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Cognitive Risk Factors for Specific Learning Disorder: Processing Speed, Temporal Processing, and Working Memory

Kristina Moll, PhD[1], Silke M. Göbel, PhD[2], Debbie Gooch, PhD[3], Karin Landerl, PhD[4], and Margaret J. Snowling, PhD[5]

Abstract

High comorbidity rates between reading disorder (RD) and mathematics disorder (MD) indicate that, although the cognitive core deficits underlying these disorders are distinct, additional domain-general risk factors might be shared between the disorders. Three domain-general cognitive abilities were investigated in children with RD and MD: processing speed, temporal processing, and working memory. Since attention problems frequently co-occur with learning disorders, the study examined whether these three factors, which are known to be associated with attention problems, account for the comorbidity between these disorders. The sample comprised 99 primary school children in four groups: children with RD, children with MD, children with both disorders (RD+MD), and typically developing children (TD controls). Measures of processing speed, temporal processing, and memory were analyzed in a series of ANCOVAs including attention ratings as covariate. All three risk factors were associated with poor attention. After controlling for attention, associations with RD and MD differed: Although deficits in verbal memory were associated with both RD and MD, reduced processing speed was related to RD, but not MD; and the association with RD was restricted to processing speed for familiar nameable symbols. In contrast, impairments in temporal processing and visuospatial memory were associated with MD, but not RD.

Keywords

Comorbidity, learning disorders, dyslexia, dyscalculia, risk factors, attention

Disorders of reading and of mathematics often co-occur (Badian, 1983; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Dirks, Spyer, van Lieshout, & de Sonneville, 2008; Gross-Tsur, Manor, & Shalev, 1996; Landerl & Moll, 2010; Lewis, Hitch, & Walker, 1994). The fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-5*; American Psychiatric Association, 2013) classifies the disorders together as "specific learning disorder" given evidence that about one third of children experiencing a deficit in one domain of learning also show a deficit in the other. However, although evidence suggests that deficits in reading and mathematics share genetic variance (Kovas et al., 2007), both the brain bases and the core cognitive deficits underlying reading disorder (RD) appear distinct from those observed in mathematics disorder (MD; Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013; Landerl, Fussenegger, Moll, & Willburger, 2009). Thus, it is widely accepted that deficits in phonological processing are the proximal cause of RD (Vellutino, Fletcher, Snowling, & Scanlon, 2004), whereas a domain-specific deficit in processing numerosities has been implicated in MD (Butterworth, 2010; Wilson & Dehaene, 2007). In addition, domain-general cognitive risk factors, such as slow processing speed, might be shared between disorders and could possibly explain why they often co-occur.

Given the frequent comorbidity of both RD and MD with attention problems (e.g., Pennington, Willcutt, & Rhee, 2005), it is reasonable to hypothesize that poor attention represents a potentially shared risk factors. Rather than investigating this important hypothesis, most previous studies analyzing the cognitive profiles of RD and MD have

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[1] Ludwig-Maximilians-University Munich, Germany
[2] University of York, UK
[3] Royal Holloway, University of London, Surrey, UK
[4] Karl-Franzens-University Graz, Austria
[5] University of Oxford, UK

Corresponding Author:
Kristina Moll, Department of Child and Adolescent Psychiatry, Psychosomatics, and Psychotherapy Ludwig-Maximilians-University Munich, Nußbaumstraße 5a, 80336 Munich, Germany.
Email: Kristina.Moll@med.uni-muenchen.de

excluded children with attention difficulties (attention-deficit/hyperactivity disorder; ADHD). This approach is at odds with the growing consensus that neurodevelopmental disorders are caused by multiple risk factors that accumulate to produce a continuous distribution of behavioral outcomes with some children reaching a diagnostic threshold for "affectedness" (Hulme & Snowling, 2009; Pennington, 2006). Thus, based on a multiple deficit framework, developmental disorders are best conceptualized as dimensional rather than categorical disorders. To understand both dissociations as well as comorbidity between developmental disorders, studies should identify the core deficits that are specific to a given disorder as well as the risk factors (be they genetic, neurobiological, or cognitive) that are shared between disorders. Here, the focus is on identifying cognitive risk factors associated with RD and MD, which are also associated with attention problems. If children with learning disorders tend to experience subclinical attention difficulties, the impact of these on the clinical manifestations of RD and MD needs to be understood.

In the current study we focused on three cognitive deficits associated with attention problems (ADHD), which have also been discussed as domain-general risk factors for RD and MD: (a) processing speed, (b) temporal processing, and (c) memory skills.

Processing speed. Processing speed deficits have long been associated with language and learning disorders (e.g., Bull & Johnston, 1997; Catts, Gillispie, Leonard, Kail, & Miller, 2002). However, whereas deficits in rapid automatized naming (RAN), a measure of verbal processing speed, are consistently found in individuals with RD, nonverbal processing speed is not always affected (Bonifacci & Snowling, 2008; Gooch, Snowling, & Hulme, 2012). Rather, general processing speed deficits may be indicative of co-occurring problems in attention. In line with this view, Willcutt et al. (2010) reported findings from a twin study showing that common genetic influences on processing speed increase susceptibility to both RD and ADHD. Similarly, in a large-scale twin study McGrath et al. (2011) demonstrated that although reading difficulties are associated with phonological deficits and inattention with problems of inhibition, processing speed deficits are common to each condition. McGrath et al. further showed that within the different processing speed tasks used in their study, the task assessing speeded processing of familiar symbols was driving the relationship with reading. Furthermore, differentiating between symptoms of inattention and hyperactivity/impulsivity revealed that processing speed was a shared predictor of RD and inattention, but not hyperactivity/impulsivity. This is in line with findings suggesting that RD and inattention are genetically more related than RD and hyperactivity/impulsivity (Willcutt, Pennington, Olson, & DeFries, 2007).

Less is known about the role of processing speed in the etiology of MD. However, Willburger, Fussenegger, Moll, Wood, and Landerl (2008) reported that children with RD were impaired on RAN tasks irrespective of stimulus type, whereas children with MD showed a domain-specific deficit in naming of quantities (also see van der Sluis, de Jong, & van der Leij, 2004).

Temporal processing. According to several classic theories, temporal processing deficits are a hallmark of dyslexia, although the exact nature of the deficit and the tasks used to assess temporal processing skills differ between theories (Nicolson, Fawcett, & Dean, 1995; Tallal, 1980). Temporal processing skills include verbal time estimation, time reproduction, and time discrimination skills. Of importance, deficits in temporal processing have also been associated with attention problems (Castellanos & Tannock, 2002; Toplak, Dockstader, & Tannock, 2006). Smith, Taylor, Warner Rogers, Newman, and Rubia (2002) reported that children with ADHD (i.e., with symptoms of both inattention and hyperactivity/impulsivity) are especially impaired on time discrimination and time reproduction tasks. Since deficits in temporal processing are associated with attention problems, their presence in children with RD may be indicative of comorbid attention disorders. In line with this view, Gooch, Snowling, and Hulme (2011) reported that deficits in temporal processing, as measured by duration discrimination, were associated with attention problems (i.e., ADHD) but not RD once subclinical symptoms of ADHD were taken into account. In a similar vein, using regression analyses in a sample of 439 reading impaired and unimpaired primary school children, Landerl and Willburger (2010) found that temporal processing, as measured by visual and auditory temporal order judgment, accounted for only a small amount of variance in reading once individual differences in attention were controlled.

More generally, the relationship between temporal and numerical processing is debated. Although some authors propose that time and number rely on a single system (Meck & Church, 1983; Walsh, 2003), others have argued that temporal and numerical magnitudes are processed independently from each other (e.g., Dehaene & Brannon, 2011). Cappelletti, Freeman, and Butterworth (2011) found that time perception was modulated by numerical quantity, such that number primes influence whether durations appear to be shorter or longer than presented. In this view, deficits in temporal processing skills are correlates of MD. However, they also showed that adults with dyscalculia were not impaired in temporal discrimination when numbers were not included in the task, providing evidence for at least partially dissociable subsystems dealing with time and number.

Memory skills. When considering the role of memory, it is important to differentiate different component skills. Castellanos and Tannock (2002) proposed that deficits in working memory, specifically in visuospatial memory, are related to attention problems. For RD, however, memory deficits are mainly circumscribed to the verbal domain and conceptualized as part of the phonological language deficit underlying reading difficulties (Vellutino et al., 2004).

For MD, findings are less consistent. Several authors report visuospatial deficits in children with MD (McLean & Hitch, 1999; Schuchardt, Maehler, & Hasselhorn, 2008; van der Sluis, van der Leij, & de Jong, 2005). McLean and Hitch (1999) also provided evidence of verbal memory deficits in children with MD but only for numerical (e.g., digit span) and not non-numerical tasks (e.g., nonword repetition), whereas Koontz and Berch (1996) reported general working memory difficulties. In contrast, Geary and Hoard (2001) argued for a semantic memory deficit as a shared risk factor between MD and RD. These findings illustrate that although deficits in memory skills have been consistently reported in individuals with MD, it is far from clear which memory systems are affected and if deficits are domain-specific or domain-general.

In summary, studies on processing speed, temporal processing, and memory skills suggest associations with specific learning disorder. However, there remains a need to clarify both separable and shared cognitive deficits associated with RD and MD to better understand the etiology of and interventions for the two different behavioral disorders. The current study investigated whether processing speed, temporal processing, and memory skills are cognitive risk factors for RD or MD or whether their association with these disorders is attributable to co-occurring symptoms of attention difficulties, as measured by parental ratings.

Based on previous research, we expected to find relationships between measures of processing speed, temporal processing, and memory and ratings of children's attention behavior, irrespective of the type of learning disorder. However, when attention was controlled, we expected that the cognitive profiles associated with RD and MD would be distinct but with possible domain-general impairments accounting for comorbidity. Finally, we examined whether the deficits observed among children with comorbid RD+MD would reflect the sum of the effects observed in the single deficit groups (i.e., be additive) or whether the comorbid group would show a unique cognitive profile. A unique cognitive profile in the comorbid group would indicate that the comorbid group represents a separate disorder distinct from both single disorders (RD and MD).

Method

Participants

A sample of children with specific learning disorder ($n = 55$) and a typically developing (TD) control group ($n = 44$) were drawn from families where a younger sibling had taken part in a study comparing children with and without family risk of dyslexia ($n = 73$: 32 with learning disorder and 41 controls) or were recruited via newspaper adverts, schools, and support agencies for children with learning difficulties ($n = 26$: 23 with learning disorder and 3 controls). All children came from British White families in the county of North Yorkshire, England, and had English as their first language. Socioeconomic status (SES) was calculated using the English Indices of Deprivation (Department of Communities and Local Government, 2010). The index is based on rankings of 32,482 areas and is calculated using postal codes. The current sample showed a relatively high SES score, indicating low deprivation with a mean percentage rank of 68%. Of importance, the four groups did not differ significantly in SES ($F = 1.15, p > .05, \eta^2 = .04$). None of the recruited children met our exclusion criteria (chronic illness, neurological disorder, English as a second language, care provision by local authority, and low school attendance rates).

Ethical approval was granted by the university's Research Ethics Committee; informed consent was given by caregivers.

A total of 99 children aged 6 to 11 years participated: 21 with RD (62% boys), 15 with MD (40% boys), 19 with RD+MD (63% boys), and 44 with age-adequate performance in reading and arithmetic (TD controls; 45% boys). Gender ratios for the total sample were balanced (52% boys), but differed with respect to specific deficit groups. In line with prevalence studies, more boys were recruited with literacy difficulties, whereas more girls were recruited to the MD group. Children were classified as "impaired" either because they had a clinical diagnosis of RD and/or MD from an educational psychologist based on a comprehensive diagnostic test battery ($n = 24$: RD = 15, MD = 4, RD+MD = 5; mean age 9 years 8 months) or because they obtained a standard score less than 85 on the individually administered literacy and/or arithmetic measures used for classification in the current study. Out of the 24 children with a clinical diagnosis, 20 children also fulfilled our cutoff criteria and 3 children scored at least half a standard deviation below the age-expected mean on the relevant tasks. One child with a diagnosis of dyslexia performed within the average range on both literacy measures, but showed a marked difference of 38 and 32 standard score points between his literacy skills and his performance on the IQ and arithmetic measures (see Note 1). For all children, who were classified as "impaired," parents reported a history of literacy and/or numeracy problems during preschool and early school years.

Only five of the children in the sample had received a clinical referral for ADHD (1 RD and 4 RD+MD), and hence there was no information regarding formal diagnosis. None of the children received medication during the period of testing. Here attention behavior was based on parental ratings of attention and hyperactivity and treated as a continuous variable. The advantage of this approach is that it allows consideration of the impact of individual differences in attention, including subclinical symptoms of ADHD, when identifying cognitive deficits associated with RD and MD.

Measures and Procedures

Children were assessed individually in a quiet room within the department.

Group classification. Literacy and arithmetic skills were assessed using the Word Reading, Spelling, and Numerical Operations subtests of the *Wechsler Individual Achievement Test* (2005).

The Word Reading subtest requires reading a list of single words of increasing difficulty as accurately as possible. In the Spelling subtest the child is asked to spell single words of increasing difficulty dictated in sentence frames. The Numerical Operations subtest consists of written calculation problems (addition, subtraction, multiplication, and division). Test–retest reliability for all three subtests for the current sample was high (Word Reading: .95; Spelling: .93; Numerical Operations: .91)

Attention ratings. Attention behavior was assessed using the SWAN (*Strengths and Weaknesses of ADHD Symptoms and Normal Behavior Scale*; Swanson et al., 2006). This parental questionnaire is based on the 18 ADHD items listed in *DSM-IV* (American Psychiatric Association, 2000) measuring inattention and hyperactivity/impulsivity. SWAN scores have been shown to be normally distributed and cover the full range from positive attention skills to attention and hyperactivity problems that are characteristic of ADHD (Polderman et al., 2007). Validity was calculated based on correlations with the *Strengths and Difficulties Questionnaire* (SDQ; http://www.sdqinfo.org/) Hyperactivity scale (also see Lakes, Swanson, & Riggs, 2012) and the *Behavior Rating Inventory of Executive Function* (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000). Correlations in the current sample were high, .72, $p < .001$ for the SDQ and .66, $p < .001$ for the BRIEF. Each item is scored on a 7-point scale (3 to −3); positive values indicate more difficulties, negative values indicate relative strength in attention skills. A total score (between 54 and −54) was calculated over all 18 items.

General cognitive ability. Verbal and nonverbal IQ was assessed using the *Wechsler Abbreviated Scale of Intelligence* (WASI; Psychological Corporation, 1999). The test includes two subtests for each scale. The Vocabulary and Similarities subtests provide an estimation of verbal IQ; Block Design and Matrix Reasoning provide an estimation of performance IQ.

Processing speed. Verbal processing speed was assessed by rapid automatized naming (RAN) of digits. Children named 40 one-syllable digits presented in five lines as quickly and accurately as possible. The number of items named correctly per second was calculated. Test–retest reliability for the current sample was .86.

Nonverbal processing speed was assessed by a cancellation task using unknown symbols (Greek letters) presented in word-like letter-strings (e.g., ζιψεδ, σατυςδαω) in seven lines. Children were asked to scan the 84 strings line by line and cross out all 48 target items (ε) as fast as possible. Two versions were presented; the average number of items marked correctly per second was calculated (Guttman's split-half coefficient for the current sample = .95).

Temporal processing. In a computerized time reproduction task (adapted from Gooch et al., 2011), a light was presented for either 1,000 ms or 3,000 ms, and the child's task was then to switch on the light bulb for the same length of time by holding down the spacebar. The 32 test trials (16 per duration) were presented randomly. The deviation from the target time was calculated separately for the two durations (Guttman's split-half coefficients for the current sample = .86 for 1,000 ms and .78 for 3,000 ms).

Memory skills. Two subtests from the standardized *Working Memory Test Battery for Children* (Pickering & Gathercole, 2001) were administered to assess verbal and visuospatial memory skills.

For the Word Recall subtest the child is asked to repeat increasing sequences of one-syllable words in the same order as the tester. The Block Recall subtest requires the repetition of visuospatial sequences by tapping a sequence of blocks. The number of items recalled correctly for each test was calculated.

Results

Table 1 shows the descriptive statistics for the four groups. It can be seen that performance on the literacy and arithmetic measures reflects the selection criteria: Children with literacy difficulties obtained lower literacy scores than control and MD only groups; children with MD obtained lower arithmetic scores than control and RD only groups. Noteworthy is that the comorbid group (RD+MD) performed worst on most tasks. Attention ratings (SWAN) suggest that children with comorbid deficits show more attention problems than TD controls and children with deficits in only one domain.

To investigate the cognitive profiles of RD and MD, a series of analyses of covariance (ANCOVAs) were run with each of the cognitive risk factors as dependent variable; in each analysis, reading status (deficit: RD and RD+MD vs. no deficit: controls and MD) and mathematic status (deficit: MD and RD+MD vs. no deficit: controls and RD) were entered as fixed factors. Since the control group was younger than the other groups ($p = .072$ for RD; $p = .027$ for MD; $p = .001$ for RD+MD), age was included as a covariate in all analyses. The same analyses were repeated with attention ratings (SWAN) included as an additional covariate.

Table 1. Means and Standard Deviations and Group Effects for Cognitive Measures and Attention Ratings for the Four Groups.

Construct	RD	MD	RD+MD	TD control	Group *F*
n	21	15	19	44	
Gender (M:F)	13:8	6:9	12:7	20:24	
Age (months)	106.9 (21.9)$_{a,b}$	110.8 (21.9)$_{b}$	117.1 (21.8)$_{b}$	96.9 (19.3)$_{a}$	4.8**
SES (% rank)[a]	76.0 (5.2)$_{a}$	62.5 (6.2)$_{a}$	68.9 (5.5)$_{a}$	66.2 (3.6)$_{a}$	1.1
VIQ[b]	115.5 (14.9)$_{a}$	104.7 (15.0)$_{b}$	98.8 (14.8)$_{b}$	120.7 (14.3)$_{a}$	11.8***
PIQ[b]	107.8 (12.4)$_{a}$	92.5 (7.8)$_{b}$	92.4 (9.6)$_{b}$	113.2 (14.7)$_{a}$	18.1***
Literacy[b]	86.1 (9.6)$_{c}$	99.5 (6.6)$_{b}$	79.0 (8.8)$_{d}$	107.4 (10.3)$_{a}$	50.6***
Arithmetic[b]	99.7 (11.2)$_{b}$	80.3 (4.2)$_{c}$	71.7 (8.1)$_{d}$	107.2 (14.1)$_{a}$	51.8***
Attention total[c]	−1.6 (14.7)$_{b}$	−8.9 (16.3)$_{a,b}$	11.2 (13.6)$_{c}$	−12.0 (18.7)$_{a}$	9.1***
Inattention	1.1 (6.9)$_{b}$	−1.3 (9.6)$_{a,b}$	9.3 (7.5)$_{c}$	−5.2 (9.4)$_{a}$	12.6***
Hyperactivity/impulsivity	−2.7 (8.7)$_{a,b}$	−7.7 (9.1)$_{a}$	1.9 (9.2)$_{b}$	−6.8 (10.5)$_{a}$	4.4**

Note. Numbers with the same subscript do not differ significantly (least significant difference post hoc tests); subscripts a to d indicate decreasing performance. Values in parentheses are standard deviations. MD = mathematics disorder; PIQ = performance IQ; RD = reading disorder; TD = typically developing; VIQ = verbal IQ.

[a] SES based on postal code in the United Kingdom, relative rank according to deprivation value; lower = more deprived (Department of Communities and Local Government, 2010). [b] Standard scores. [c] Range = 54 to −54 (positive scores indicate more problems).

**p < .01. ***p < .001.

This design allows us to investigate which domain-general cognitive deficits are associated with RD and/or MD. Including attention ratings as a covariate enables us to investigate whether any association between RD and/or MD and the cognitive risk factors might be attributed to weaknesses in attention or whether they are shared with RD or MD. Finally, this design allows the comparison of children with comorbid RD+MD with those with MD only or RD only and thus to determine whether the effects of RD and MD are independent (additive) or interactive.

The age covariate was significant in all analyses, and its effect was larger for speeded measures (processing speed: *F*s between 69.2 and 106.0, *p*s < .001) compared to nonspeeded measures (temporal processing and memory: *F*s between 4.5 and 33.8, *p*s < .05). Similarly, the covariate of attention was significant for all three domain-general cognitive risk factors; the only exception was the 1,000 ms condition of the temporal processing task, for which none of the effects were significant.

There were also differences in IQ with a trend for the MD and comorbid groups to score lower than the RD and control groups. However, preliminary analyses with full IQ entered as covariate found that the effect of IQ was not significant, and hence it was not considered further. The only exception was for verbal memory, where IQ exerted a highly significant impact ($F = 22.34$, $p < .001$, $\eta^2 = .19$) and the effects of RD status, MD status, and attention fell below significance once IQ was included. Given that verbal memory is correlated with verbal IQ ($r = .47$ in our sample), it could be argued that controlling full IQ is too stringent a measure. Indeed, rerunning the analysis with nonverbal IQ as covariate reduced the impact of IQ ($F = 11.42$, $p < .01$, $\eta^2 = .11$) and a significant effect for RD status on verbal memory remained ($F = 4.51$, $p < .05$, $\eta^2 = .05$), comparable to the result reported here without including IQ in the analysis.

Processing Speed

Figure 1 shows the age-corrected performance of the RD, MD, RD+MD, and control groups in tasks tapping (a) processing speed, (b) temporal processing, and (c) memory tasks.

In Figure 1a it can be seen that the groups with RD are slower in verbal processing speed than the groups without RD. Analyses revealed a strong effect of RD status ($F = 14.1$, $p < .001$, $\eta^2 = .13$) but not MD status ($F = 0.3$, $p > .05$, $\eta^2 = .00$) on *verbal processing speed.* Children with MD only outperformed both groups with literacy difficulties (*p*s < .01), but did not differ from controls. The effect of RD status remained ($F = 6.9$, $p < .05$, $\eta^2 = .07$), although was somewhat reduced, when attention ratings ($F = 5.7$, $p < .05$, $\eta^2 = .06$) were included as covariate in the analysis. Neither RD nor MD status had a significant effect on *nonverbal processing speed* (*F*s < 1, *p*s > .05), though performance on this task was again related to ratings of children's attention ($F = 4.4$, $p < .05$, $\eta^2 = .05$).

Temporal Processing

Figure 1b shows performance on the temporal processing task measured by the discrepancy of the children's estimates from the standard time interval. It can be seen that 1,000 ms condition was not sensitive to group differences,

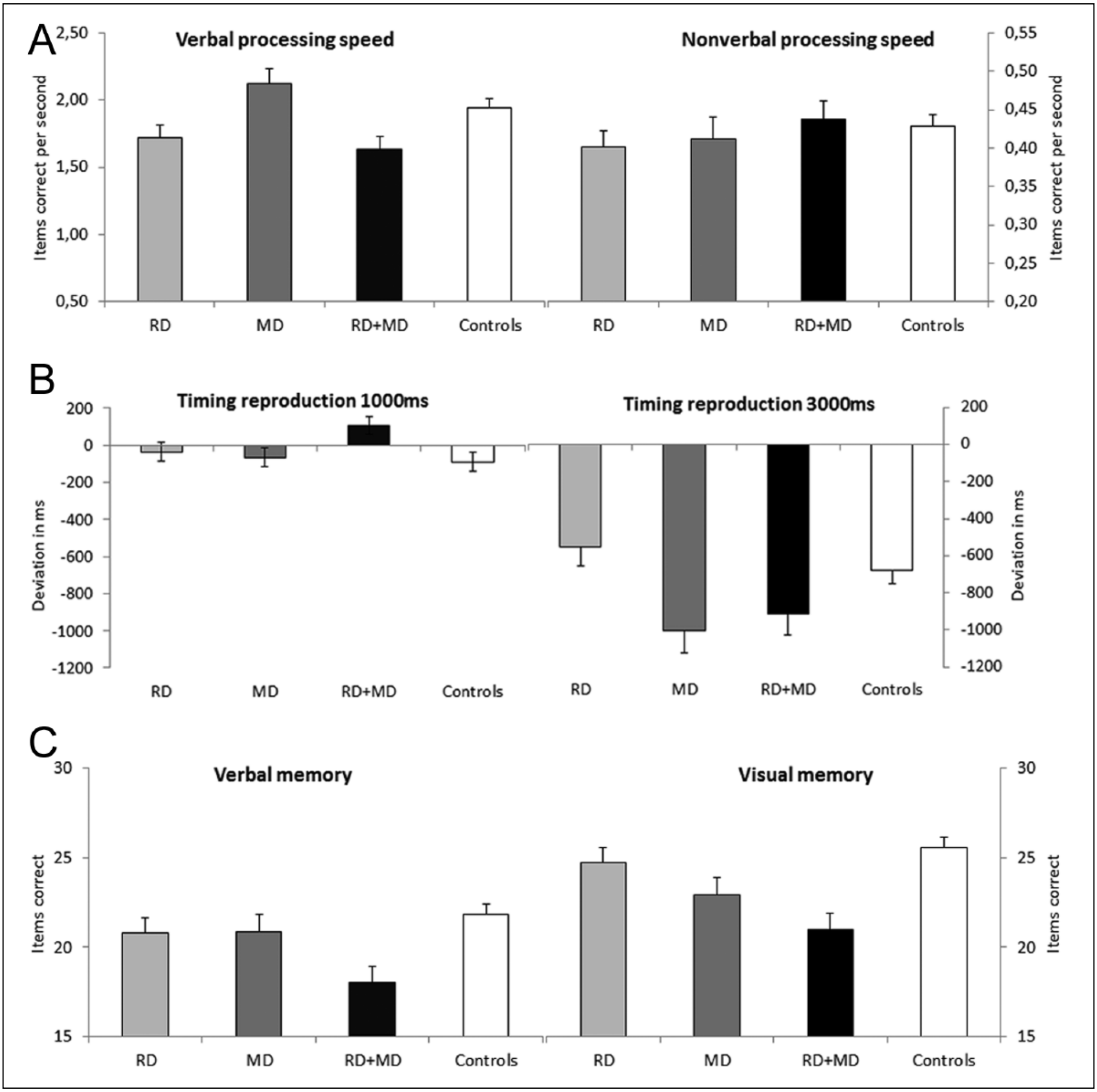

Figure 1. Age-corrected means (and standard errors) for RD, MD, RD+MD, and control groups on (a) verbal and nonverbal processing speed, (b) time reproduction, and (c) verbal and visual memory skills.

but in the 3,000 ms condition the MD groups showed poorer performance than the other groups. Analyses of the 3,000 ms condition found a significant effect of MD ($F = 10.7$, $p < .01$, $\eta^2 = .10$) but not RD ($F = 1.1$, $p > .05$, $\eta^2 = .01$) status. Children with RD only outperformed both groups with mathematical difficulties (*p*s < .05), but did not differ from the controls. On average children with MD underestimated the 3,000 ms by 908 ms, compared to only 663 ms for children without MD. This group difference remained significant ($F = 7.8$, $p < .01$, $\eta^2 = .08$) after controlling for attention ratings, which were also predictive of task performance ($F = 5.4$, $p < .05$, $\eta^2 = .05$).

Memory Skills

Figure 1c shows performance on the memory tasks. For verbal memory, it appears that both the RD and MD groups do less well than controls, but the effects are small (*d*s = −0.27

for RD and −0.26 for MD). For visual memory, the two MD groups do less well than the other groups. In line with this, there were significant main effects of both RD and MD status ($F = 5.7, p < .05, \eta^2 = .06$ and $F = 5.2, p < .05, \eta^2 = .05$) on the measure of *verbal memory*. The comorbid group (RD+MD) scored most poorly on this task ($d = -1.01$), differing significantly from all other groups (ps < .05). However, the RD by MD interaction was not significant, indicating that performance in the comorbid group reflects the sum of the two single deficit groups (additive effect). There was a highly significant main effect of MD status ($F = 14.3, p < .001, \eta^2 = .13$) on *visuospatial memory*, but the effect of RD status was not significant ($F = 2.7, p > .05, \eta^2 = .03$). Post hoc tests confirmed that both MD groups differed significantly from controls (ps < .05, ds = −0.68 for MD and −1.18 for RD+MD). When attention was entered as a covariate, neither the main effect of RD nor MD status remained significant for the verbal memory task, but the effect of MD remained highly significant ($F = 11.3, p < .01, \eta^2 = .11$) for the visual memory task.

In summary, the analyses revealed that attentional difficulties are associated with poorer performance on domain-general measures of verbal and nonverbal processing speed, temporal processing, and verbal and visual memory skill. Independent of the effects of attention, RD but not MD status was associated with deficits in verbal processing speed and MD, but not RD status, with temporal processing deficits, as measured by a 3,000 ms time reproduction task.

Both RD and MD status were associated with poor memory skills, but interpretation is complicated by the impact of verbal IQ and attention on performance. For verbal memory, neither the effect of RD or MD status survived controlling for full IQ, but the effect of RD status was significant when nonverbal IQ only was entered as covariate. Independent of this, the effect of RD was not significant once variation in attention skills was control for. Finally, the RD by MD interaction did not reach significance (ps > .05) in any of the analyses (processing speed, temporal processing, and memory). Thus, any effects found in the single deficit groups are likely to be additive for the comorbid group.

Discussion

The study investigated three domain general cognitive abilities associated with attention problems in children with RD and MD that might be shared between disorders, namely processing speed, temporal processing, and memory. As expected, poor performance on these tasks was associated with poor attention behavior as measured by parent ratings on the SWAN questionnaire. Confirming our hypothesis, RD and MD were associated with different cognitive profiles: slow verbal processing speed and poor verbal memory were associated with RD, whereas poor temporal processing, as measured by time reproduction, and limitations of verbal and visuospatial memory were related to MD status. A complication was that between-group differences in verbal memory were confounded by IQ differences, especially in verbal IQ. Thus, the deficit in visual but not verbal memory is robust in MD. There is also some evidence of an association between verbal memory impairments and RD in the present sample, but this effect was removed after controlling for attention problems.

Together the findings are consistent with evidence that slow processing speed is a shared risk factor for the comorbidity of RD and attention problems (Shanahan et al., 2006; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005); and furthermore, in line with the findings of McGrath et al. (2011), it was slow speed of processing of unfamiliar items in the cancellation task that was related to attention, whereas speeded processing of familiar symbols was related to both attention and reading. It follows from our data that domain-specific deficits in verbal processing speed (RAN) are risk factors for RD regardless of whether or not a child also has poor attention.

Furthermore, the finding that children with RD only did not differ from TD controls in their ability to reproduce durations confirms that temporal processing deficits in children with RD can be explained by (sub)clinical deficits in attention (Gooch et al., 2011; Landerl & Willburger, 2010). If individual differences in attention skills are not taken into account, deficits in temporal processing are likely to be overestimated in children with RD and might be mistaken as deficits associated with poor literacy skills. Deficits in attention can at least partly explain the inconsistent findings reported for temporal processing deficits in children with RD. Thus, future studies analyzing temporal processing skills in children with RD will have to consider the role of attention difficulties, including subclinical problems in attention. In contrast, children with MD performed poorly when estimating longer temporal durations. Poor performance was not fully accounted for by individual differences in attention skills, suggesting that impaired temporal processing may be a deficit shared by MD and attention difficulties. At first glance, our results contradict those of Cappelletti et al. (2011), who reported unimpaired temporal discrimination in adults with dyscalculia. However, at least two explanations could account for the discrepant findings: First, developmental changes may explain the stronger association between temporal and number processing found in primary school years compared to adulthood. Second, associations between MD and temporal processing may depend on task characteristics. Cappelletti et al. asked participants to decide which of two successively presented lines was longer in duration. Durations were rather short, ranging between 360 and 840 ms. Consistent with Cappelletti et al., we did not find any group differences for short durations (1,000 ms) in our time reproduction task.

Rather, children with MD were impaired when confronted with longer durations. It could be argued that for longer durations participants are likely to rely on counting strategies to perform well on the task. Deficits in temporal processing might therefore reflect reduced automaticity in counting in children with MD compared to controls.

Finally, verbal memory was the only risk factor associated with both RD and MD status, whereas visuospatial memory was related to MD only. Although this might suggest that children with MD have more generalized memory deficits compared to children with RD, group differences in attention and IQ complicate interpretation. The children in the present RD sample were of high ability, and although they underperformed relative to controls on the verbal task, consistent with previous findings (Fletcher, 1985; Jorm, 1983; Libermann, Mann, Shankweiler, & Werfman, 1982; McDougall, Hulme, Ellis, & Monk, 1994), the strength of the relationship between children's verbal memory skills and their reading status was reduced when individual differences in attention skills or in verbal IQ (but not nonverbal IQ) were controlled. In addition, the word recall task used to assess verbal memory clearly draws on vocabulary knowledge, which may further explain the reduced association between verbal memory and reading status once individual differences in verbal IQ were taken into account.

A clearer picture emerges for the measure of visuospatial memory on which children with MD performed worse than children without MD, even when individual differences in attention and IQ were controlled. Consistent with this, De Smedt et al. (2009) reported that visuospatial memory at the beginning of first grade was a unique predictor of mathematics achievement 4 months later.

The study found no evidence of an interaction of RD by MD for any of the domain-general cognitive deficits. We conclude that the comorbid group shows an additive profile reflecting the sum of the deficits observed in the single deficit groups, rather than a unique cognitive profile, speaking against the idea that comorbid RD+MD may constitute a separate disorder. A proviso is that given the relatively small sample size, power is low to detect a statistically significant interaction.

The current study was set up within the multiple deficit framework for developmental disorders (e.g., Pennington, 2006). Compared to studies focusing on the core deficits that are distinct between disorders, the current study contributes to the identification of shared cognitive risk factors that may explain the comorbidity between deficits in reading, mathematics and attention. The results show that three domain-general cognitive risk factors related to attention behavior are associated differentially with RD and MD. Our findings suggest that slow verbal processing is a risk factor for RD, but not for MD; it is also associated with poor attention in the group. Second, temporal processing and visuospatial memory deficits, while also associated with attention problems, were specific to MD. Only verbal memory was found to be a risk factor shared by RD and MD. However, in each condition, the association between "caseness" and verbal memory was related to problems of attention. In summary, when variability in attention is controlled, the three domain-general risk factors relate differently to RD and MD. Future studies are needed to investigate other risk factors that may be shared between RD and MD.

The study had a number of limitations. First, the null effects of both nonverbal processing speed and time reproduction in the 1,000 ms condition suggest that these tasks were not sensitive, and the absence of group effects therefore cannot be taken as conclusive. Second, the failure to find a strong effect of RD on verbal memory was surprising. Although verbal memory is a known risk factor for RD, verbal memory skills are strongly moderated by individual differences in attention as well as by verbal cognitive abilities; the high verbal IQ of the RD group and the task chosen here—word span—which draws on broader oral language skills, might have weakened the relationship between verbal memory and reading status. This interpretation is supported by the finding that the effect for RD status on verbal memory was significant when controlling for nonverbal IQ instead of full IQ. Future studies should analyze the relationship between RD status and verbal memory by tasks (e.g., nonword span), which draw less on vocabulary knowledge than the word recall task used in the current study.

To conclude, although the cognitive core deficits for RD and MD are domain specific, the present results indicate that additional risk factors shared with attention problems can be identified. In short, processing speed, temporal processing, and memory skills reflect variations in attention skills, and hence task performance deteriorates as a consequence of subclinical problems in attention. This interpretation highlights both the difficulty in devising pure tasks to measure cognitive constructs and the issues surrounding single-deficit accounts of developmental cognitive disorders.

The findings have important implications: Theoretically, our findings support the view that neurodevelopmental disorders such as RD and MD are the outcome of multiple risk factors; however, their distinct profiles may be taken to argue against grouping them together under the umbrella term of "specific learning disorder." Methodologically, given that children with specific learning disorders frequently experience attention difficulties without fulfilling diagnostic criteria for ADHD, it is essential that future studies take individual differences in attention skills into account when assessing risk factors of RD and MD. Educationally, the cognitive profiles associated with RD, MD, and comorbid RD+MD should direct choice of interventions and take into account the distinct profiles associated with RD and MD. Future research should consider the developmental relationships between different developmental disorders and how their comorbidities change over time.

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Note

1. An additional analysis excluding the four children with a diagnosis who did not fulfill our research criteria did not change the results. It was therefore decided to keep them in the sample to avoid reducing the sample size.

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