Working Memory in Children with Reading Disabilities and/or Mathematical Disabilities

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Abstract

Elementary school children with reading disabilities (RD, *n* = 17), mathematical disabilities (MD, *n* = 22) or combined reading and mathematical disabilities (RD+MD, *n* = 28) were compared to average achieving (AA, *n* = 45) peers on working memory measures. 2 (RD versus no RD) x 2 (MD versus no MD) factorial ANCOVA's revealed clear differences between children with and without RD on all working memory components. Children with MD had lower span scores than the AA children on measures of the phonological loop and the central executive. A significant interaction-effect between RD and MD was only found for listening recall and had a small partial effect size. In addition, analyses showed that the best logistic regression model consisted of a visuospatial and a central executive task. The model significantly distinguished between the AA and clinical groups, and between the MD and RD+MD group. Evidence was found for domain-general working memory problems in children with learning disabilities. Management of working memory loads in structured learning activities in the classroom, at home or during therapy may help these children to cope with their problems in a more profound manner.

Keywords: reading disabilities, mathematical disabilities, working memory, comorbidity

Working memory in children with reading and/or mathematical disabilities[1]

Introduction

Working Memory in Children with Reading Disabilities

Reading disabilities (RD) are defined as persisting impairments in reading and/or spelling abilities, at a level that remains significantly below expected given the age, and despite good instruction, and that are not explained by extraneous factors, such as sensory deficits (Schatschneider & Torgesen, 2004; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Prevalence is estimated between 5-12% of children (Schumacher, Hoffmann, Schmal, Schulte-Korne, & Nothen, 2007). Deficits in phonologically related processes are considered the core problem of RD (e.g., Vellutino et al., 2004), but working memory impairments are reported as well (e.g., Savage, Lavers, & Pillay, 2007; Siegel & Ryan, 1989).

The multicomponent model of Baddeley (1986) is used by the main part of learning disabilities studies investigating working memory (e.g., Passolunghi & Siegel, 2004; van der Sluis, van der Leij, & de Jong, 2005). Baddeley (1986) considers working memory as the active system that regulates complex cognitive behavior and consists of a central executive attentional control system, answering for the processing aspect of a task and strongly interacting with two domain-specific storage systems. The phonological loop is responsible for the storage and maintenance of verbal information; the visuospatial sketchpad has similar responsibilities for visual and spatial information (Baddeley, 1986). Recall tasks are frequently used measures of these slave systems, whereas central executive capacity is mostly measured by complex span tasks that require simultaneous storage and processing of information (Bayliss, Jarrold, Gunn, & Baddeley, 2003). Forward recall tasks have a minimal

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processing load, whereas this load is much higher in backward spans (Baddeley, 1996) and maximized in dual tasks (Bayliss et al., 2003). (Backward) recall and dual tasks are often used in learning disabilities research (e.g., Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Passolunghi & Siegel, 2004).

In a later stage, the episodic buffer was added to the model (Baddeley, 2000) and conceptualized as a multidimensional but essentially passive store that can be fed from the other working memory components, from long-term memory or through perception (Baddeley, Allen, & Hitch, 2010). To our knowledge, no research on working memory in children with learning disabilities has taken this component into account, probably because the episodic buffer has to be seen as a vague, shadowy concept, which is – in spite of its high importance – still in its infancies (Baddeley et al., 2010). Since Baddeley's model of 1986 is without any doubt the most empirically verified (Miyake et al., 2000), the focus of our study lies on this model.

Despite its important status, Baddeley's model is not the only influential one (see Miyake and Shah (1999) for an overview of working memory models). For instance, the continuity model of Cornoldi and Vecchi (2003) presents working memory on two continuums. The horizontal dimension makes a distinction between the stimulus modalities (e.g., verbal, visual and spatial), while the vertical dimension distinguishes passive storage from active processing (Passolunghi & Mammarella, 2010). In the latter, transformation and manipulation of the stimuli and thus involvement of the central executive are asked for (Passolunghi & Cornoldi, 2008). Recall tasks (e.g., digit -, word list – en block recall) can be considered passive storage tasks. Backward recall tasks (e.g., backward digit -, backward word list – en backward block recall) can be seen as more active processes and dual tasks (e.g., listening recall, spatial span) as the most active ones (Passolunghi & Cornoldi, 2008).

The phonological loop is often seen as a component of phonological awareness (Gathercole, Alloway, Willis, & Adams, 2006). Hence, it is not surprising that a substantial body of research has shown that the phonological loop is impaired in children with RD (Kibby, Marks, Morgan, & Long, 2004). In addition, several studies have reported problems in the central executive (e.g., Siegel & Ryan, 1989). In a meta-analysis of 88 studies on working memory in children with RD of average intelligence, Swanson, Zheng, and Jerman (2009) found that overall memory problems were primarily moderated by deficiencies related to the central executive and the phonological loop. Knowledge concerning the visuospatial sketchpad in children with reading disabilities is restricted and findings are ambiguous (e.g., Gathercole et al., 2006; Kibby et al., 2004).

Working Memory in Children with Mathematical Disabilities

Mathematical disabilities (MD) are defined in exactly the same way as RD, but concerning persisting deficits in mathematical skills (Landerl, Bevan, & Butterworth, 2004). Most researchers currently report a prevalence of approximately 7% of children (Geary, 2011). Besides the important emphasis on an inborn core deficit in the number module (i.e., a capacity specialized for recognizing and mentally manipulating numerosities; Butterworth, 1999), research focuses on working memory as well (e.g., Bull & Scerif, 2001; Swanson & Jerman, 2006; Temple & Sherwood, 2002). Some studies revealed deficits in all three components of working memory (e.g., Geary et al., 2007), others marked only problems in the central executive (Passolunghi & Siegel, 2004; Swanson & Sachse-Lee, 2001) or the central executive and the visuospatial sketchpad (e.g., Gathercole & Pickering, 2000; McLean & Hitch, 1999). Hence, results are mixed.

Despite the fact that comorbidity between MD and RD is estimated between 30% and 50% (Shalev, Auerbach, Manor, & Gross-Tsur, 2000), studies concerning working memory in children with specific RD, specific MD, as well as combined reading and mathematical disabilities (RD+MD) are rare (van der Sluis et al., 2005). Although RD frequently co-occur with MD , only few RD studies have taken mathematics into account (Swanson et al., 2009; Vukovic, Lesaux, & Siegel, 2010). The same is true for spelling and reading in MD research (e.g., Fuchs & Fuchs, 2002; Swanson & Jerman, 2006). Some of the inconsistent results may be explained by differences between children with specific and combined learning disabilities (Landerl & Moll, 2010). However, research studying working memory in RD, MD as well as in RD+MD is rather scarce (van der Sluis et al., 2005).

Comorbidity

Since cognitive deficits in RD and MD are heterogeneous (Rubinsten & Henik, 2009), the emerging etiological models for both RD and MD are considered to be multifactorial (Pennington, 2006). The fact that working memory deficits are reported both in RD and MD, may point into the direction of a working memory deficit as a shared cognitive risk factor between RD and MD (Pennington, 2006). The aim of this study was therefore to investigate working memory in children with RD, with MD and with MD+RD. If the same working memory problems are found both in RD and in MD, it might be considered a cognitive risk factor. Underadditivity would be the case: the comorbid group would perform at a similar level than the RD and the MD group (Shanahan et al., 2006). If the opposite is true and the working memory deficits in MD are independent of the deficits in RD, then the RD+MD group would be nothing more than the sum or the additive combination of the deficits in each pure group (Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005).

Objectives and Research Questions

Taking RD, MD as well as RD+MD into account, might reveal a different picture than when just comparing one clinical group with age-matched average achieving peers (AA; Dirks, Spyer, van Lieshout, & de Sonneville, 2008). The purpose of the current study is twofold. In the first place, we want to investigate differences and commonalities in working memory performance between AA children, children with RD, MD and RD+MD. In accordance, we want to look for a shared cognitive risk factor (Pennington, 2006). Secondly, since most of the studies report working memory deficits in children with learning disabilities, but seem to find mixed results, we would like to investigate which working memory tasks best predict learning disabilities.

Method

Participants.

Four groups of children between 8 and 12 years old participated in this study: AA children from third to sixth grade of regular elementary schools and children diagnosed with RD, MD or RD+MD referred by paraprofessionals. All children with learning disabilities were tested with standardized math -, reading – and spelling tests, treated and diagnosed by a recognized paraprofessional or in a specialized center. Each child was screened for inclusion in the study. Parents who had given their child permission to participate, completed questions about previous diagnoses or other (medical) problems their child suffered from. Only native Dutch-speaking children from regular elementary schools with an average intelligence above 80 and without reported histories of sensory impairment, brain damage, a chronic medical condition, insufficient instruction, serious emotional or behavioral disturbance or developmental disorders, such as behavior motor problems, autism or ADHD were included.

To control for ADHD, children who achieved a (sub)clinical score on both the parent and teacher version of the Disruptive Behavior Disorder (DBD) rating scale (Pelham, Gnagy, Greenslade, & Milich, 1992; Dutch translation: Oosterlaan et al., 2008) were eliminated from the study.

All children were tested on math-, reading - and spelling measures to control if criteria were met. If that was not the case, they were excluded from the study. AA children had to achieve a score above the 25^{th} percentile on all math and spelling tests and at least standard score (SS) 8 on all reading tests. In congruence with Geary (2011) referred children with MD had to score below the 11^{th} percentile on at least one of the frequently used standardized math tests, measuring mental arithmetic and number knowledge (procedural skills) and fact retrieval. Children with RD had to achieve a score below the 11^{th} percentile on a spelling test and/or below SS6 on at least one of the reading tests, measuring word reading speed and pseudoword reading. Children with RD+MD had to score below the 11^{th} percentile on at least one math test and below the 11^{th} percentile (spelling) or SS 6 (reading) on at least one spelling- or reading test (Dirks et al., 2008; Murphy, Mazzocco, Hanich, & Early, 2007).

The final sample consisted of 45 AA children, 17 children with RD, 22 children with MD and 28 children with RD+MD. Mean age was 10 years, 0 months. Subject characteristics are presented in Table 1.

< Insert Table 1 about here >

Measures

IQ, mathematics, reading and spelling measures. We calculated an estimated IQ, using an abbreviated version of the Dutch WISC-III (Wechsler et al., 2005). This shortened version is recommended by Grégoire (2000), has a high correlation (r = .93) with Full Scale IQ (Kaufman, Kaufman, Balgopal, & McLean, 1996) and consists of four subtests: Vocabulary, Similarities, Picture Arrangement and Block Design.

In order to obtain a complete overview of the mathematical abilities of children, two math tests were used. The Arithmetic Number Facts Test (Tempo Test Rekenen, TTR; De Vos, 1992) is a numerical facility test consisting of five subtests with arithmetic number fact problems: addition, subtraction, multiplication, division and mixed exercises. Children have to solve as many items as possible in five minutes; they can work one minute on every colon. The TTR is a standardized test that is frequently used in Flemish education as a measure of number fact retrieval (e.g., Stock, Desoete, & Roeyers, 2010).

The Kortrijk Arithmetic Test Revision (Kortrijkse Rekentest Revisie, KRT-R; Baudonck et al., 2006) is a standardized test on mathematical achievement which requires that children solve mental arithmetic and number knowledge tasks. The KRT-R is frequently used in Flemish education as a measure of procedural mathematical skills (e.g., Stock et al., 2010). In TTR and KRT-R, raw scores were the numbers of correct items and were converted in percentile- and z-scores. All z-score conversions were based on the entire sample.

Furthermore, all children were tested with standardized Dutch reading and spelling measures. Word reading speed or fluency was assessed by the One Minute Reading Test (EMT; Brus & Voeten, 1999) and pseudoword reading by the Klepel (Van den Bos, Spelberg, Scheepstra, & de Vries, 1994). Both reading tests consist of lists of 116 unrelated words. Children are instructed to read as many words as possible in one (EMT) or two minutes (Klepel) without making errors. On both tests, the raw scores were the numbers of words read correctly. These raw scores were then converted into SS (mean: 10, SD: 3) and z-scores, based on the entire sample.

Spelling was assessed with Paedological Institute-dictation (PI-dictation; Geelhoed & Reitsma, 2000), a Dutch standardized test in which children have to write down the repeated word from each sentence. The test consists of nine blocks of 15 words. Each block has a higher difficulty level and testing is stopped once a child made seven or more errors in a block. Raw score was the number of words spelled correctly and was converted in a percentile- and z-score.

Working memory measures. (Backward) digit -, word list -, listening - and block recall (inspired on Corsi, 1972) of the Working Memory Test Battery for Children (WMTB-C; Gathercole & Pickering, 2001) were used (e.g., Geary et al., 2007). In addition, in line with St Clair- Thompson and Gathercole (2006), all children were tested with the spatial span; an adapted version of the Automated Working Memory Assessment (AWMA; Alloway, 2007). Finally, backward word list recall and backward block recall were used (e.g., Passolunghi & Mammarella, 2010).

All span tasks were based on Baddeley's working memory model (1986). Maximum span length was nine for digit - and block recall; seven for (backward) word list -, backward digit - and backward block recall, and six for listening recall and spatial span. Sequence of onset was two for backward digit recall, backward word recall and backward block recall and one for all other tasks. In accordance with the WMTB-C, each length series consisted of six trials. The task was discontinued if three errors or more were made in one block. As for the other tasks, for listening recall and spatial span, a trial was only considered correct if the child recalled the right sequence in the correct serial position. Span score was calculated by counting each correct trial as one sixth and adding the total number of sixths - except for backward digit -, backward word list- and backward block recall, where the total number of sixths were added and incremented with one (Smyth & Scholey, 1992). This option was chosen, since this measure was more sensitive than taking the individual span as the longest sequence length for which four out of six sequences are correctly recalled (Imbo, Szmalec, & Vandierendonck, 2009).

All tasks were programmed in Affect 4.0 (Hermans, Clarysse, Baeyens, & Spruyt, 2005) and presented on a desk-top, the CRT screen was placed in front of the participant (refresh rate: 75 Hertz). The main task was not started until the child thoroughly understood the task instructions. For spatial span and (backward) block recall, a mouse was used as response device. In order to effectively eliminate reading demands of a task and to avoid spurious results arising from reading and/or spelling abilities associated with RD, all instructions were presented to the participants both in a visualized and verbal modality (Smith-Spark & Fisk, 2007; Vukovic et al., 2010). Furthermore, all verbal stimuli were read to the children. Sound was presented via two speakers located at the left- and right side of the screen. Finally, by use of a voice key as response device, verbal reports were taken into account instead of written responses. This was the case for (backward) digit recall, (backward) word list recall and listening recall. In all tasks, the experimenter pressed a key in order to trigger the next item (Landerl et al., 2004). As the subtest order of the WMTB-C was followed, all tasks were presented in a fixed order.

< Insert Figure 1 about here >

Phonological loop. Digit - and word list recall are measures for the verbal recall of sequences. Children have to repeat sequences of digits or high frequent words (see Figure 1 for a trial representation). Digit sequences were random lists of digits ranging from 1 to 9.

The word sequences consisted of lists of monosyllabic words, adopted from the Dutch translation of Braams (2002).

Visuospatial sketchpad. Block recall measures dynamic spatial recall of series. Children have to repeat sequences of squares. Nine blue squares were irregularly arranged over the screen. Squares that were part of a sequence that had to be recalled, were enlightened in orange one by one. Afterwards, a screen with nine blue squares was shown. Children were asked to repeat the sequence of the orange squares by clicking on the different blue squares (see Figure 1).

Central executive. In backward digit recall, backward word list recall and backward block recall, children are required to recall sequences of digits, words or squares in the reverse order. Trials were constructed in the same way as in digit -,word list – and block recall (see Figure 1). Finally, two dual tasks were measured. In listening recall, children are presented with a sequence of spoken sentences (e.g., 'Lions have four legs'), sentences were based on the Dutch translation of Braams (2002). The instructions are twofold. In the processing task, they have to verify the sentence by stating 'true' or 'false'. In the memorization task, the final word for each sentence has to be recalled in sequence (see Figure 1). The second dual task, i.e., spatial span, measures the processing of static spatial information. A picture of two identical shapes in which the shape on the right side has a red dot, is shown to the children. In the processing task, the child has to identify whether the shape on the right side is the same or opposite of the shape on the left. In the recall task, the child has to show the location of each red dot on the shape in the correct sequence (see Figure 1).

Procedure

Data Collection. All children were tested by a trained researcher in a quiet room at home for three different sessions, each session lasting up to 90 minutes. To maximize vigilance and persistence in completing tasks, breaks were included. During the first session, tests were used to tap mathematics and spelling. In the second session, reading and intelligence were measured. During the last session, working memory tasks were administered.

Datatrimming, missing data and outlieranalysis. For each participant, all RTs less than 150 ms were eliminated, as were all RTs from voice key - or other errors. This affected no more than 10% of the trials for any measure. At the sample level, both RT and accuracy measures exceeding the group mean by 3SDs were replaced by values 3 SDs from the group mean (Friedman & Miyake, 2004). In all of the tasks, the percentage of outliers was less than 2%. Missing values were replaced by the group mean. In (backward) digit recall and (backward) word recall, this was the case for less than .80%. In block recall for less than 2.70%, in backward block recall and spatial span for less than 4% and in listening recall for less than 7%.

Statistical analysis. After assumptions of normality and homogeneity were met, 2 (RD versus no RD) x 2 (MD versus no MD) factorial univariate analyses of covariance (ANCOVAs) were carried out to examine task performance in AA children and children with learning disabilities. The 2 x 2 design instead of analyses with the four groups (AA, RD, MD and RD+MD), was chosen to gain the necessary information about the performance of the RD+MD group. A significant interaction between the RD and MD factor provides evidence for the underadditivity hypothesis, whereas no interaction-effect points in the direction of RD+MD as an additive combination of RD and MD (Willcutt et al., 2005). Post hoc tests (Bonferroni) were conducted when significant main - and interaction effects were found.

In addition, multinomial logistic regression analysis was used to clarify to what extent working memory predicts the probability of RD, MD and RD+MD.

Our sample was rather small. For this reason, effect sizes were included in this section to be able to judge the risk of type 1 errors. Moreover, AA and clinical groups showed different IQ-, gender- and age profiles. Consequently, univariate analyses of variance (ANOVA's) were carried out with a carefully matched sample. They revealed similar results. However, the sample was small (n = 48) and thus suffered from a lower power with a risk for type 2 errors. Sample size is not a problem for significant correlations or regressions. However, when analyses have insufficient power and are not significant, a risk of type 2 – or β – mistakes (concluding from the cohort that there were no differences although in reality there were differences in the population) cannot be excluded. Therefore, all analyses were performed with the whole sample and in control of gender, age and intelligence.

Results

Univariate analyses of covariance

In the first place, 2 (RD versus no RD) x 2 (MD versus no MD) factorial ANCOVAs were carried out with accuracy (represented by span scores) or RT of each working memory task and gender, intelligence and age as covariates.

< Insert Table 2 about here >

The ANCOVA with RT of backward block recall as dependent variable revealed a significant effect of the RD factor. Children with RD were significantly slower on backward block recall than children without RD ($F(1, 102) = 19.92$, $p < .001$, $\eta_p^2 = 0.16$). However, none of the other analyses with RT as dependent variable were significant. Hence, RT results will not be reported here. We refer to Table 2 for means and standard deviations of span scores and RTs of the AA, RD, MD and RD+MD group.

ANCOVAs were conducted with span score as dependent variable (see Table 3). Concerning the RD factor, analyses revealed that children without RD performed better than children with RD on digit recall ($p < .001$), block recall ($p = .002$), backward digit recall ($p < .001$), backward word list recall ($p = .002$), backward block recall ($p = .017$), listening recall ($p = .046$) and spatial span ($p = .046$). No significant differences were found for word list recall ($p = .333$). Span scores of children with MD were lower than span scores of children without MD on digit recall ($p = .002$), backward digit recall ($p = .006$), backward word list recall ($p = .006$), listening recall ($p = .030$) and spatial span ($p = .031$). There were no significant effects of word list recall ($p = .344$), block recall ($p = .148$) and backward block recall ($p = .153$). The ANCOVA with listening recall revealed a significant interaction-effect ($F(1, 102) = 4.08$, $p = .046$, $\eta_p^2 = 0.04$). A trend was found for the interaction-effect of block recall ($F(1, 102) = 3.21$, $p = .076$, $\eta_p^2 = 0.03$). ANCOVAs with digit recall ($F(1, 102) = 1.61$, $p = .208$), word list recall ($F(1, 102) = 1.57$, $p = .213$), backward digit recall ($F(1, 102) = 1.41$, $p = .239$), backward word list recall ($F(1, 102) = 0.07$, $p = .786$), backward block recall ($F(1, 102) = 0.21$, $p = .649$) and spatial span ($F(1, 102) = 0.16$, $p = .687$) revealed no significant interaction-effects between RD and MD.

<Insert Table 3 about here>

Multinomial logistic regression model

To detect which of the working memory span scores best predicted learning disabilities, a multinomial logistic regression model was carried out. Logistic regression produces odds ratios. Odds ratios represent the ratio change in the odds of the event (e.g., belonging to the AA group) for a one unit change in the predictor variable (e.g., accuracy of the phonological loop) and may vary from 0 to infinity. An odds ratio can be seen as an estimate of effect size. An odds ratio below 1 indicates a higher risk not to be in the reference group and as such reflects problems if the AA group functions as reference category. In contrast, an odds ratio higher than 1, suggests a higher chance to belong to the reference category and thus directs towards a protective factor if the AA group is the reference group. When the odds ratio is 1 (or close to it), no effect is found. Not only their nearness to 1, but also the significance of odds ratios - indicated by the *p* value of the Wald statistic - plays an important role in the decision process about the strength of a model. Besides, model fitting results provide information about the significance of the model and log likelihood ratio tests show us to what extend the model changes if we omit a particular predictor. Finally, *Nagelkerke* R^2 is used to express the explanation power, it ranges from 0 to 1.

Based on this information, several multinomial logistic regression analyses were conducted in search for the best model, i.e., the model that best fitted the data. Predictors that did not fit well, were left out until the model was maximized. The analyses started with all working memory measures as predictors, along with group as dependent variable and in control of age, gender and intelligence. Since previous bivariate logistic regression analyses had shown that none of the interaction effects were significant or odds ratios were nearby 1, they were not entered.

The two predictors of the best model were the span scores of block recall and backward digit recall. Model fit was significant, χ^2 (15, N = 112) = 86.13, p < .001 and Nagelkerke R^2= 0.58. Moreover, log-likelihood-tests showed significant results for block recall (χ^2 (3, N = 112) = 14.01, p = .003) and backward digit recall (χ^2 (3, N = 112) = 30.50, p < .001). As evident from Table 4, this model generated a set of significant effects. Relative to the AA group, the odds ratios of the RD- (odds ratio (OR) = 0.08; confidence interval (CI) = 0.02 - 0.40; p = .002), the MD- (OR = 0.13; CI = 0.03-0.56; p = .006) and the RD+MD group (OR = 0.03; CI = 0.01 - 0.15; p < .001) showed a significant decrease concerning backward digit recall. Block recall was a significant predictor for the RD group (OR = 0.13; CI = 0.03 - 0.51; p = .004), the MD group (OR = 0.19; CI = 0.05-0.74; p = .017) and the RD+MD group (OR = 0.14; CI = 0.04-0.52; p = .003) as well. The higher the accuracy on block recall and backward digit recall, the higher the chance the child belonged to the AA group. Results concerning the clinical groups only were less clear. The RD+MD group showed a significant odds ratio decrease relative to the MD group for backward digit recall (OR = 0.23; CI = 0.06 - 0.94; p = .040). However, compared to the RD group, no significant change was found in the odds ratio of children with MD, nor in the odds ratio of the children with RD+MD for block recall and backward digit recall.

< Insert Table 4 about here >

Discussion

This study wished to investigate if working memory problems can be considered as a shared cognitive risk factor and if working memory can predict learning disabilities. Lower span scores than the AA group on digit recall and backwards digit recall were associated with all learning disabilities groups. In addition, analyses with the AA, RD, MD and RD+MD group revealed similar span scores for the clinical groups on all working memory tasks. Moreover, the best logistic regression model showed that the predictors block recall and backward digit recall could differentiate children with learning disabilities from children without learning disabilities. They could not distinguish the RD group from the MD or RD+MD group. Hence, one should expect that the comorbid group is underadditive (Willcutt et al., 2005). However, there was a significant interaction effect of the RD and MD factors for listening recall only, with a small partial effect size (η^2= 0.04). Moreover, none of the other central executive – or even working memory - tasks revealed a significant interaction-effect. Based on this information it is hard to conclude that a deficit in the central executive might be an important shared cognitive risk factor (Pennington, 2006). Rather, it seems like working memory problems are manifested in another way in children with RD than in children with MD. These findings are in congruence with studies that point in the direction of RD and MD as distinct disorders (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009).

Since listening recall is often used as a measure of inhibition (e.g., Passolunghi, 2011), one can wonder if these findings rather implicate an inhibition deficit as shared cognitive risk factor. This certainly needs further investigation.

Except for word list recall, children with RD differed significantly from children without RD on all working memory tasks. Span scores of children with MD were significantly lower than span scores of children without MD for digit recall, backward digit recall, backward word recall, listening recall and spatial span. Significant differences were found between the AA and RD and RD+MD group on every working memory component and between the AA and MD group on both the phonological loop and the central executive.

Evidence was found for a domain general rather than a domain specific working memory capacity deficit in children with RD and RD+MD. Since the well-known core contribution of phonologically related processes to RD (e.g., Vellutino et al., 2004), it is quite surprising that children with RD seem to experience problems on all working memory components instead of on the phonological loop only (Kibby et al., 2004). Despite the fact that several studies found evidence for a domain general deficit in children with MD (e.g., Murphy et al., 2007), our findings are less clear-cut. In congruence with Swanson and Jerman (2006), evidence is rather found for a verbal working memory deficit: ANCOVAs revealed no significant differences between the AA group and the group with MD on block recall and block recall backwards. However, in the multinomial regression model, both backward digit recall and block recall were strong predictors of the MD group in comparison with the AA group. These findings are a bit ambiguous and might partly be explained by the fact that we used only spatial tasks and no visual ones. Moreover, backward digit recall was of higher influence than digit recall in the regression model, probably because of the more active role of executive control of the former. This was not the case for backward block recall and block recall. Recent studies found evidence for another relationship between the visuospatial sketchpad and the central executive than between the phonological loop and the central executive (Mammarella & Cornoldi, 2008). Moreover, backward spatial tasks (e.g., backward block recall) would not rely as much on central executive skills than complex spatial tasks do (Mammarella, Pazzaglia, & Cornoldi, 2008). However, other research has linked backward block recall explicitly with central executive functioning (Vandierendonck, Kemps, Fastame, & Szmalec, 2004).

This study revealed interesting findings, but some limitations have to be mentioned as well. Different operationalizations for RD may, to a certain extent, lead to selection of other participants (Dirks et al., 2008). In line with several authors (Schatschneider & Torgesen, 2004; Vellutino et al., 2004), our definition of RD captures deficits in reading or spelling. As a consequence, patterns reported here may not apply to reading or spelling if considered separately. Both in English and in German language, studies found different deficiencies of working memory involved in reading versus spelling disabilities (Hasselhorn, Schuchardt, & Mahler, 2010; Savage et al., 2005). Future research is recommended.

In addition, the reported lack of differentiation between the clinical groups might be due to our sample selection. In this study, children were only referred to the RD+MD group if they scored below the 11th percentile on math and reading or spelling tests (Dirks et al., 2008). This indicates that some children of the specific MD group also had reading or spelling scores below the 25th percentile and some children of the specific RD group math scores below the 25th percentile. However, analyses concerning reading, spelling and math scores revealed different profiles for all clinical groups (see Table 1). Nevertheless, further research with more severe selection criteria would be enlightening.

In congruence with other research, working memory seems to be associated with learning disabilities irrespective of intelligence (e.g., Gathercole et al., 2006; Maehler & Schuchardt, 2009). The logistic regression model marked an important role of intelligence, but this did not rule out the predictive value of working memory. Moreover, a stronger odds ratio decrease in children with RD, MD, and RD+MD was found compared to AA children for working memory than for IQ. Since we used a brief IQ measure, the impact of working memory beyond the effects of IQ might be related to the use of this measure. The brief IQ correlates strongly with Full Scale IQ (Kaufman et al., 1996). As such, one might expect a minimal influence of the use of a brief instead of a Full Scale IQ measure.

In addition, all participants were well screened and children with disorders other than RD, MD or RD+MD were excluded from this study. However, we were not able to control for the possible co-occurrence of other undiagnosed disabilities. For instance, one out of four children with learning disabilities suffers from motor problems (Pieters et al., 2012), but due to practical restrictions, parents were only asked if their child suffered from it. Another screening question just concerns the fact that screening inevitably excludes particular groups and as such may affect the results by contributing to a generalized as opposed to a specific finding. In future studies, it will be important to establish whether working memory problems reported here might partly reflect the performance of children with learning disabilities and other comorbid disorders; e.g., ADHD (Savage et al., 2005). Finally, working memory spans are susceptible to proactive interference (Mammarella & Cornoldi, 2008). Hence, this might have influenced our results to some extent. Future research counterbalancing the spans in an ascending and a descending presentation format is recommended.

Overall, this study showed some clear differences in working memory between AA children and children with learning disabilities. Although differences between the clinical groups are less clear-cut and further research is needed, it seems that all groups of children with learning disabilities suffer from domain-general working memory problems. Therefore, management of working memory loads in structured learning activities in the classroom, at home or during therapy may help these children to cope with their problems in a more profound manner (Gathercole et al., 2006).

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Tables

Table 1
Subject Characteristics of the Sample

Characteristic	AA (*n*=45) M *(SD)*	RD (*n*=17) M *(SD)*	MD (*n*=22) M *(SD)*	RD+MD (*n*=28) M *(SD)*
Age in months	120.91 (10.37)	119.53 (13.41)	117.55 (9.01)	122.29 (12.43)
Male : female	19:26	10:7	6:16	9:11
IQ	108.42 (9.86)[a]	105.18 (8.47)[ab]	94.82 (9.21)[c]	99.57 (11.45)[bc]
Z-score TTR	0.94 (0.62)[a]	-0.27 (0.61)[b]	-0.27 (0.82)[b]	-0.87 (0.71)[c]
Z-score KRT-R	0.80 (0.39)[a]	0.50 (0.52)[a]	-1.02 (0.64)[b]	-0.92 (0.69)[b]
Z-score PI	0.91 (0.41)[a]	-0.90 (0.57)[c]	0.49 (0.51)[b]	-0.90 (0.49)[c]
Z-score EMT	0.90 (0.65)[a]	-0.78 (0.42)[c]	0.41 (0.70)[b]	-0.79 (0.60)[c]
Z-score Klepel	0.84 (0.63)[a]	-0.81 (0.42)[b]	0.47 (0.84)[a]	-0.89 (0.50)[b]

Note. AA = average achieving; RD = reading disabilities; MD = mathematical disabilities; RD+MD = reading- and mathematical disabilities; TTR = Arithmetic Number Facts Test (fact retrieval); KRT-R = Kortrijk Arithmetic Test Revision (procedural mathematical skills); PI = Paedological Institute-dictation (spelling); EMT = One Minute Reading Test (word reading speed).
[a,b,c] posthoc indices at $p < .05$.

Table 2
Means and Standard Deviations of Children With and Without Learning Disabilities on Working Memory

	AA (*n*=45)	RD (*n*=17)	MD (*n*=22)	RD+MD (*n*=28)
Working memory	M *(SD)*	M *(SD)*	M *(SD)*	M *(SD)*
Span score				
Digit recall	4.83 (0.55)[a]	4.18 (0.76)[b]	4.37 (0.50)[b]	4.08 (0.52)[b]
Word list recall	3.86 (0.57)	3.50 (0.75)	3.57 (0.57)	3.57 (0.63)
Block recall	4.63 (0.53)[a]	3.97 (0.95)[b]	4.15 (0.64)[ab]	4.11 (0.57)[b]
Backward digit recall	3.50 (0.53)[a]	2.89 (0.40)[b]	3.01 (0.54)[b]	2.79 (0.40)[b]
Backward word recall	3.01 (0.45)[a]	2.73 (0.42)[ab]	2.78 (0.46)[ab]	2.52 (0.41)[b]
Backward block recall	4.21 (0.50)[a]	3.92 (0.55)[ab]	3.88 (0.41)[ab]	3.68 (0.75)[b]
Listening recall	2.29 (0.51)[a]	1.87 (0.41)[b]	2.02 (0.48)[ab]	1.92 (0.43)[b]
Spatial span	3.25 (1.19)[a]	2.62 (1.11)[ab]	2.48 (1.14)[ab]	2.14 (1.24)[b]
Reaction Time				
Digit recall	996.85 (402.53)	1213.29 (730.51)	953.03 (385.32)	945.40 (347.42)
Word list recall	968.05 (400.17)	1012.50 (458.25)	925.10 (456.44)	1056.68 (440.45)

Block recall	1112.14 (331.91)	1044.41(307.82)	1020.62 (162.54)	1153.66 (324.66)
Backward digit recall	1537.01 (854.63)	1837.01 (992.95)	1267.79 (630.85)	1685.73 (904.24)
Backward word recall	1171.99 (516.02)	1572.19 (1015.67)	1092.43 (503.24)	1425.04 (768.52)
Backward block recall	1026.11 (277.52)^{a}	1371.16 (446.11)^{b}	1019.22 (155.51)^{a}	1289.95 (399.30)^{b}*
Listening recall	2742.18 (1277.11)	2676.84 (1047.09)	3029.73 (2137.65)	3259.29 (2004.81)
Spatial span	1640.41 (860.74)	1423.00 (439.95)	1570.28 (439.87)	1804.89 (987.70)

Note. AA = average achieving; RD = reading disabilities; MD = mathematical disabilities; RD+MD = reading- and mathematical disabilities.
^{a,b} posthoc indices at $p \leq .05$.

Table 3
2 x 2 Factorial ANCOVAs: Differences between Children With and Without Reading Disabilities and between Children With and Without Mathematical Disabilities on Working Memory, in Control of Gender, Age and Intelligence

	RD (n = 45) versus no RD (n = 67)				MD (n = 50) versus no MD (n = 62)			
	RD	No RD			MD	No MD		
Span score	M *(SD)*	M *(SD)*	F(1,102)	η_p^2	M *(SD)*	M *(SD)*	F(1,102)	η_p^2
Digit recall	4.11 (0.62)	4.68 (0.57)	16.03	.14***	4.21 (0.52)	4.65 (0.68)	10.08	.09**
Word list recall	3.54 (0.67)	3.76 (0.58)	0.95	.01	3.57 (0.60)	3.76 (.064)	0.91	.01
Block recall	4.06 (0.73)	4.47 (0.61)	10.31	.09**	4.13 (0.60)	4.45 (0.73)	2.13	.02
Backward digit recall	2.83 (0.40)	3.34 (0.58)	19.09	.16***	2.88 (0.48)	3.33 (0.56)	7.88	.07**
Backward word recall	2.60 (0.43)	2.94 (0.47)	10.25	.09**	2.63 (0.45)	2.94 (0.46)	7.80	.07**
Backward block recall	3.77 (0.68)	4.11 (0.50)	5.93	.06*	3.77 (0.62)	4.13 (0.53)	2.07	.02
Listening recall	1.90 (0.42)	2.20 (0.51)	4.07	.04*	1.97 (0.45)	2.17 (0.52)	4.85	.05*
Spatial span	2.32 (1.20)	3.00 (1.22)	4.09	.04*	2.29 (1.20)	3.08 (1.19)	4.78	.05*

Note. RD = reading disabilities; MD = mathematical disabilities.
*** p < .001; ** p < .01; * p < .05.

Table 4
Multinomial Logistic Regression Model for Predicting Learning Disabilities based on Working Memory, in Control of Gender, Age and Intelligence

			95% CI for OR		
Group comparison	Model	OR	Lower	Upper	Wald *(df)*
RD vs AA[a]	Gender[d]	1.03	0.25	4.23	0.00 (1)
	Age	1.07	0.99	1.16	2.77 (1)
	IQ	0.95	0.88	1.02	2.23 (1)
	Acc BR	0.13	0.03	0.51	8.52 (1)**
	Acc BDR	0.08	0.02	0.40	9.60 (1)**
MD vs AA	Gender	0.41	0.10	1.65	1.60 (1)
	Age	1.06	0.98	1.14	1.80 (1)
	IQ	0.86	0.80	0.92	16.79 (1)**
	Acc BR	0.19	0.05	0.74	5.74 (1)*
	Acc BDR	0.13	0.03	0.56	7.48 (1)**
MD+RD vs AA	Gender	0.27	0.07	1.11	3.26 (1)
	Age	1.11	1.03	1.20	7.69 (1)**
	IQ	0.91	0.85	0.97	8.14 (1)**
	Acc BR	0.14	0.04	0.52	8.60 (1)**
	Acc BDR	0.03	0.01	0.15	18.66 (1)**
MD vs RD[b]	Gender	0.39	0.09	1.76	1.49 (1)
	Age	0.99	0.92	1.06	0.14 (1)
	IQ	0.91	0.84	0.98	6.91 (1)**
	Acc BR	1.51	0.51	4.49	0.54 (1)
	Acc BDR	1.54	0.32	7.34	0.30 (1)
RD+MD vs RD	Gender	0.27	0.06	1.11	3.31 (1)
	Age	1.04	0.97	1.12	1.29 (1)
	IQ	0.96	0.90	1.02	1.76 (1)
	Acc BR	1.07	0.39	2.94	0.02 (1)
	Acc BDR	0.36	0.07	1.70	1.69 (1)
RD+MD vs MD[c]	Gender	0.67	0.17	2.68	0.31 (1)
	Age	1.06	0.99	1.12	3.12 (1)
	IQ	1.06	0.99	1.12	2.92 (1)

	Acc BR	0.71	0.27	1.87	0.48 (1)
	Acc BDR	0.23	0.06	0.94	4.19 (1)*

Note. OR = odds ratio; CI = confidence interval; AA = average achieving children; RD = reading disabilities; MD = mathematical disabilities; RD+MD = reading - and mathematical disabilities; Acc BR = span score on block recall; Acc BDR = span score on backward digit recall.
[a] average achieving group as reference category; [b] reading disabilities group as reference category; [c] mathematical disabilities group as reference category; [d] girls as reference category.
** $p \leq .01$; * $p \leq .05$.

Figures

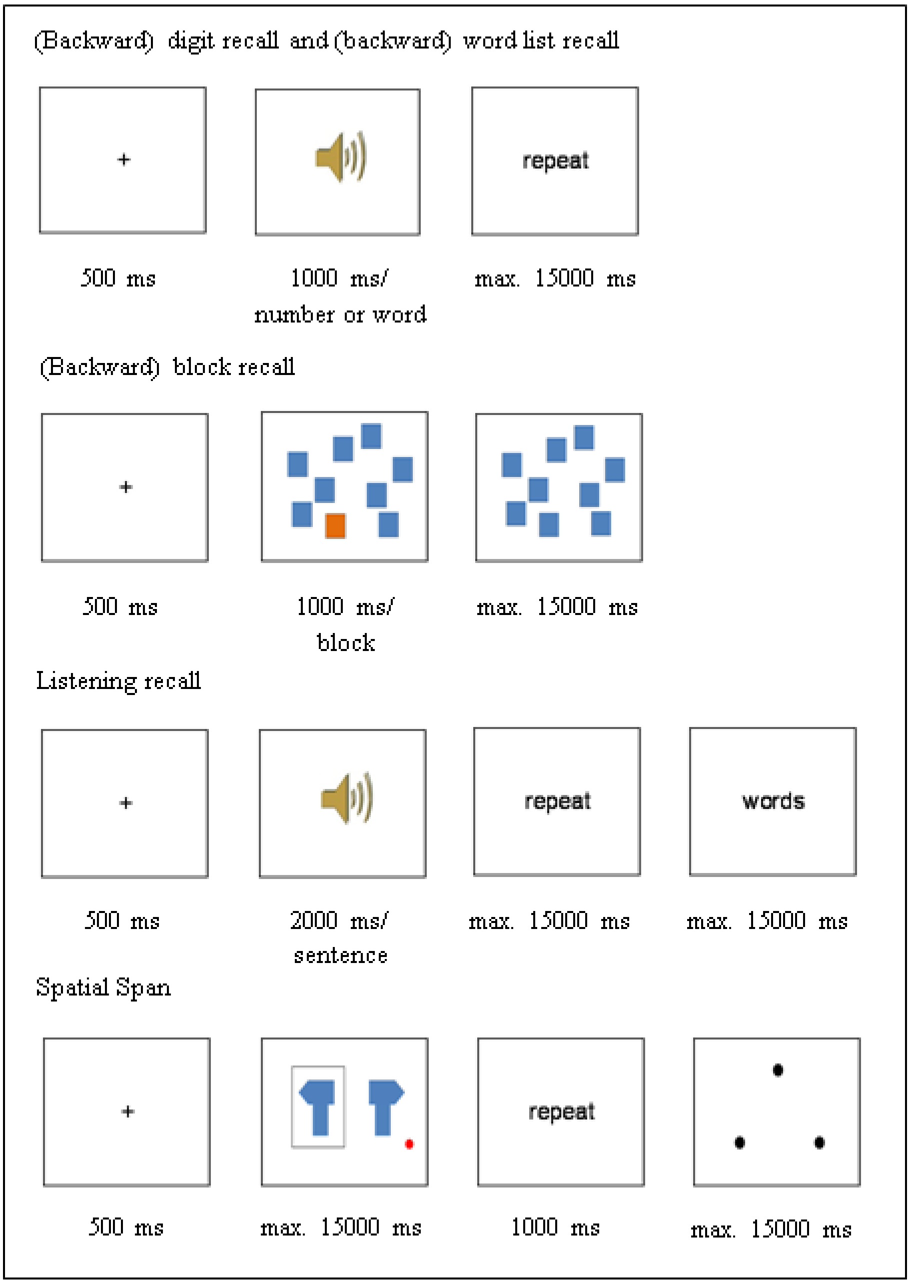

Figure 1. Visualization of the working memory tasks.