tested interaction terms were significant. The working memory profile of children with a combined RD+SD is therefore best described as an additive combination of the isolated disabilities rather than a distinct disorder: These children exhibit phonological loop impairments that are merely due to their spelling problems, and they also exhibit central-executive deficits that are reflective of their reading problems.

There are, however, some limitations of the present study worthwhile to be considered in future research. First, the operational criteria for learning disabilities used in the present study are less rigorous than those proposed in the *ICD-10 Diagnostic Criteria for Research* (WHO, 1993). Whereas the latter requires reading and/or spelling skills to be at least 2 *SD* below the level expected given the child's chronological age, the present study used a cutoff score of at least 1 *SD* as an indicator for poor literacy skills. This inclusion of children with less severe literacy difficulties could have had a negative impact on the magnitude of calculated effect sizes: Effect sizes in the present study were in the small to medium range according to Cohen's (1988) classification of eta-square. Working memory deficits might have been more pronounced, if only children with reading and/or spelling scores below the 2nd percentile had been included in the study.

Second, although our study clearly demonstrates that RD is associated with another working memory profile than SD, it is not possible to draw conclusions on causal relationships due to the cross-sectional nature of the data. Longitudinal studies are needed to examine the particular interplay that exists between working memory and literacy acquisition in the long run.

Third, our study provides empirical support for the domain-general hypothesis in children with RD. However, we incorporated only phonologically based tasks to assess central-executive functioning. Future studies should include subtests that assess the central executive in combination with the sketchpad, to provide a more conclusive test of the domain-general hypothesis.

Notwithstanding the limitations, this is the first study showing that children with RD and those with SD can be distinguished by their working memory profile. While central-executive impairments were solely associated with RD, comprehensive phonological impairments were only evident for SD.

Thereby, the present study has some crucial implications for researchers and practitioners. First, when it comes to diagnostics, it is important to take both reading and spelling into account. Relying on either a reading or a spelling test leads to two different forms of misclassifications: Children with isolated deficits in the unconsidered literacy domain as well as children with combined literacy difficulties will not be identified. However, the correct classification of these children is crucial because our study showed that all three subgroups of literacy difficulties are associated with distinct working memory profiles. The importance of comprehensive diagnostics also applies to empirical studies: Only if we continue to investigate the dissociation of reading and spelling skills in a systematic manner will we gain a deeper understanding of the cognitive factors that lead to isolated or combined literacy difficulties in transparent orthographies, which is essential to meet the special learning needs of these children.

Second, our results also provide implications on teaching children with RD and/or SD: To support learning in these children it might be fruitful to create learning environments that selectively release those working memory components that are associated with poor reading and poor spelling skills, respectively. For example, Gathercole and Alloway (2008) have developed a set of teaching principles proven to be effective in reducing working memory demands. Applying these principles to the present study, we would suggest that children with SD who exhibit comprehensive deficits in the phonological loop are likely to benefit from teaching principles that aim to compensate for poor phonological storage. For example, keeping instructions short and linguistically simple is an effective way of preventing phonological overload (Alloway, 2006; Gathercole & Alloway, 2008). Also, using visual memory aids that tap their unaffected visuospatial memory skills may be useful in helping children with SD to compensate for their phonological loop impairments. Children with RD exhibiting deficits in the central executive should especially benefit from teaching principles that reduce processing demands in working memory. According to Gathercole and Alloway (2008), this includes restructuring complex tasks in a step-by-step manner as well as increasing the meaningfulness of the reading material.

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