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A Meta-Analysis of Working Memory Deficits in Children With Learning Difficulties: Is There a Difference Between Verbal Domain and Numerical Domain?

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Abstract

Children with learning difficulties suffer from working memory (WM) deficits. Yet the specificity of deficits associated with different types of learning difficulties remains unclear. Further research can contribute to our understanding of the nature of WM and the relationship between it and learning difficulties. The current meta-analysis synthesized research on verbal WM and numerical WM among children with reading difficulties (RD), children with mathematics difficulties (MD), and children with reading and mathematics difficulties (RDMD). A total of 29 studies subsuming 110 comparisons were included. Results showed that compared to typically developing children, all learning difficulty groups demonstrated deficits in verbal WM and numerical WM, with RDMD children showing the most severe WM deficits. MD children and RD children showed comparable verbal WM deficits, but MD children showed more severe numerical WM deficits than RD children. Neither severity of learning difficulties nor type of academic screening emerged as a moderator of WM deficit profiles. Although the findings indicate the domain-general nature of WM deficits in RD, MD, and RDMD children, the numerical WM deficits of children with MD and RDMD may reflect the domain-specific nature of WM deficits.

Keywords

working memory, verbal, numerical, reading difficulties, mathematics difficulties

Working memory (WM) refers to the capacity to store information for short periods of time when engaging in cognitively demanding activities (Baddeley, 1986). Compared to short-term memory, WM plays a more influential role in children's academic performance. This is because many academic tasks involve multiple steps with intermediate solutions, and children need to remember those intermediate solutions as they proceed through the tasks (e.g., Cain, Oakhill, & Bryant, 2004; McKenzie, Bull, & Gray, 2003).

WM deficits contribute to learning difficulties. Many studies have documented WM deficits in children with different types of learning difficulties. These include reading difficulties (e.g., Gathercole, Alloway, Willis, & Adams, 2006), mathematics difficulties (e.g., Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007), and a combination of reading and mathematics difficulties (e.g., Swanson & Beebe-Frankenberger, 2004). However, previous research is unclear about whether WM deficits are domain specific (i.e., deficits are limited to or more severe in one domain) or domain general (i.e., deficits are not limited to one domain or do not differ among different types of learning difficulties). Although authors of prior systematic reviews have investigated WM deficits in the verbal domain versus the visuospatial domain (e.g., Swanson & Jerman, 2006; Swanson, Zheng, & Jerman, 2009), no review has focused on WM deficits within the verbal domain (i.e., comparing verbal skills to numerical skills). Moreover, there has been no quantitative synthesis that has explored the possible specificity of WM deficits (verbal vs. numerical) among children with reading difficulties (RD), mathematics difficulties (MD), and reading and mathematics difficulties (RDMD). The current meta-analysis synthesized research on verbal WM and numerical WM among children with RD, MD, and RDMD to better understand the nature of WM; relations between WM and learning difficulties; and implications for tasks design in WM interventions involving these children.

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Working Memory: Domain General Versus Domain Specific

WM is a complex construct. Although many researchers acknowledge that WM is the mechanism responsible for simultaneous information storage and processing (Miyake & Shah, 1999), there are several ongoing debates. One is whether WM is domain general or domain specific.

Domain general. An influential domain-general WM model has been proposed by Baddeley (1986), who contends that WM consists of two “slave systems” that are responsible for short-term maintenance of domain-specific information (verbal and visuospatial), and a central executive that coordinates the ongoing processing and storage of information in the slave systems. The central executive directs attention to relevant information, suppressing irrelevant information and inappropriate actions, and it coordinates cognitive processes when more than one task must be accomplished simultaneously. It also differentiates WM from short-term memory, and for this reason more than any other, it is considered by many to be the core component of WM. Indeed, some considered the central executive component to be WM itself (e.g., Engle, 2002; Engle & Kane, 2004). Based on this model, the relation between WM and learning is largely mediated by the central executive. Thus, WM should be considered a domain-general construct for learning (Baddeley, 1986) and deficits in WM are domain general and are related to all types of learning difficulties.

Domain specific. Other researchers claim that WM is closely related to domain-specific skills and knowledge, and thus is strongly affected by domain specificity (Ericsson & Kintsch, 1995; Unsworth & Engle, 2007). According to Ericsson and Kintsch (1995), long-term memory can supplement WM. When individuals are knowledgeable in a particular domain, they can encode and retrieve information specific to it more efficiently than they can encode and retrieve information from a domain in which they are less knowledgeable. In accordance with this view, WM is not a general capacity that can support different learning activities to a similar degree. Instead, it should be discussed in the context of specific activities because it integrates domain-specific skills, knowledge, and procedures to meet the particular demands of learning tasks within a particular domain. Thus, deficits in WM are domain specific and are related to specific learning difficulties.

Although both domain-general and domain-specific models of WM receive evidence from research on typically developing individuals (e.g., Ericsson & Kintsch, 1995; Shah & Miyake; 1996), research seems to suggest a pattern of domain specificity of WM deficits among children with learning difficulties. For example, Swanson and colleagues reviewed research on verbal WM and visuospatial WM among children with mathematics problems and children with reading problems. They found that although these children showed deficits in WM across both domains, the visuospatial WM deficits were more distinctive in children with mathematics problems. By contrast, the verbal WM deficits were more severe in children with reading problems (Swanson et al., 2009; Swanson & Jerman, 2006). These results suggest that children with learning difficulties show extensive WM deficits and that the severity of WM deficits varies by domain and type of learning difficulties.

More evidence that supports the domain-specific WM model among children with learning difficulties comes from WM training studies. According to a domain-general model, WM affects academic development, and WM deficits are a potential explanation for learning difficulties (Baddeley, 2003). Thus, strengthening WM, regardless of domain, is expected to ameliorate or mitigate learning difficulties. However, findings from most WM training studies do not support this hypothesis. Some research shows that training visuospatial WM can improve visuospatial WM, but there were small or no transfer effects for WM in the verbal or numerical domain, or for verbal-related academic performance (Melby-Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012). In contrast, there is also research that shows, compared to domain-general WM training (training WM using tasks across visuospatial, verbal, and numerical domains), training WM in the numerical domain (using only numerical WM tasks) produced stronger effects on numerical WM and numeracy skills among children with learning problems (Kroesbergen, Van’t Noordende, & Kolkman, 2014).

Working Memory Deficits: Numerical Versus Verbal

Although empirical studies suggest that children with different types of learning difficulties may show domain-specific WM deficits, this possibility has not been adequately researched. It remains unclear whether WM deficits among these children are different within the verbal domain: verbal versus numerical. Findings from neuropsychological and behavioral studies suggest that the numerical domain is different from the verbal domain (e.g., Cappelletti, Butterworth, & Kopelman, 2001).

More precisely, there is evidence of a neurobiological disassociation between numerical and verbal processing (e.g., Cappelletti et al., 2001), and there is a specific brain region (i.e., the horizontal segment of the intraparietal sulcus) that is primarily activated during tasks that require only numerical processing (Dehaene, Piazza, Pinel, & Cohen, 2003). Behavioral studies on children’s mathematics development suggest that numerical processing skills play a unique and critical role in mathematics development. For example, children’s number sense, what numbers mean and an ability to perform mental mathematics, is critical to mathematics development (Berch, 2005; Gersten & Chard, 1999). Children with poor number sense often have a poor mental representation of problems, which leads to persistent problems in many areas of mathematics (Woodward & Baxter, 1997). Moreover, research shows that children with mathematics problems demonstrate more severe deficits in numerical processing skills than their deficits in verbal processing skills (e.g., Peng, Sun, Li, & Tao, 2012; Raghubar, Barnes, & Hecht, 2010).

We are aware that several studies did examine whether children with learning difficulties display differences in WM in the verbal and numerical domains (e.g., Andersson & Lyxell, 2007; Passolunghi & Siegel, 2004; Peng, Tao, & Li, 2013; Siegel & Ryan, 1989), but the results are unclear. Whereas several investigators have found children with learning difficulties, regardless of learning difficulty types, suffer from verbal and numerical WM deficits to a similar degree (e.g., Andersson & Lyxell, 2007), others have found that children with mathematics problems suffer from only or more severe numerical WM deficits (e.g., Passolunghi & Siegel, 2004; Siegel & Ryan, 1989). Related findings have suggested children with reading problems experience only or more severe verbal WM deficits (e.g., Peng et al., 2013). One possible reason for these inconsistent findings is comorbidity. Children with learning difficulties are a heterogeneous group. They may be conceptualized in terms of several subgroups. Some subgroups are RD, MD, and RDMD (Velluntino & Fletcher, 2007). RDMD has been postulated to be cognitively different from the other two subgroups. That is, compared to RD and MD children, RDMD children are believed to suffer from more comprehensive and serious cognitive impairments (e.g., van der Sluis, de Jong, & van der Leij, 2004). However, most previous studies on WM for RD or MD did not distinguish these two groups from children with RDMD (e.g., Jeffries & Everatt, 2004). Because reading problems often co-occur with math problems (the rate of comorbidity is approximately 80%; Light & DeFries, 1995), the WM deficit findings from most previous studies may actually reflect a mixed pattern of WM deficits for RD, MD, and RDMD.

Possible Moderators of WM Performance

Another possible reason for the conflicting findings for numerical WM and verbal WM deficit profiles is the method used for identifying children with learning difficulties. Identification methods vary across studies, and different methods may lead to different cognitive profiles (Fletcher et al., 1994; Murphy, Mazzocco, Hanich, & Early, 2007). In this synthesis, we investigated two methodological issues that are potentially related to the verbal and numerical WM profiles among children with different types of learning difficulties: severity of learning difficulties and type of academic screening measure.

Severity of learning difficulties. Low-achievement identification is a widely adopted approach in the area of learning difficulties research (e.g., Andersson & Lyxell, 2007; Geary et al., 2007; Murphy et al., 2007; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989; Swanson et al., 2009). In accordance with low-achievement identification, children with learning difficulties are identified if their IQs are in a normal range but their performance is below a cutoff point on academic screening measures (Fuchs, Mock, Morgan, & Young, 2003). However, one major problem associated with this approach is the inconsistent cutoff criterion on the academic screening measure. Specifically, the cutoff criterion used to establish learning difficulties varies from the 35th percentile to less than the 5th percentile across studies (e.g., Geary, Hamson, & Hoard, 2000; Landerl, Bevan, & Butterworth, 2004). Different cutoff scores lead to different degrees of severity in learning difficulties (e.g., Fuchs, Fuchs, & Compton, 2004), which may affect cognitive profiles of learning difficulties, especially MD.

For example, Murphy et al. (2007) studied relations between the cognitive profiles of children with MD and the achievement cutoff criterion. Murphy et al. found there were qualitative group differences in the profiles of math-related cognitive skills across groups defined by different cutoff scores (11th percentile and 25th percentile on math measures). Children with less severe MD appeared to show less severe cognitive deficits than children with more severe MD. These results highlight the potential effects that severity of academic low achievement may have on cognitive profiles of children with learning difficulties. The severity of cognitive deficits (e.g., WM deficits) may vary as a function of their severity of learning difficulties.

Type of academic screening measure. The type of academic screening measure also varies across relevant WM studies. For the identification of RD, many investigators used measures assessing word-level decoding (e.g., Landerl et al., 2004; Peng et al., 2012; Swanson, 1994), reading comprehension (e.g., Andersson, 2010), or word-level decoding combined with reading comprehension (e.g., Swanson, 2012). For the identification of MD, some researchers measured only numerical skills (e.g., calculation, magnitude comparison, and counting; e.g., Geary et al., 2000; Geary, Hoard, & Hamson, 1999), whereas others used measures of numerical and verbal skills (e.g., calculation and word problems; e.g., Swanson, 1994, 2012).

Research shows that different reading and mathematics skills correlate differently with WM. Specifically, it has been suggested that word decoding and reading comprehension draw from WM in different ways. Compared to word reading, reading comprehension is more closely related to

WM, especially in the verbal domain (Cain et al., 2004; Savage, Lavers, & Pillay, 2007). Likewise, different mathematics skills relate to WM differently (e.g., Bull & Johnston, 1997; Gathercole & Pickering, 2000; Geary, 2004; McLean & Hitch, 1999; Passolunghi & Siegel, 2004; Swanson, Jerman, & Zheng, 2008). Although numerical processing, such as calculations, often involve numerical WM (Iuculano, Moro, & Butterworth, 2011; Swanson, 2006), measures that tap both calculation and word problem solving seem to place greater load on both numerical and verbal WM (Swanson & Beebe-Frankenberger, 2004). Thus, the type of academic screening measure used to define both RD and MD may influence the degree to which learning difficulty subgroups are related to verbal and numerical WM.

Research Objectives

The purpose of this synthesis was to examine three questions. First, compared to typically developing (TD) children, do RD children, MD children, and RDMD children show WM deficits in the verbal domain, the numerical domain, or both domains? Second, are verbal WM and numerical WM differentially important among RD children, MD children, and RDMD children? Third, do WM differences between TD children and each of the learning difficulty subgroups vary as a function of severity of learning difficulties or type of academic screening measure?

We began with three hypotheses. First, if WM deficits are domain general, they will be equally related to verbal and numerical domains for RD children, MD children, and RDMD children. The severity of WM deficits will vary as a function of learning difficulties severity, regardless of domain and learning difficulty subgroups. In addition, the profiles of WM deficits will not be affected by the type of academic screening measure. The second hypothesis is if the WM deficits are domain specific, we expect that RD children will show only verbal WM deficits, MD children will have only numerical WM deficits, and RDMD children will show deficits in both domains. The severity of verbal WM deficits will vary only as a function of the severity of RD, whereas the severity of numerical WM deficits will vary only as a function of the severity of MD. RD and RDMD children in the area of comprehension will show more severe verbal WM deficits than those with difficulties in word reading. MD and RDMD children identified by numerical and verbal skills will show more severe numerical and verbal WM deficits than those identified by numerical skills only. Third, if, as suggested by previous reviews (Swanson et al., 2009; Swanson & Jerman, 2006), the WM deficits are both domain general and domain specific, we expect RD, MD, and RDMD children to show both verbal and numerical WM deficits. However, MD children and RDMD children will demonstrate more severe numerical WM deficits than RD children, whereas RD children and RDMD children will display more severe verbal WM deficits than MD children. The severity of verbal WM deficits will be more closely related to the severity of RD than it will be to the severity of MD, whereas the severity of numerical WM deficits will be more closely related to the severity of MD than to the severity of RD. RD and RDMD children identified by reading comprehension will show more severe verbal WM deficits than those identified by word reading. MD and RDMD children identified by numerical and verbal skills will show more severe numerical and verbal WM deficits than those identified by numerical skills only.

Method

Inclusion Criteria for Studies in This Review

To be included in the present analysis, each study was required to meet the following criteria:

1. The study included measures of verbal WM or numerical WM tasks. Verbal WM tasks required simultaneous verbal processing and verbal storage. Numerical WM tasks required simultaneous numerical information processing and numerical information storage.
2. The study compared children (5–20 years) with RD, MD, or RDMD to TD children on at least one measure of verbal WM or numerical WM. The study reported that all children's IQ scores were in the normal range (standardized score = 80–120). TD children were matched with RD, MD, and RDMD children on age and IQ.
3. The study reported information showing that children with RD were below at least the 35th percentile or 1 standard deviation on reading screening measures and had normal mathematics ability comparable to TD. Children with MD were below at least 35th percentile or 1 standard deviation on mathematics measures and had normal reading ability comparable to TD children. Those with RDMD were below the 35th percentile on reading and math screening measures.

Literature Search

Articles for this meta-analysis were identified in two ways. First, a computer search of the PsycINFO, ERIC, and Medline databases for literature from 1963 to July 2013 was conducted. Titles, abstracts, and keywords were searched for the terms *working memory* or *executive function** AND *learning disabilit*, learning difficult**, *reading disabilit*, reading difficult**, *dyslexi**, *math* disabilit*, math** *difficult**, or *dyscalcul**. The terms *function**, *disabilit**, *difficult**, *dyslexi**, and *dyscacul** allowed for inclusion of *functions/functioning, disabilities/disability, difficulties/difficulty, dyslexia/dyslexic, dyscalculia/dyscalculic*, and so forth. Second, we searched citations in prior relevant reviews. We also searched unpublished literature (e.g., dissertations), and we contacted several researchers to check the appropriateness of certain studies.

The initial search yielded 81 studies. Several were excluded because TD children were not sampled or because they did not provide information on IQ and/or mathematics and reading performance. A total of 29 studies met criteria for inclusion and are shown in Tables 1, 2, and 3.

Coding Procedure

A research assistant—a doctoral student in special education—coded 11 of the 29 studies independently of the first author. The first author and the research assistant achieved 97% interrater agreement across all coding categories.

Analytic Strategies

Hedges's *g*, corrected for sample size bias, was used as the measure of effect size. We chose Hedges's *g* as it provides better estimate of effect sizes than Cohen's *d* on small sample sizes (most studies in this review had small sample sizes; Grissom & Kim, 2005). For studies reporting means, standard deviations, and sample size, the following formulas were used,

$$g^{u} = g\left(1 - \frac{3}{4(N_{LD} + N_{TD} - 2) - 1}\right)$$

with $$g = \frac{\overline{X}_{LD} - \overline{X}_{TD}}{S}$$ and $$g = \sqrt{\frac{(N_{LD} - 1)s^2_{LD} + (N_{TD} - 1)s^2_{TD}}{N_{LD} + N_{TD} - 2}}$$

in which g^{u} is the unbiased estimate of Hedges's *g*, *g* is Hedges's *g* as traditionally defined, N_{LD} is the number of participants in the learning difficulties (LD) group, N_{TD} is the number of participants in the TD group, $\overline{X}_{LD}$ is the mean of WM scores for participants in the LD group, $\overline{X}_{TD}$ is the mean of WM scores for participants in the TD group, S is the pooled standard deviation, S^2_{LD} is the variance of WM scores for the participants in the LD group, and S^2_{TD} is the variance of WM scores for the participants in the TD group.

We first estimated the effect sizes of verbal WM and the effect sizes of numerical WM deficits for RD children, MD children, and RDMD children, in comparison to TD children. We considered all eligible effect sizes in each study. That is, studies can contribute multiple effect sizes as long as the sample for each effect size is independent. For studies that reported multiple effect sizes from the same sample (e.g., two effect sizes based on two verbal WM measures are calculated for the comparison of RD vs. TD in one study), we accounted for the statistical dependencies using the random effects robust standard error estimation technique developed by Hedges, Tipton, and Johnson (2010). This analysis allows for the clustered data (i.e., effect sizes nested within samples) by correcting the study standard errors to take into account the correlations between effect sizes from the same sample. The robust standard error technique requires that an estimate of the mean correlation (ρ) between all the pairs of effect sizes within a cluster be estimated for calculation of the between-study sampling variance estimate, τ^2. In all analyses, we estimated τ^2 with ρ equal to .80; sensitivity analyses showed that the findings were robust across different reasonable estimates of ρ.

Because we hypothesized that the research body is reporting a distribution of effect sizes with significant between-study variance, as opposed to a group of studies attempting to estimate one true effect size, a random-effects model was appropriate for the current study (Lipsey & Wilson, 2001). Weighted random-effects meta-regression models using Hedges et al.'s (2010) corrections were run with ROBUMETA in Stata (Hedberg, 2011) to summarize effect sizes and examine potential moderators. For each analysis on verbal WM and numerical WM, we first estimated only the overall weighted mean effect size for RD children, MD children, and RDMD children, in comparison to TD children. Then, subgroup analysis was used to examine whether RD, MD, and RDMD children differed on verbal WM or numerical WM. Next, we examined the effects of two potential moderator variables: (a) severity of LD and (b) type of academic screening measure.

Forest plots were used to examine the distributions of effect sizes and to detect outliers. Sensitivity analyses were run to examine adjusted overall effect size after removing observed outliers. Publication bias (the problem of selective publication, in which the decision to publish a study is influenced by its results) was investigated using the method of Egger, Smith, Schneider, and Minder (1997). Publication bias is suggested when the Egger et al. publication bias statistic is significantly greater than zero ($p < .05$), and funnel plot was further examined for potential publication bias.

Results

Study Characteristics

Studies included in this meta-analysis involved 2,598 participants, 428 of whom were children with RD, 471 with MD, and 524 with RDMD, and 1,175 were TD. They ranged in age from 5 to 20. A total of 110 effect sizes were calculated. Most of the studies used complex span tasks as WM tasks (see the appendix for the task

Table 1. Study Characteristics for RD Children.

Citation	Age, RD (TD)	*n* RD	*n* TD	Verbal WM	Numerical WM	Screening Measure for RD	Screening Measure for MD	ES Reading
Swanson, 1994	10.78 (10.78)	26	47	Rhyming task		Word reading	Calculation	–2.86
Swanson & Trahan, 1996	10.5 (10.5)	60	60	Sentence span		Vocabulary, reading comprehension	Math in *Comprehensive Test of Basic Skills*	–4.48
Geary et al., 1999	6.75 (6.75)	15	35		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	–2.65
Geary et al., 2000	6.83 (6.75)	14	26		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	–3.39
Landerl et al., 2004	9.18 (9.06)	10	18		Backward digit	Word reading	Calculation	–3.02
van der Sluis et al., 2005	10.66 (10.79)	18	24	Listening Span	Backward digit	Word reading in a minute	Calculation	–3.44
van der Sluis et al., 2005	10.93 (10.64)	25	18	Listening Span	Counting span	Word reading in a minute	Calculation	–3.82
Schuchardt et al., 2008	9.05 (9.06)	30	30	Backward word span	Backward digit, counting span	Word reading	Calculation, word problems, and geometry problems	–1.85
Landerl et al., 2009	9.33 (9.13)	21	42		Backward digit	Word reading, sentence reading	Calculation	–1.92
Andersson, 2010	11.42 (11.42)	36	94	Listening span		Reading comprehension	Calculation	–1.65
Swanson et al., 2010	11.41 (11.1)	14	14	Listening span		Word reading, comprehend sentences	Calculation	–2.94
Swanson, 2011	11.62 (11.62)	13	23	Rhyming task		Word reading	Calculation	–2.15
Göthe et al., 2012	8 (7.7)	21	20		Backward digit	Word reading	Calculation	–2.67
Göthe et al., 2012	11.1 (11.1)	19	20		Backward digit	Word reading	Calculation	–0.6
Swanson, 2012	15.81 (15.73)	19	15	Rhyming task	Random number generation	Word reading, reading comprehension	Calculation and word problems	–3.39
Jerman et al., 2012	12 (11.98)	25	25	Listening span		Word reading	Calculation	–3.13
Jerman et al., 2012	12.66 (11.98)	23	25	Listening span		Reading comprehension	Calculation	–2.24
De Weerdt et al., 2013	9.96 (10.08)	17	45	Backward word recall, listening span	Backward digit recall	Word reading	Calculation	–2.8
Peng et al., 2013	11.1 (10.99)	22	31	Reading span	Complex calculation span	Word reading	Calculation and word problems	–7.98

Note. ES = effect size; MD = mathematics difficulties; RD = reading difficulties; TD = typically developing; WM = working memory.

description in each study). The number of participants and effect sizes contributing to each analysis are indicated in Tables 1, 2, and 3.

For children with RD, 10 studies included verbal WM deficits and 12 studies included numerical WM deficits. For children with MD, 13 studies involved verbal WM deficits and 15 studies included numerical WM deficits. For children with RDMD, 17 studies explored verbal WM deficit and 16 studies investigated numerical WM deficit.

Table 2. Study Characteristics on MD Children.

Citation	Age, MD (TD)	*n* MD	*n* TD	Verbal WM	Numerical WM	Screening Measure for RD	Screening Measure for MD	ES Math
Swanson, 1994	10.78 (10.78)	24	47	Rhyming task		Word reading	Calculation	–3.05
Geary et al., 1999	6.91 (6.75)	15	35		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	–2.63
Geary et al., 2000	6.92 (6.75)	12	26		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	–3.04
Landerl et al., 2004	8.64 (9.06)	10	18		Backward digit	Word reading	Calculation	–1.55
Passolunghi & Siegel, 2004	10.4 (10.4)	22	27	Listening span, backward word	Counting span, backward digit	Reading comprehension	Word problems, manipulation of Arabic (sequencing numbers) and verbal numerals	–4.44
van der Sluis et al., 2005	10.69 (10.64)	17	18	Listening span	Backward digit, counting span	Word reading	Calculation	–2.81
Rosselli et al., 2006	11.44 (11.25)	17	20		Backward digit	Word reading	Calculation	–8.05
Andersson & Lyxell, 2007	10.33 (10.25)	31	47	Animal dual task	Counting span	Reading comprehension	Calculation, magnitude comparison, number coding	–1.75
Swanson et al., 2008	6.67 (6.67)	77	54	Listening span, semantic association	Backward digit	Word reading and comprehension	Calculation, word problem, digit naming fluency	–1.92
Censabella & Noel, 2008	10.49 (10.33)	20	20	Listening span		Reading comprehension	Calculation, decimal and metric knowledge, comprehension of volume and masses	–5.07
Schuchardt et al., 2008	8.61 (9.06)	17	30	Backward word	Backward digit, counting span	Word reading	Calculation, word problems, and geometry problems	–3.85
Landerl et al., 2009	9.2 (9.13)	20	42		Backward digit	Word reading, sentence reading	Calculation	–3.36
D'Amico & Passolunghi, 2009	9.36 (9.39)	12	12	Listening span		Reading comprehension, word reading	Calculation, number knowledge	–1.39
Andersson, 2010	11.33 (11.42)	39	94	Listening span		Reading comprehension	Calculation	–1.4
Chan & Ho, 2010	9 (9)	49	76		Backward digit	Word reading, word dictation	Calculation, measure, shape and space, and data handling	–3.16
Passolunghi, 2011	9.61 (9.63)	18	18	Listening span		Teacher report of normal reading skills	Calculation, number magnitude judgment	–6.02
Vukovic, 2012	8 (8)	19	165		Backward digit	Letter, word reading	Calculation	–1.66
Peng et al., 2012	11.01 (10.98)	18	30	Reading span	Calculation span	Word reading	Calculation, word problems	–2.42
Swanson, 2012	16.1 (15.73)	12	15	Rhyming task	Random number generation	Word reading, reading comprehension	Calculation, word problems	–4.23
De Weerdt et al., 2013	9.80 (10.08)	28	45	Backward word, listening span	Backward digit recall	Word reading	Calculation	–1.75

Note. ES = effect size; MD = mathematics difficulties; RD = reading difficulties; TD = typically developing; WM = working memory.

Table 3. Study Characteristics on RDMD Children.

Citation	Age RDMD (TD)	*n* RDMD	*n* TD	Verbal WM	Numerical WM	Screening Measure for RD	Screening Measure for MD	ES Reading	ES Math
Swanson, 1994	10.78 (10.78)	17	47	Rhyming task		Word reading	Calculation	−2.87	−1.86
Geary et al., 1999	6.91 (6.75)	25	35		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	−2.82	−2.79
Geary et al., 2000	6.75 (6.75)	16	26		Backward digit	Word attack, letter–word identification	Counting, subtraction, graph reading, and time telling	−3.77	−3.46
Swanson & Sachse-Lee, 2001	11.52 (11.69)	24	29	Sentence span, story retelling		Reading comprehension	Calculation	−2.39	−2.23
Swanson, 2003	7.8 (7.71)	17	25	Semantic association		Word reading	Calculation	−4.48	−2.59
Swanson, 2003	10.66 (10.66)	43	38	Semantic association		Word reading	Calculation	−4.48	−2.59
Swanson, 2003	12.86 (13.35)	15	25	Semantic association		Word reading	Calculation	−4.48	−2.59
Landerl et al., 2004	8.66 (9.06)	11	18		Backward digit	Word reading	Calculation	−2.77	−1.58
van der Sluis et al., 2005	10.82 (10.79)	15	24	Listening span	Backward digit	Word reading in a minute	Calculation	−3.83	−2.69
van der Sluis et al., 2005	10.69 (10.64)	16	18	Listening span	Backward digit	Word reading in a minute	Calculation	−3.17	−2.81
Rosselli et al., 2006	11.36 (11.25)	13	20		Backward digit	Word reading	Calculation	−2.43	−5.45
Andersson & Lyxell, 2007	10.42 (10.25)	37	47	Animal dual task	Counting span	Reading comprehension	Calculation, magnitude comparison, number coding	−1.62	−1.76
Schuchardt et al., 2008	8.64 (9.06)	20	30	Backward word	Backward digit	Word reading	Calculation, word problems, and geometry problems	−2.9	−3.5
Maehler & Schuchardt, 2009	8.97 (8.97)	27	27	Backward word	Backward digit	Word reading	Calculation, word problems, and geometry problems	−1.83	−2.46
Landerl et al., 2009	9.35 (9.13)	26	42	Backward word	Backward digit	Word reading, sentence reading	Calculation	−2.08	−3.28
Andersson, 2010	11.25 (11.42)	80	94	Listening span		Reading comprehension	Calculation	−1.93	−1.48
Chan & Ho, 2010	9.16 (9)	28	76		Backward digit	Word reading, word dictation	Calculation, measure, shape and space, and data handling	−3.61	−3.21
Swanson, 2011	11.62 (11.62)	15	23	Rhyming task		Word reading	Calculation	−1.72	−1.16
Vukovic, 2012	8 (8)	19	165		Backward digit	Letter, word reading	Calculation	−2.25	−1.54
Peng et al., 2012	10.9 (10.98)	20	30	Reading span	Calculation span	Word reading	Calculation, word problems	−3.07	−2.64
Swanson, 2012	16.18 (15.73)	12	15	Rhyming task	Random number generation	Word reading, reading comprehension	Calculation, word problems	−2.12	−3.14
De Weerdt et al., 2013	10.19 (10.08)	28	45	Backward word, listening span	Backward digit			−2.68	−2.76
Peng et al., 2013	11.09 (10.99)	24	31	Reading span	Calculation span	Word reading	Calculation, word problems	−6.64	−3.06

Note. ES = effect size; MD = mathematics difficulties; RD = reading difficulties; RDMD = reading and mathematics difficulties; TD = typically developing; WM = working memory.

Table 4. Working Memory Deficits in LD Subgroups and Moderation Effects of Severity of Learning Difficulties and Screening Measure.

	Verbal WM				Numerical WM			
	Number of ESs	ES (Hedges's *g*)	ES Confidence Interval	Between-Study Sampling Variance (τ^2)	Number of ESs	ES (Hedges's *g*)	ES Confidence Interval	Between-Study Sampling Variance (τ^2)
LD subgroups								
RD	14	−0.59***	−0.82, −0.37	.04	14	−0.42**	−0.64, −0.20	.02
MD	20	−0.64***	−0.86, −0.41	.07	20	−0.85***	−1.31, −0.40	.35
RDMD	23	−0.88***	−1.05, −0.70	.05	19	−1.21***	−1.56, −0.87	.29
	Number of ESs	Coefficient	Coefficient Confidence Interval	Between-Study Residual Sampling Variance (τ^2)	Number of ESs	Coefficient	Coefficient Confidence Interval	Between-Study Residual Sampling Variance (τ^2)
Severity of LD								
Severity of RD for RD group	14	−0.03	−0.10, 0.05	.05	14	−0.001	−0.05, 0.05	.04
Severity of RD for RDMD group	23	−0.03	−0.10, 0.05	.05	19	−0.05	−0.19, 0.10	.31
Severity of MD for MD group	20	−0.06	−0.22, 0.09	.07	20	−0.40	−1.02, 0.22	.37
Severity of MD for RDMD group	23	−0.07	−0.38, 0.24	.05	19	−0.70	−1.57, 0.18	.25
Screening measures								
Reading screening measure type for RD group	14	−0.03	−0.15, 0.09	.05	12	0.07	−0.08, 0.22	.05
Reading screening measure type for RDMD group	23	0.02	−0.07, 0.10	.05	19	0.05	−0.10, 0.19	.32
Mathematics screening measure type for MD group	20	0.02	−0.15, 0.18	.08	20	0.09	−0.39, 0.56	.39
Mathematics screening measure type for RDMD group	23	0.02	−0.10, 0.14	.05	19	0.10	−0.18, 0.38	.31

Note. ES = effect size; LD = learning difficulties; MD = mathematics difficulties; RD = reading difficulties; RDMD = reading and mathematics difficulties; WM = working memory.
$^{**}p < .01$. $^{***}p < .001$.

Verbal Working Memory Deficits

Table 4 shows verbal WM differences among RD, MD, and RDMD groups. Figure 1 shows the forest plot of verbal WM differences (Hedges's *g*) of RD versus TD, MD versus TD, and RDMD versus TD. Specifically, there were 14 effect sizes comparing the verbal WM of RD and TD (n_{RD} = 328, n_{TD} = 451). The mean effect size was medium and significant (Hedges's $g = -0.59$, 95% CI [–0.82, –0.37], $p < .001$), and the between-study sampling variance (τ^2) was .04. Egger's test indicated a possible publication bias ($t = 2.85$, $p = .02$). A funnel plot (see Figure 2) was examined, and there seemed to be insufficient studies that reported RD children with more severe verbal WM deficits.

Regarding the verbal WM comparison between MD and TD, 20 effect sizes were calculated ($n_{MD} = 329$, $n_{TD} = 457$). The mean effect size was medium and significant (Hedges's $g = -0.64$, 95% CI [–0.86, –0.41], $p < .001$), and the between-study sampling variance (τ^2) was .07. Egger's test indicated no publication bias ($t = 0.48$, $p = .64$).

In all, 23 effect sizes were calculated to compare verbal WM between RDMD and TD ($n_{RDMD} = 386$, $n_{TD} = 517$). The mean effect size was large and significant (Hedges's $g = -0.88$, 95% CI [–1.05, –0.70], $p < .001$), and the between-study sampling variance (τ^2) was .05. Egger's test indicated no publication bias ($t = 0.55$, $p = .59$).

Further analyses were run to investigate whether the mean effect sizes for verbal WM deficits differed across LD subgroups. Results demonstrated that RDMD children showed a greater verbal WM deficit than RD children ($t = 2.06$, $p = .05$), but it was comparable to that of MD children ($t = 0.84$, $p = .41$). The severities of verbal WM deficits in MD children and RD children were comparable ($t = 1.13$, $p = .28$). To summarize, compared to TD, all LD subgroups showed significant verbal WM deficits. RDMD children showed more severe verbal WM deficits than RD children, whereas RDMD children and MD children, RD children and MD children showed comparable verbal WM deficits.

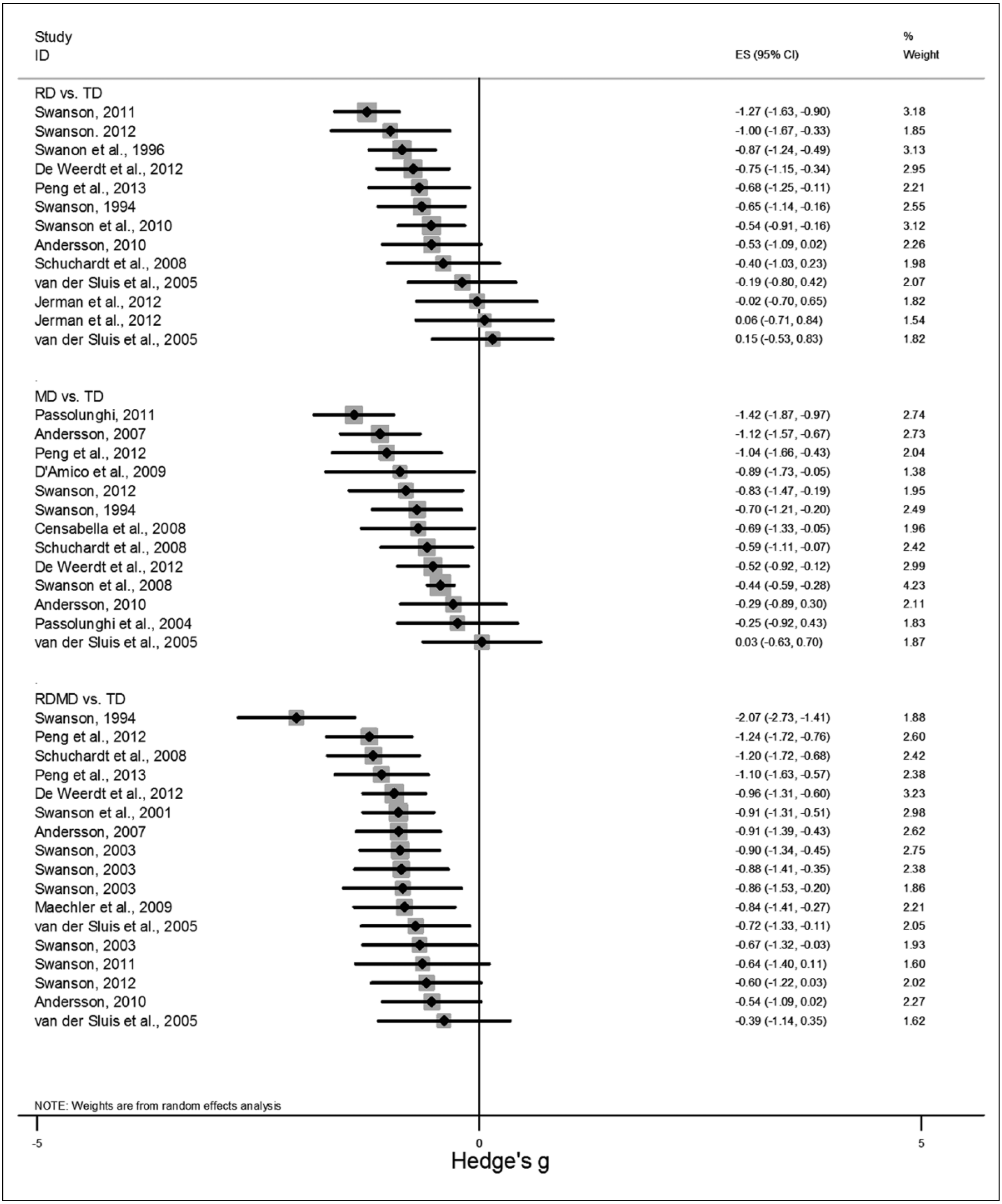

Figure 1. Forest plot of verbal WM differences (Hedges's *g*) of RD versus TD, MD versus TD, and RDMD versus TD.
Note. For studies that provided multiple effect sizes within one sample, the mean effect size was used to graph this forest plot. MD = mathematics difficulties; RD = reading difficulties; RDMD = reading and mathematics difficulties; TD = typically developing; WM = working memory.

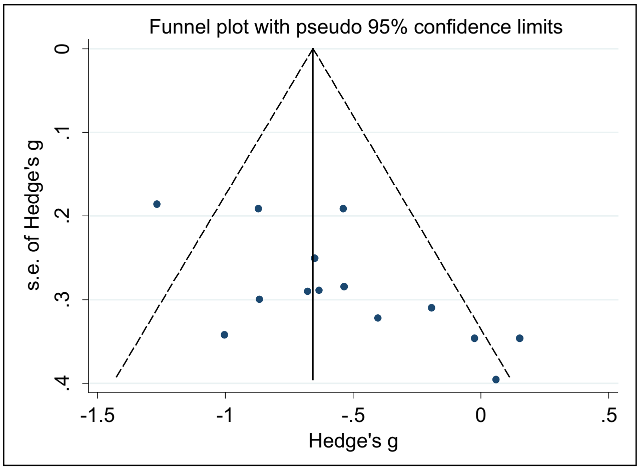

Figure 2. Funnel plot for the verbal WM comparison between RD and TD.
Note. RD = reading difficulties; TD = typically developing; WM = working memory.

Numerical Working Memory Deficits

Table 4 shows numerical WM differences among RD, MD, and RDMD groups. Figure 3 shows the forest plot of numerical WM differences (Hedges's *g*) of RD versus TD, MD versus TD, and RDMD versus TD. Specifically, there were 14 effect sizes comparing numerical WM between RD and TD (n_{RD} = 231, n_{TD} = 324). The mean effect size was medium and significant (Hedges's $g = -0.42$, 95% CI [–0.64, –0.20], $p = .001$), and the between-study sampling variance (τ^2) was .02. Egger's test indicated no publication bias ($t = 0.66$, $p = .53$).

In all, 20 effect sizes were calculated to comparing numerical WM between MD and TD (n_{MD} = 358, n_{TD} = 648). The mean effect size was large and significant (Hedges's $g = -0.85$, 95% CI [–1.31, –0.40], $p = .001$), and the between-study sampling variance (τ^2) was .35. Egger's test indicated no publication bias ($t = 1.84$, $p = .09$). Because Rosselli, Matute, Pinto, and Ardila (2006) appeared to be an outlier, we ran a sensitivity analysis by excluding this study. After excluding this study, the mean effect size was medium and significant (Hedges's $g = -0.68$, 95% CI [–0.93, –0.44], $p < .001$), and the between-study sampling variance (τ^2) was .09. Egger's test indicated no publication bias ($t = 0.01$, $p = .99$).

There were 19 effect sizes comparing numerical WM between RDMD and TD (n_{RDMD} = 313, n_{TD} = 618). The mean effect size was large and significant (Hedges's $g = -1.21$, 95% CI [–1.56, –0.87], $p < .001$), and the between-study sampling variance (τ^2) was .29. Egger's test indicated no publication bias ($t = -1.96$, $p = .07$). Because the study Rosselli et al. (2006) appeared to be an outlier, we ran a sensitivity analysis by excluding this study. After excluding this study, the mean effect size was large and significant (Hedges's $g = -1.08$, 95% CI [–1.29, –0.88], $p < .001$), and the between-study sampling variance (τ^2) was .07. Egger's test indicated no publication bias ($t = 0.38$, $p = .51$).

Further analyses were run to investigate whether the mean effect sizes for numerical WM deficits differed among LD subgroups. Results showed that RDMD children demonstrated a significantly greater numerical WM deficit than RD children ($t = 2.30$, $p = .036$) and MD children ($t = 4.77$, $p < .001$). MD children also showed a marginally significantly greater numerical WM deficit than RD children ($t = 2.12$, $p = .05$). After removing the outlier (i.e., Rosselli et al., 2006), results showed the same pattern. That is, RDMD children demonstrated a significantly greater numerical WM deficit than RD children ($t = 3.45$, $p = .004$) and MD children ($t = 5.54$, $p < .001$) and MD children showed a significantly greater numerical WM deficit than RD children ($t = 4.53$, $p = .02$). To summarize, compared to TD, children with LD show significant numerical WM deficits. Both RDMD children and MD children suffered from more severe numerical WM deficits than did RD children, but RDMD children showed the most severe numerical WM deficits.

Effects of the Severity of Learning Difficulties

We used a meta-regression analysis to investigate whether severity of LD explain the variance of verbal or numerical WM deficits among LD subgroups. The severity of LD is defined by the difference (Hedges's *g*) on reading performance between RD children and TD children, the difference on math performance between MD children and TD children, and the difference on reading and math performance between RDMD children and TD children. As Table 4 shows, for RD children and RDMD children, the severity of their RD did not significantly explain the between-study variance in their verbal WM deficits ($\beta = -0.03$/–0.03, CI [–0.01, 0.05]/[–0.10, 0.05], $t = -0.79$/–0.73, $p = .45$/.48, $\tau^2 = .05$/.05) or the between-study variance in their numerical WM deficits ($\beta = -0.001$/–0.05, CI [–0.05, 0.05]/[–0.19, 0.10], $t = -0.05$/–0.70, $p = .96$/.50, $\tau^2 = .04$/.31). For MD children and RDMD children, the severity of their MD did not significantly explain the between-study variance in verbal WM deficits ($\beta = -0.06$/–0.07, CI [–0.22, 0.09]/[–0.38, 0.24], $t = -0.86$/–0.48, $p = .41$/.64, $\tau^2 = .07$/.05) or the between-study variance in their numerical WM deficits ($\beta = -0.40$/–0.70, CI [–1.02, 0.22]/[–1.57, 0.18], $t = -1.4$/–1.71, $p = .18$/.11, $\tau^2 = .37$/.25). The meta-regression analysis was repeated for numerical WM deficits among MD children and RDMD children excluding the outlier study (Rosselli et al., 2006), and the results pattern stayed the same. To summarize, the verbal and numerical WM deficits in RD children, MD children, and RDMD children did not vary as a function of their LD severity.

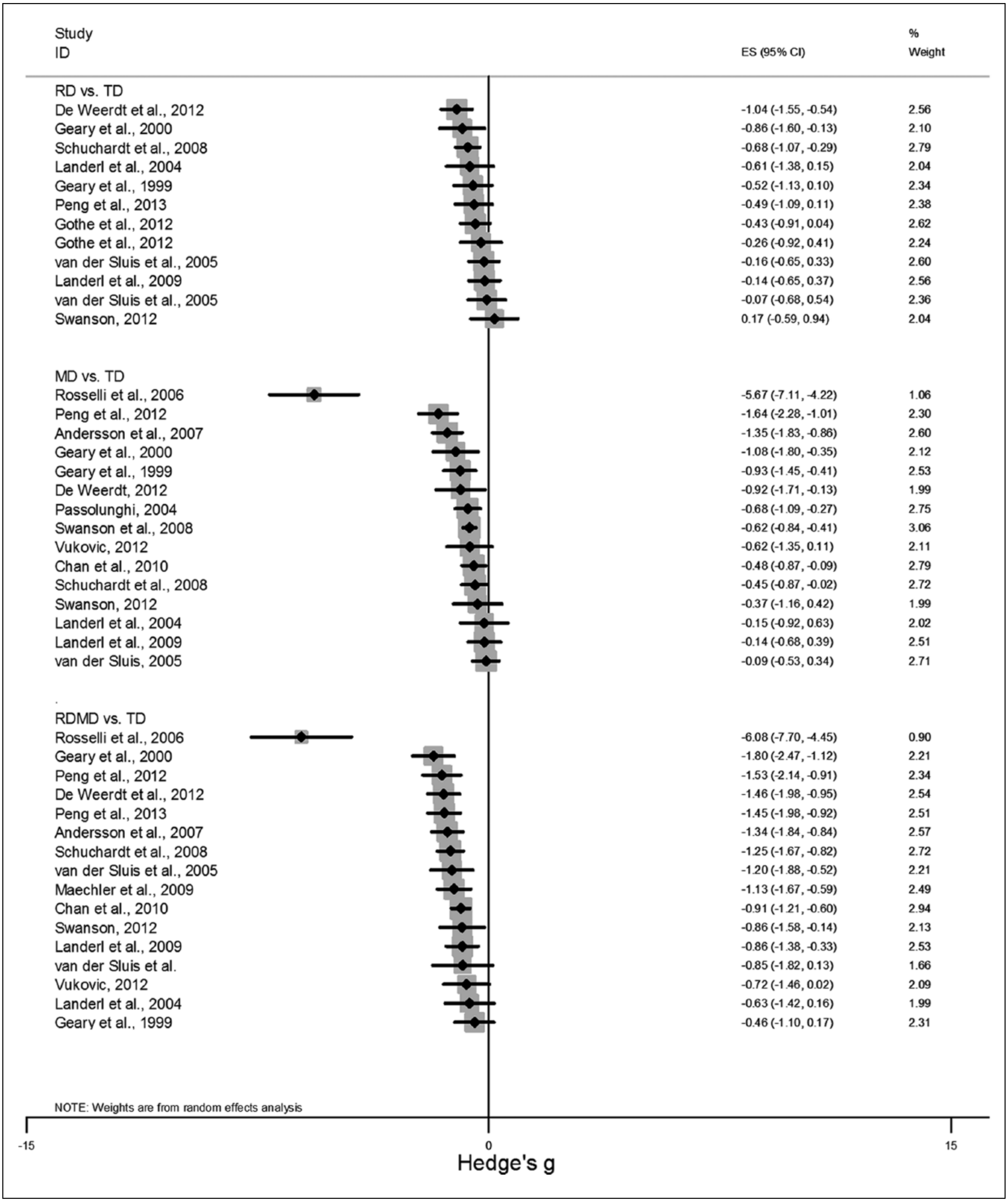

Figure 3. Forest plot of numerical WM differences (Hedges's *g*) of RD versus TD, MD versus TD, and RDMD versus TD.
Note. For studies that provided multiple effect sizes within one sample, the mean effect size was used to graph this forest plot. MD = mathematics difficulties; RD = reading difficulties; RDMD = reading and mathematics difficulties; TD = typically developing; WM = working memory.

Effects of Reading and Mathematics Screening Measure

We used meta-regression to examine whether the type of academic screening measure influences the WM deficit profiles for LD subgroups. For RD and RDMD children, three types of screening measures for RD were coded in the analysis: (a) word-level decoding, (b) reading comprehension, and (c) word-level decoding combined with reading comprehension. As Table 4 shows, regarding to the verbal WM deficits in RD children and RDMD children, there was no difference among groups identified by word-level decoding, groups identified by reading comprehension, and groups identified word-level decoding combined with reading comprehension ($\beta = -0.03/0.02$, CI [–0.15, 0.09]/[–0.07, 0.10], $t = -0.51/0.39$, $p = .62/.70$, $\tau^2 = .05/.05$). Regarding to the numerical WM deficits in RD children and RDMD children, we had only studies using word-level decoding and studies using word-level decoding combined with reading comprehension. Results showed that there was no significant difference between groups identified by word-level decoding and groups identified by word-level decoding combined with reading comprehension ($\beta = 0.07/0.05$, CI [–0.08, 0.22]/[–0.10, 0.19], $t = 1.03/0.71$, $p = .33/.49$, $\tau^2 = .05/.32$). To summarize, the type of reading screening measures did not affect verbal WM deficits or numerical WM deficits among RD children and RDMD children.

For MD and RDMD children, two types of screening measures for MD were coded in the analysis: (a) numerical-related skills (e.g., calculation and magnitude comparison) and (b) numerical and verbal processing skills (combinations of calculation and word problems). As Table 4 shows, for MD children and RDMD children the type of math screening measure was not a significant moderator of either verbal WM deficits ($\beta = 0.02/0.02$, CI [–0.15, 0.18]/[–0.10, 0.14], $t = 0.23/0.28$, $p = .82/.78$, $\tau^2 = .08/.05$) or numerical WM deficits ($\beta = 0.09/0.10$, CI [–0.39, 0.56]/[–0.18, 0.38], $t = 0.40/0.78$, $p = .70/.45$, $\tau^2 = .39/.31$). Analyses on numerical WM deficits were repeated for MD and RDMD groups excluding the outlier study (i.e., Rosselli et al., 2006). Results showed the same pattern. To summarize, we did not find significant moderating effects of academic screening measure type on verbal or numerical WM deficits among LD subgroups.

Discussion

This synthesis reviewed studies on verbal WM and numerical WM among children with RD, MD, and RDMD. Results indicated that compared to TD children, all LD subgroups showed significant verbal and numerical WM deficits. RDMD children demonstrated the most severe verbal and numerical WM deficits. Although RD and MD children showed comparable verbal WM deficits, the MD group showed more severe numerical WM deficits than RD children. No significant moderating effects emerged for the severity of LD or for the type of academic screening measure.

Working Memory Deficits Among RD, MD, and RDMD Children

Most previous work exploring whether WM deficits are domain specific have focused on comparisons between the verbal domain and the visuospatial domain (e.g., Swanson et al., 2009; Swanson & Jerman, 2006). It remains unclear whether children with LD display different WM deficits in the verbal domain versus the numerical domain. The primary goal of the current synthesis was to investigate this question. We found RD, MD, and RDMD children showed similar WM deficits in both verbal and numerical domains. Moreover, RD children seem to display comparable verbal and numerical WM deficits, and their verbal WM deficits appear the same as those of MD children. This suggests that RD children do not suffer from more severe verbal WM deficits than MD children and that verbal WM deficit may represent a common feature of RD and MD children. Taken together, these findings suggest that WM deficits are domain general in children with LD, which are consistent with the domain-general model proposed by Baddeley (1986). In this model, the *central executive* is a major component and is responsible for coordinating the *phonological loop* and *visuospatial sketchpad* systems, directing attention to relevant information and suppressing irrelevant information and inappropriate actions (Baddeley, 1986), and problems in the central executive may be a correlate, or common cause, of LD.

However, we also found that MD and RDMD children showed more severe numerical WM deficits than RD children. This finding was robust even when we excluded the outlier study (Rosselli et al., 2006). This adds to the literature, indicating that children with mathematics problems not only experience domain-general WM deficits (because they show both verbal and numerical deficits) but also demonstrate a pattern of numerical-specific WM deficits. This result may support the domain-specific WM hypothesis, indicating that the distinctive numerical WM deficits in MD and RDMD children may reflect their insufficient knowledge and skills in mathematics (Ericsson & Kintsch, 1995). More precisely, children with mathematics problems may not have sufficient mathematics skills or knowledge to help encode and retrieve numerical information efficiently; hence, their difficulty in establishing a numerical retrieval structure in WM may not allow efficient numerical retrieval from long-term memory and efficient numerical processing. That MD and RDMD children displayed more severe numerical deficits is also in line with evidence from neuropsychological and behavioral studies, which suggests that numerical processing skills are different from verbal processing skills, and they may play an important role in mathematics development (Cappelletti et al., 2001; Swanson, 2006).

One more potentially important finding is that among LD subgroups, RDMD children showed the most severe WM deficits in both verbal and numerical domains. This is consistent with the hypothesis that RDMD children suffer from more severe cognitive impairments than RD and MD children (e.g., van der Sluis et al., 2004). Moreover, this finding indicates that it is necessary to differentiate RD or MD children from RDMD children when investigating the cognitive profiles among subgroups of LD.

Severity of Learning Difficulties

Because the severity of academic low achievement seems to affect cognitive profiles of children with LD (Murphy et al., 2007), we expected it would affect verbal and numerical WM deficits among LD subgroups. However, we found that the severity of low reading performance did not explain between-study variance in verbal or numerical WM deficits. This finding is not consistent with the domain-specific hypothesis, but it is in consistent with previous research, which shows that reading level did not mediate WM differences among children with different reading levels (Swanson et al., 2009). Moreover, this finding extends previous research by showing that the comorbidity of MD did not affect the relations between severity of RD and verbal/numerical WM deficits for children with reading problems.

Similarly, we found that the severity of low mathematics performance did not moderate the relations between verbal WM or numerical WM and LD. However, it is worth noting that in Rosselli et al. (2006), MD and RDMD children demonstrated much more severe numerical WM deficits (Hedges's $g = -5.7, -6.12$) and MD (Hedges's $g = -5.45, -8.05$) than the children in other studies (Hedges's $g = -0.5 \sim -1.8/-1.3 \sim -3$). Because the literature indicates that children with more severe mathematics problems show more severe numerical WM deficits (Geary et al., 2000), and the severity of mathematics problems exerts a significant influence on cognitive profiles of children with mathematics problems (Geary, Hoard, Nugent, & Bailey, 2012; Murphy et al., 2007), our finding may be the result of having too few studies examining the relationship between the severity of mathematics problems and numerical WM deficits. Future studies are needed to focus on children with more severe mathematics problems.

Type of Academic Screening Measure

Different reading and math skills tap WM skills differently (e.g., Bull & Johnston, 1997; Carretti, Cornoldi, De Beni, & Romanò, 2005; Gathercole & Pickering, 2000). Thus, different types of academic screening measures may affect the WM deficit profiles among LD subgroups. That is, children with RD identified by word-level decoding measures may show less severe verbal WM deficits than those identified by reading comprehension measures. MD and RDMD children identified by numerical skills (e.g., calculation, magnitude comparison, and digit naming) may show less severe numerical and verbal WM deficits than those identified by numerical and verbal skills (i.e., calculation and word problems).

However, we found that neither verbal nor numerical WM deficits were significantly affected by the type of academic screening measure among low achieving subgroups. This is in accordance with the domain-general WM model that suggests that children with LD, regardless of subgroups, all suffer from deficits in domain-general executive functions. An alternative explanation, however, is that our analyses had insufficient power to detect significant differences, especially for studies that used reading comprehension measures to screen RD/RDMD children ($n = 2 \sim 6$) and for studies using word-level decoding measures combined with reading comprehension measures to screen RD/RDMD children ($n = 2 \sim 3$). Another plausible reason for this finding relates to the classification of subgroups. Specifically, for studies that used measures of word-level decoding for RD/RDMD identification, few provided information about children's reading comprehension performance. Similarly, for studies that measured only numerical skills for MD/RDMD identification, few clarified that these children did not experience verbal skills deficits (e.g., problem-solving problem). Based on the limited screening information in these studies, it is possible that RD/RDMD children identified as having word-level RD may also experience reading comprehension problems. MD/RDMD children identified by their numerical skills (e.g., calculation problems) may likely suffer from difficulties in verbal skills (e.g., word problem solving). Thus, future research is needed to examine whether verbal and numerical WM differ among RD subgroups (e.g., children with only word RD and children with only reading comprehension difficulties) and MD subgroups (e.g., children with only calculation difficulties and children with difficulties in only word problem solving).

Study Limitations

Although a rigorous approach was used to review studies, this meta-analysis is constrained by some limitations. The first limitation is publication bias. Although we searched for unpublished literature (e.g., dissertations), and we also contacted researchers in the field, we did not manage to retrieve unpublished studies. Hence, publication bias potentially represents a missing data problem. In other words, we may not have enough studies that reported insignificant verbal WM or numerical WM deficits for LD. Second, this meta-analysis was unable to investigate the effect of study quality. Although we used peer-reviewed studies and adopted relatively strict study inclusion criteria (e.g., studies must provide evidence on group equivalence on IQ, reading between MD children and TD children, and math between RD children and TD children), we could not index the study quality because of limited information provided in each study. For example, few studies provided reliability coefficient for their WM measures, which may potentially cause some measurement effects on our results. Another possible limitation is the relatively small number of studies for the moderation analysis involving academic screening measures. This small number of studies is the result of our strict criteria for study inclusion, which took account of both the clear identification of subgroups (RD, MD, and RDMD) and the specificity of WM tasks (only verbal WM and only numerical WM). However, these few studies may cause insufficient power to detect statistical significance for the moderation analysis. Therefore, results associated with type of the screening measure should be interpreted with caution and regarded as exploratory. Moreover, as mentioned in the appendix and in Tables 1, 2, and 3, the majority of the WM tasks in this meta-analysis are considered to be complex span tasks. Future research is needed to examine whether our results can be applied to other WM tasks such as updating, switching, and inhibition.

Future Research on Working Memory for Children With Learning Difficulties

Even with these limitations, the present findings, however, may provide several theoretical and practical implications for WM research. First, the findings add to our understanding of the domain-general and domain-specific nature of WM deficits in children with LD. They suggest that WM deficits are domain general as well as domain specific. Deficit specificity appears in the numerical domain. The numerical WM deficits may reflect insufficient mathematics knowledge of MD and RDMD children. However, whether the severity of MD affects numerical WM deficits and whether subgroups of RD and MD children show different profiles of domain-specific WM deficits remain unanswered issues that require further investigation.

Second, our findings may have implications for the tasks design in WM intervention programs. Specifically, an increasing number of studies in recent years have examined WM interventions for children with LD, with most studies primarily using visuospatial WM training tasks (Melby-Lervåg & Hulme, 2013; Shipstead et al., 2012). Few of these studies, however, have found that WM intervention effects generalized to nontrained verbal WM, numerical WM tasks, or academic performance (Melby-Lervåg & Hulme, 2013; Shipstead et al., 2012). In contrast, there is also research showing that compared to domain-general WM training (training WM using tasks across visuospatial, verbal, and numerical domains), training WM in the numerical domain (using only numerical WM tasks) produced stronger training effects on numerical WM and numeracy skills among children with learning problems (Kroesbergen et al., 2014). These results, together with our findings, suggest that tasks may be an important factor when designing WM training for different LD subgroups. It may be necessary to focus not only on visuospatial WM training but also on verbal and numerical WM training. Moreover, most WM training studies on children with LD did not include academic skills instructions. Considering that the distinctive numerical WM deficits among children with mathematics problems may reflect these children's insufficient mathematics knowledge, and those children also suffer from distinctive visuospatial WM deficits (Swanson & Jerman, 2006), we suggest that the combination of mathematics instructions, numerical WM training, and visuospatial WM training may be particularly efficient for those children. That said, further investigations are needed to determine appropriate procedures for the combination of academic instruction and WM training for LD subgroups.

Appendix

Measures of Verbal Working Memory

Six measures of verbal working memory (WM) were used in the studies included in this synthesis. Listening span was used by the authors of 10 studies (e.g., Andersson, 2010; Passolunghi & Siegel, 2004). In this task, a child heard sequences of multiple simple sentences. The child was asked to state whether each sentence made sense (e.g., "the fish drove the car"; "the rabbit was fast"). Then, at the end of the sequence, the child had to recall the last word in correct serial order. Two studies used a reading span task (Peng, Sun, Li, & Tao, 2012; Peng, Tao, & Li, 2013), which is similar to listening span except that the sentences were visually presented and the child read each one out loud.

Two studies used a rhyming task (Swanson, 1994, 2012), whereby the child listened to sets of words that rhyme and then recalled all the words. Before recalling the words, the child was asked whether a particular word was included in the set (referred to as a process question). For example, the words "lip-slip-clip" were presented, and then the child was asked if "ship or lip" was presented in the word set. The child was then asked to recall the previously presented words ("lip-slip-clip") in order. One study used a semantic association task (Swanson, 2003), in which the child was orally presented a set of words, asked a process question, and asked to recall the words that go together. For example, the child was presented with a list of words (e.g., "car-baseball-truck-football"), then asked if there were animals in the word string (no). Then the child was asked to group the words according to their categories ("car" and "truck" together; "baseball" and "football" together).

One study used a "dual-animal task" (e.g., Andersson & Lyxell, 2007), in which the child was visually and orally presented with lists of words. The child needed to tap the table to indicate whether a word was the name of an animal. At the end of the sequence of word lists, the child recalled the last word in each word list. One study used story retelling (Swanson & Sachse-Lee, 2001), in which the child was read a paragraph and was asked a process question, and then the child needed to recall all the events of the paragraph in order.

There were also two studies using backward word recall (De Weerdt, Desoete, & Roeyers, 2013; Schuchardt, Maehler, & Hasselhorn, 2008), in which the child was orally presented a list of words and asked to recall the words in the backward order. For example, if the child was presented "car-sun-bus-light," the child should recall "light-bus-sun-car."

Measures of Numerical Working Memory

For the numerical WM, five measures were used in the studies of the current synthesis. A backward digit recall task was adopted in 11 studies (e.g., Geary, Hamson, & Hoard, 2000; Landerl, Bevan, & Butterworth, 2004). In this task, the child was orally presented with lists of single digits and asked to recall the digits in backward order. For example, if the child was presented "1-5-8-7-3," the child should recall "3-7-8-5-1."

Two studies used counting span (e.g., Passolunghi & Siegel, 2004), in which the child had to count several sets of dots and later, after counting all sets, recall the number of dots in each set in correct serial order. Two studies used calculation span (Peng et al., 2012; Peng et al., 2013). In this task, the child was visually presented with a list of simple operations (e.g., 2 + 3 = ?), asked to say the answer immediately, and remembered a single-digit number that appeared right after his or her response to the operation. After finishing several operations, the child was required to recall all the single-digit numbers in correct serial order. One study used random number generation (Swanson, 2012). This task required the child to write down as many digits as possible, in a random fashion, in 90 s. The number of random digits written down was the dependent measure. To perform this task, the child needed to simultaneously memorize the number he or she just wrote down and generate a nonadjacent number.

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Declaration of Conflicting Interests

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