Journal of Educational Psychology
2016, Vol. 108, No. 4, 455–473

0022-0663/16/$12.00 http://dx.doi.org/10.1037/edu0000079

A Meta-Analysis of Mathematics and Working Memory: Moderating Effects of Working Memory Domain, Type of Mathematics Skill, and Sample Characteristics

Peng Peng
George Washington University

Jessica Namkung
University at Albany, State University of New York

Marcia Barnes
The University of Texas at Austin

Congying Sun
Georgia State University

The purpose of this meta-analysis was to determine the relation between mathematics and working memory (WM) and to identify possible moderators of this relation including domains of WM, types of mathematics skills, and sample type. A meta-analysis of 110 studies with 829 effect sizes found a significant medium correlation of mathematics and WM, r = .35, 95% confidence interval [.32, .37]. Moderation analyses indicated that mathematics showed comparable association with verbal WM, numerical WM, and visuospatial WM. Word-problem solving and whole-number calculations showed the strongest relation with WM whereas geometry showed the weakest relation with WM. The relation between WM and mathematics was stronger among individuals with mathematics difficulties that are associated with other disorders or cognitive deficits compared with that among typically developing individuals and individuals with only mathematics difficulties. The implications of these findings with respect to mathematics instruction and WM training are discussed.

Keywords: mathematics, working memory, domain, sample type

Supplemental materials: http://dx.doi.org/10.1037/edu0000079.supp

Working memory (WM) refers to the capacity to store information for short periods of time when engaging in cognitively demanding activities (Baddeley, 1986). Theoretically, WM plays an important role in mathematics development because many mathematics tasks involve simultaneous information processing and storage (e.g., remembering intermediate numbers during multidigit calculations and word-problem solving; e.g., Raghubar, Barnes, & Hecht, 2010; Swanson & Jerman, 2006). However, despite the widely held view of the relation between WM and mathematical competence, substantial differences have been found in the percentage of variance in mathematics explained by WM (e.g., Andersson & Lyxell, 2007; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Passolunghi & Siegel, 2004; Tirre & Pena, 1993). Although some research has found that the contribution of WM to mathematics performance is negligible, with R^2 values ranging from 0 to .02 (e.g., Meyer et al., 2010; Tirre & Pena, 1993), other research suggests that WM and mathematics performance are much more strongly related, with R^2 values ranging from .50 to .70 (e.g., Andersson & Lyxell, 2007; Passolunghi & Siegel, 2004).

Clearly, it is important to gain better insight into why different percentages of variance in mathematics performance are explained by WM across different studies. In the present meta-analysis, we focused on three moderators that potentially explain these variations including domains of WM, types of mathematics skills, and sample type. From a theoretical perspective, exploring domain of WM as a moderator would inform theories relating to the domain-specific/domain-general nature of WM (Miyake & Shah, 1999); that is, is WM similarly related to mathematics, regardless of domain of measurement (i.e., verbal, visuospatial, number/quantity WM tasks)? Investigating the relation of WM to different types of mathematics skills and to groups with and without mathematics difficulties is also of interest to theories of mathematical cognition and mathematics disability (Geary & Hoard, 2005). For example, know-

This article was published Online First September 7, 2015.

Peng Peng, Department of Special Education and Disability Studies, George Washington University; Jessica Namkung, Department of Educational Psychology, University at Albany, State University of New York; Marcia Barnes, Department of Special Education, The University of Texas at Austin; Congying Sun, Department of Educational Psychology, Special Education and Communication Disorders, Georgia State University.

Peng's contributions were supported by University Facilitating Fund from George Washington University. Barnes' contributions were supported by grant R342A110270 from the Institute of Education Sciences (NCSER), U.S. Department of Education to the University of Texas at Austin. The opinions expressed are those of the authors and do not necessarily represent views of the Institute or the U.S. Department of Education or of George Washington University.

Correspondence concerning this article should be addressed to Peng Peng, Department of Special Education and Disability Studies, Graduate School of Education and Human Development, George Washington University, 2134 G Street Northwest, Washington, DC 20037. E-mail: kevpp2004@hotmail.com

ing whether WM is differentially related to performance on different types of mathematics tasks such as whole-number calculations versus geometry is of interest to theories of mathematical cognition in terms of understanding the cognitive abilities that may be implicated in the development of different types of mathematics skills (e.g., Barnes et al., 2014; LeFevre et al., 2010). From a practical perspective, understanding whether the relation of WM and mathematics differs in different populations, could have implications for intervention research and intervention design. For example, different mathematics difficulty groups may demonstrate different WM deficit profiles (Peng & Fuchs, 2014; Swanson & Jerman, 2006), which may interact with mathematics instruction such that particular instructional strategies might be more effective for individuals with particular cognitive profiles (e.g., Case et al., 1996; Fuchs, Schumacher, et al., 2014; Swanson, 2014). Thus, investigating the strength of the relation between WM and different types of mathematics performance among individuals with and without mathematics difficulties may be important for instructional design.

Another way in which a meta-analysis on the relation of mathematics and WM is important for informing research and practice is related to studies in which WM is trained. An increasing number of studies in recent years have investigated whether training WM has effects on WM and whether there is far transfer to academic skills such as reading and mathematics (e.g., Dahlin, 2011; Holmes, Gathercole, & Dunning, 2009; Kroesbergen, Van't Noordende, & Kolkman, 2014). The rationale for expected far-transfer effects is based on the presumed strong relation between WM and academic skills. Although some of these studies have found training effects on WM, most have failed to find far-transfer effects on academic skills (e.g., Jacob & Parkinson, 2015; Melby-Lervåg & Hulme, 2012; Redick, Shipstead, Wiemers, Melby-Lervåg, & Hulme, 2015; Shipstead, Redick, & Engle, 2012). The lack of far transfer to academic skills has often been discussed as being related to (a) variability across studies in terms of the type of WM training materials that are used (e.g., some focused on visuospatial WM training, some focused on verbal WM training, whereas others focused on numerical WM training; Peng & Fuchs, 2014), (b) variability in the specific mathematics skills being measured by far transfer tests (e.g., some assessed evidence for far-transfer effects based on basic numeracy tasks, whereas others used tests assessing more advanced mathematics skills; e.g., Kroesbergen et al., 2014; Holmes et al., 2009), and (c) variability in the population receiving the training (e.g., is WM training more effective for individuals with mathematics difficulties than typically developing individuals?; Shipstead et al., 2012). Thus, investigating the moderation effects of domains of WM, types of mathematics skills, and sample type on the relation between WM and mathematics can provide empirical correlational evidence that may help address these variable findings in WM intervention research and transfer to mathematics.

Although there are a few narrative reviews on the relation between mathematics and WM (e.g., LeFevre, DeStefano, Coleman, & Shanahan, 2005; Raghubar et al., 2010), only one meta-analysis has been conducted so far to our best of knowledge (Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013). Friso-van den Bos et al. (2013) found that WM measured in the forms of short-term storage and executive functions (e.g., inhibition, updating, and shifting) was associated with mathematical performance, with the highest correlation between mathematics and verbal updating. However, Friso-van den Bos et al. only focused on the relation between WM and mathematics among elementary children (4–12 years old), and the WM tasks included in their study may be confounded with short-term memory (STM) tasks and the executive function system. More importantly, they did not investigate the possible moderating effects of domains of WM. Thus, in the present meta-analysis, we focused on WM tasks, as defined by Daneman and Carpenter (1980), which reflect simultaneous information processing and storage (e.g., complex span and dual-task performance). We expanded on Friso-van den Bos et al.'s findings by exploring the relation between WM and mathematics across the life span and investigating three moderators that might influence the strength of this relation: domains of WM, types of mathematics skills, and sample type.

Domains of WM

Although many researchers acknowledge that WM tasks measure the ability to simultaneously process and store information (Miyake & Shah, 1999), there are several ongoing debates about the nature of WM tasks in different domains (i.e., verbal, numerical or visuospatial WM). One is whether WM tasks in different domains measure domain-general WM or domain-specific WM. The domain-general WM model proposed by Baddeley (1986) contends that WM consists of two "slave systems" that are responsible for short-term maintenance of domain-specific (i.e., verbal, numerical, and visuospatial) information 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 STM and, for this reason more than any other, the central executive is either considered by many to be the core component of WM or to represent the construct of WM (e.g., Engle, 2002; Engle & Kane, 2004). Based on the domain-general model of WM, the relation between WM and mathematics should not be influenced by different domains of WM; that is, the relation of WM and mathematics should be invariant whether WM is measured using verbal, visuospatial or numerical materials.

However, other researchers claim that the operation of WM depends on domain knowledge, and thus, is strongly affected by domain specificity (Ericsson & Kintsch, 1995). According to Ericsson and Kintsch (1995), long-term memory can supplement or facilitate 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 integrates domain-specific skills, knowledge, and procedures to meet the particular demands of learning tasks within a particular domain. Thus, the relation between WM and mathematics may be influenced by the content domain of WM such that compared with verbal WM, numerical WM may show a stronger relation with number-related mathematics tasks (e.g., calculation), and visuospatial WM may show a stronger relation with performance on mathematics tasks with a strong visuospatial component (e.g., geometry).

There is evidence to support both domain-general and domain-specific models of the relation between WM and mathematics. Some studies have shown that the content domain of the WM task is not differentially related to different types of mathematics skills (e.g., Jarvis & Gathercole, 2003; Passolunghi, Vercelloni, & Schadee, 2007; Swanson & Kim, 2007; Swanson & Sachse-Lee, 2001). Other studies have shown that numerical WM and visuospatial WM were more strongly related to performance on particular mathematics tasks, such as numeracy and calculations, than was verbal WM (e.g., Andersson & Lyxell, 2007; Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013). In the present meta-analysis, we further investigated this issue by examining the relation between different types of mathematics skills and WM tasks from different domains.

Types of Mathematics Skills

Mathematics is a broad concept, addressing the measurement, properties, and relations of quantities as expressed in numbers or symbols. Mathematics is often conceptualized in strands that include (but are not limited to) basic number knowledge (cardinality, ordinality, counting words, Arabic digits knowledge, and number estimation), whole-number calculations (single-digit and multidigit calculations), fractions, geometry, algebra, and word-problem solving (Common Core State Standards Initiative, 2010). In this study, we focused on these mathematics skills. One general hypothesis for the relation between WM and different mathematics skills is based on views about cognitive load during mathematics performance (Sweller, 1994). That is, multistep mathematics tasks that require the calculation and maintenance of intermediate values, and integration of different sources of knowledge are hypothesized to draw more on WM resources than mathematics tasks that consist of fewer steps or just involve simple fact retrieval. According to this view, word-problem solving is hypothesized to show stronger correlation with WM than basic number knowledge. Usually, any individual study only investigates the relation between WM and one or two mathematics skills, which is insufficient to test this hypothesis. In this meta-analysis, we synthesized studies across the six mathematics skills identified above and investigated whether their relations with WM varied. In the following sections, we specifically discuss empirical findings and hypotheses about the relation of WM and different mathematics skills.

Basic number knowledge. Basic number knowledge refers to knowledge of numerosity (i.e., cardinality) as well as the relation between numbers (i.e., ordinality), counting words, and Arabic digits (i.e., symbolic knowledge; Ostergren & Traff, 2013). The relation between basic number knowledge and WM is unclear. Some research has found that, compared with other mathematics skills that require multistep procedures (e.g., word-problem solving and multidigit calculations), basic number knowledge, which is less procedurally complicated, is not significantly correlated with WM (e.g., Andersson & Ostergren, 2012; Kolkman, Kroesbergen, & Leseman, 2014; Passolunghi, Mammarella, & Altoè, 2008; Passolunghi & Siegel, 2004; Passolunghi et al., 2007). However, other research found that basic number knowledge tasks are related to WM. The explanation for these findings has been that particular number knowledge tasks may involve components that are coordinated by WM, such as phonological coding in counting, visuospatial coding for number tasks involving the mental number line, and fact retrieval from long-term memory in number naming and comparison tasks (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008; Mazzocco, Feigenson, & Halberda, 2011). Therefore, one might expect basic number knowledge to be related to WM, although the size of this relation may not be as large as it is for other mathematics skills or as suggested by some studies (e.g., Morsanyi, Devine, Nobes, & Szucs, 2013; Nunes et al., 2007).

Whole-number calculations. Whole-number calculations refer to abilities to carry out single-digit or multidigit addition, subtraction, multiplication, and division. Whole-number calculation procedures require regulating and maintaining arithmetic combinations derived either through retrieval from long-term memory or by relying on counting while simultaneously attending to regrouping demands and place values. Thus, WM is thought to contribute to whole-number calculations because of the need for simultaneous storage and processing (e.g., Fuchs et al., 2005; Swanson, 2006a; Swanson & Beebe-Frankenberger, 2004). However, it is unclear whether the relation between WM and whole-number calculations differs for single-digit versus multidigit calculations and also whether these relations depend on domains of WM. For example, compared with single-digit calculations, multidigit calculations, which involve maintenance of intermediate sums and management of regrouping demands, may show stronger relations with WM (DeStefano & LeFevre, 2004). Also, some studies suggest that the domain of WM (e.g., verbal WM and visuospatial WM) is differentially associated with whole-number calculations depending on age. That is, visuospatial WM tends to show stronger relations with whole-number calculations in younger children whereas both visuospatial and verbal WM are related to calculations in older children (e.g., McKenzie, Bull, & Gray, 2003). One explanation for these findings is that younger children may rely on visual strategies whereas older children rely on both verbal and visual strategies. Thus, in the present meta-analysis, we examined whether the relation between WM and whole-number calculations is moderated by single- versus multidigit calculations or domains of WM. Also, as mentioned above, because the relation between whole-number calculations and verbal WM or visuospatial WM may vary with age because of age-related differences in strategy-use, we also investigated whether the influence of age on the relation between WM and whole-number calculations is different for verbal WM and visuospatial WM.

Word-problem solving. Word-problem solving is a complex activity that requires not only mathematical abilities but also text comprehension abilities to understand the purpose and the structure of the problem (Cummins, Kintsch, Reusser, & Weimer, 1988; Nathan, Kintsch, & Young, 1992). For example, word-problem solving requires students to understand the problem narrative, focus on relevant and ignore irrelevant information, construct a number sentence, and solve for the missing number to find the answer. This multistep nature of word-problem solving along with the requirement to process both mathematical and linguistic information may draw upon significant WM resources. A number of studies have provided evidence for the strong relation between WM and word-problem solving (e.g., Passolunghi & Siegel, 2001; Swanson, Jerman, & Zheng, 2008; Swanson & Sachse-Lee, 2001). However, it is not clear from these studies whether the relation between word-problem solving and WM is influenced by domains of WM. Although various studies found that verbal WM, numerical WM, and visuospatial WM are all related to word-problem solving (e.g., Holmes & Adams, 2006; Logie, Gilhooly, & Wynn, 1994), other studies found no relation between visuospatial WM and word-problem solving (e.g., Rasmussen & Bisanz, 2005). In the present meta-analysis, we examined whether the relation between WM and word-problem solving is moderated by domains of WM.

Fractions. Fraction knowledge refers to the understanding of the part-whole relation, measurement interpretation of fractions, and mathematics problems that involve fractional quantities (Hecht, 1998; Hecht, Close, & Santisi, 2003). Because fraction tasks, such as the measurement interpretation of fractions and fraction calculations, require children to simultaneously consider the contribution of the interacting role of numerators and denominators when comparing fractions or placing them on a number line, WM is proposed to play a role. Not many studies have investigated the relation between WM and fractions, and mixed findings exist; that is, the correlation between WM and performance on fractions problems ranges from .03 to .47. (e.g., Fuchs, Geary, Fuchs, Compton, & Hamlett, 2014; Hecht et al., 2003; Hecht & Vagi, 2010). In the present meta-analysis, we investigated whether fraction performance (e.g., matching to visual representation, fraction calculations, and word-problem solving with fractions) is related to WM.

Geometry. Geometry involves problem solving and reasoning about shape, size, relative position of figures, and the properties of space. Because geometry tasks often involve simultaneous manipulation and storage of visuospatial materials, theoretically, geometry should be correlated with WM, especially with visuospatial WM. Very few studies have looked at the relation of geometry and WM. Those that exist have reported that the relation between WM and geometry is small (r = .11–.26; e.g., Giofrè, Mammarella, Ronconi, & Cornoldi, 2013), and not influenced by domains of WM (e.g., Giofrè, Mammarella, & Cornoldi, 2014; Passolunghi et al., 2008). Thus, in the present meta-analysis, we investigated whether geometry is correlated with WM and whether this relation is influenced by domains of WM.

Algebra. There are many definitions of algebra, and in this meta-analysis, we defined algebra as problems that can be solved by prelearned symbol manipulation algorithms that are taught in many algebra curricula (e.g., if $x + 2 = 3$, then $x - 5 = ?$; Tolar, Lederberg, & Fletcher, 2009). Theoretically, WM should relate to algebra. This is because algebra requires individuals to actively maintain multiple conceptions of mathematical expressions while solving algebraic problems and switch between them as appropriate. Not many studies have focused on the relation between WM and algebra. Among these studies, this relation is relatively weak (r = .07–.27; Lee, Ng, Bull, Pe, & Ho, 2011; Tolar et al., 2009). In this meta-analysis, we investigated whether there was a significant relation between algebra and WM.

Sample Type

Previous research shows that different populations, including those with mathematics difficulties, may have different WM profiles (e.g., Peng & Fuchs, 2014; Swanson & Jerman, 2006). For these groups, WM may interact with mathematics instruction (e.g., Fuchs, Schumacher, et al., 2014; Swanson, 2014). For example, Fuchs, Schumacher, et al. (2014) found that students with very weak WM learned fractions better with conceptual activities, but students with more adequate (but still low) WM learned fractions better with fluency activities. Swanson (2014) found that at-risk children with relatively higher WM were more likely to benefit from strategy training in a word-problem solving intervention, whereas children with lower WM may have had their already low cognitive resources overtaxed by strategy training. Thus, for mathematics instruction, it may be important to investigate whether the relation between WM and mathematics varies among different populations. In this study, we included sample type as another moderator and specifically focused on three groups: typically developing individuals, individuals with mathematics difficulties not associated with other learning disorders or cognitive deficits (MD), and individuals with MD that are associated with other disorders or cognitive deficits (MD + DCD; e.g., attention-deficit/ hyperactivity disorder [ADHD], intellectual disabilities, Turner syndrome, cerebral palsy, velo-cardio-facial syndromes, developmental coordination disorder, fetal alcohol syndrome).

Compared with typically developing children, individuals with MD + DCD and individuals with MD are more likely to have WM deficits (e.g., Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Rasmussen & Bisanz, 2011; van Rooijen et al., 2014). Moreover, some studies suggest that WM may play a compensatory role in mathematics performance among individuals who have MD, especially those who suffer from severe MD (e.g., Geary et al., 2007; Klein & Bisanz, 2000). That is, compared with typically developing individuals, individuals with severe MD lack effective strategies or the ability to directly retrieve facts from long-term memory to help accomplish mathematics tasks, and thus they would, instead, rely more on their high-level cognitive skills, such as WM, to help them solve mathematics problems. Based on these views, the relation between mathematics and WM should be stronger among individuals with MD and individuals with MD + DCD compared with that among typically developing individuals.

Research Questions

In summary, we examined three major questions: (a) whether there is a significant correlation between WM and mathematics; (b) whether the relation between WM and mathematics is affected by domains of WM, types of mathematics skills, and sample type; and (c) whether the relation between WM and different types of mathematics skills is affected by domains of WM and sample type. Because there are more studies of WM and whole-number calculations than for other types of mathematics skills, we were able to ask some additional questions about the relation of WM and whole-number calculations, namely, whether the relations of WM to single-digit and multidigit calculations are similar, and whether the relation of whole-number calculations and verbal WM or visuospatial WM is affected by age.

Method

Literature Search

Articles for this meta-analysis were identified in two ways. First, a computer search of the PsycINFO, ERIC, ProQuest, MEDLINE databases for literature was conducted. We used the earliest possible start date (1964) through August 2014. Titles, abstracts, and keywords were searched for the following terms:

working memory AND *math**, *arithmetic**, *calculation**, *num**, *fraction**, *geometr**, *algebr**, *word problem**, or *problem solving**. The terms *math**, *arithmetic**, *calculation**, *num**, *fraction**, *geometr**, *algebra**, or *word problem** allowed for inclusion of mathematics/mathematical skills, fraction/fractions, geometry/geometrical skills, algebra/algebraic skills, word problem/word problems, and so forth. Second, we hand searched citations in prior relevant reviews (Friso-van den Bos et al., 2013; LeFevre et al., 2005; Raghubar et al., 2010). We searched unpublished literature through Dissertation and Masters Abstract indexes in ProQuest, Cochrane Database of Systematic Reviews, relevant conference programs (e.g., Pacific Coast Research Conference, Conference of Society for Research on Educational Effectiveness, and Annual Conference of American Educational Research Association), and e-mailed researchers likely to have conducted work in this area. We also contacted several researchers to check the appropriateness of certain studies in terms of our selection criteria (e.g., we contacted authors to clarify the specific skills their mathematics tasks measure if this information was not clearly described in the study). The initial search yielded 1,070 studies. The first author and one doctoral student in psychology then reviewed all studies. After excluding the duplicate 49 articles, the remaining 1,021 articles were closely reviewed using the specific criteria described below.

First, studies had to include at least one quantitative task measuring WM and at least one quantitative task measuring mathematics. In order to be considered a WM task, the measure(s) in included studies had to tap processing and storage simultaneously (e.g., complex span tasks and dual-tasks WM). Measures that tap executive functions, such as inhibition, switching, or updating, were not considered to be WM measures in this meta-analysis, nor were simple span measures (storage without simultaneous processing) considered to tap WM. *Mathematics measures* refer to the tasks that tap one of the following skills: basic number knowledge, whole-number calculations, word-problem solving, fractions, geometry, and algebra. Specifically, tasks that tap one or more of the following mathematics skills were coded as basic number knowledge: knowledge of numerosity (i.e., cardinality), the relation between numbers (i.e., ordinality), counting words, Arabic digits (i.e., symbolic knowledge), and knowledge related to approximate number system (cognitive system that supports the estimation of the magnitude of a stimulus set without relying on language or symbols). Whole-number calculations were defined as single-digit/multidigit addition, subtraction, multiplication, and division. Word-problem solving was defined as problems in which significant background information on the problem is presented as text rather than in a mathematical notation. Fractions included tasks that tap understanding of the part-whole relation, measurement interpretation of fractions, or mathematics problems (calculations and word-problem solving) that involve fractional quantities. Geometry included tasks on shape, size, relative position of figures, and the properties of space. Algebra included problems that can be solved by prelearned symbol manipulation algorithms taught in many algebra curricula (e.g., if $x + 2 = 3$, then $x - 5 = ?$). Table 1 presents the description of codes and examples of response categories for domains of WM and types of mathematics skills.

Second, studies had to report at least one correlation (r) between any measure of WM and any measure of mathematics, or the percentage of variance (R^2) in mathematics accounted for by WM only. The measures of WM and mathematics used to calculate the direct correlation (not partial correlation) had to be taken at the same time point, because we were interested in the concurrent direct relation between WM and mathematics and how this relation was affected by the moderators proposed in this study. After a screening of the 1,021 articles based on the above-mentioned criteria, a total of 110 studies were included in the current meta-analysis.

Coding Procedure and Interrater Reliability

Studies were coded according to the characteristics of participants and tasks used to measure WM and mathematics. Not all studies provided sufficient information on the variables of interest for the present study. In case of insufficient information, authors were contacted to obtain the missing information. In addition to these variables, we also coded the number of participants (N) used to obtain each correlation. The latter was needed to weight each effect size, so that correlations obtained from larger samples were given more weight in the analysis than those obtained from smaller samples. The important features of individual studies are provided in the online supplemental material for the Appendix.

Variables were discussed until a consensus was reached between the first and second authors. Then, first author used this coding system to conduct the final coding of all studies. To assess interrater reliability, second author independently coded 20% of the studies. Across the total variable matrix, the mean interrater agreement was .97, with acceptable values for all codes as follows: .94 for age, 1.00 for sample type, .95 for domains of WM, and 1.00 for types of mathematics skills. Any disagreements between raters were resolved by consulting the original article or by discussion.

Analytic Strategies

The effect size index used for all outcome measures was Pearson's r, the correlation between WM and mathematics. We considered all eligible effect sizes in each study. That is, studies could contribute multiple effect sizes as long as the sample for each effect size was independent. For studies that reported multiple effect sizes from the same sample, we accounted for the statistical dependencies using the random effects robust standard error estimation technique developed by Hedges, Tipton, and Johnson (2010). This analysis allowed 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 calculating the between-study sampling variance estimate, τ^2. In all analyses, we estimated τ^2 with $\rho = .80$; sensitivity analyses showed that the findings were robust across different reasonable estimates of ρ.

Analyses were based on Borenstein, Hedges, Higgins, and Rothstein's (2005) recommendations. Specifically, we converted the correlation coefficients to Fisher's Z scale, and all

Table 1
Description of Codes and Examples of Response Categories for Domains of Working Memory (WM) and Types of Mathematics Skills

	Definition	Examples of response categories
Domains of WM		
Verbal WM	Tasks that tap simultaneous process and storage of verbal information	complex reading span; sentence span; listening recall; alphabet recoding; backward word recall; continuous paired associates task; story retelling; letter span; semantics association; rhyming span; animal dual task performance
Numerical WM	Tasks that tap simultaneous process and storage of numerical information	backward digit span; calculation span; counting span; auditory digit sequencing; composite of counting recall and backward digit recall
Visuospatial WM	Tasks that tap simultaneous process and storage of visual or spatial information	backward block span, visual matrix mapping and directions; odd-one-out; mr. x; spatial recall; jigsaw puzzle; dot matrix; visual pattern test
Composite WM	Tasks that tap simultaneous process and storage of information tapping more than one of the following domains: verbal, numerical, and visuospatial, Or composite score of WM tasks tapping more than one the following domains: verbal, numerical, and visuospatial	operation span, digit sentence span; composite of listening recall and backward digit recall and counting span; letter–number sequencing; stanford–binet fifth edition working memory (Roid, 2003); verbal–spatial complex span; animal–color span
Types of mathematics skills		
Basic number knowledge	Questions that tap numerosity (i.e., cardinality) as well as the relation between numbers (i.e., ordinality), counting words, and Arabic digits (i.e., symbolic knowledge)	counting; seriation; classification of numbers; number comparison; compare pairs of piles of objects; quantity estimation; number line; number identification/naming; early numeracy test; place value; transcoding from Arabic to verbal numerals
Whole-number calculations	Single-digit or multidigit addition, subtraction, multiplication, and division	addition (e.g., $2 + 1 =$; $20 + 60 =$;), subtraction (e.g., $6 - 4 =$; $20 - 15=$), division (e.g., $6/2 =$; $20/10 =$), multiplication (e.g., $2 \times 4 =$; $20 \times 12=$;); WJ3–Calculation (Woodcock, McGrew, & Mather, 2001); CBM-Calculation (Fuchs, Hamlett, & Fuchs, 1990); WRAT-4-Math (Wilkinson & Robertson, 2006); WIAT-Arithmetic (Psychological Corporation, 1992)
Fractions	Questions that tap the understanding of the part–whole relation, measurement interpretation of fractions, and mathematics problems that involve fractional quantities	fractions calculations (e.g., $\frac{1}{4} + \frac{1}{2}$); fractions comparisons (e.g., $\frac{1}{4}$ ___ $\frac{1}{2}$); NAEP-Fraction (U. S. Department of Education, 2013); symbol–picture correspondence; calculations and word-problem solving involving fractions; Fractional Estimate
Word-problem solving	Questions that involve the ability to understand the problem narrative, focus on relevant and ignore irrelevant information, construct a number sentence, and solve for the missing number to find the answer	WISC-Word Problem (Wechsler, 2003); arithmetic word problems (e.g., John had nine pennies. He spent three pennies at the store. How many pennies did he have left?); Key-Math Problem Solving (Connolly, 1988)
Geometry	Questions of shape, size, relative position of figures, and the properties of space	symmetrical comparison; intuitive geometry; MT Advanced Geometry (Cornoldi et al., 2010); properties of simple geometric figures; figure identification; notions of topology; concepts of shapes
Algebra	Problems that can be solved by prelearned symbol manipulation algorithms that are taught in many algebra curricula	algebra problem solving (e.g., if $x + 2=3$, then $x - 5=$); algebra judgement (e.g., $3y + 2 = 20$; $y = 2$)

Note. Stanford Stanford Working Memory = Stanford-Binet Intelligence Scale Fifth Edition - Working Memory; WJ3-Calculation = Woodcock–Johnson III-Calculation; CBM-Calculation = Curriculum-based Math Computation and Concepts/Applications; WRAT-4 Math = Wide Range Achievement Test (WRAT4)-Math Subtest; WIAT-Arithmetic = Wechsler individual achievement test-Arithmetic; NAEP-Fraction = National Assessment of Educational Progress - Fraction problems; WISC-Word Problem = Wechsler Intelligence Scale for Children - Arithmetic; MT Advanced Geometry = Advanced MT Test of Reading and Mathematics for 9th and 10th Grades - Geometry.

analyses were performed using the transformed values. The results, such as the summary effect and its confidence interval, were then converted back to correlation coefficients for presentation. Also, because we hypothesized that this body of research reports a distribution of correlation coefficients with significant between-studies variance, as opposed to a group of studies that attempts to estimate one true correlation, a random-effects model was appropriate for the current study (Lipsey & Wilson, 2001). Weighted, random-effects metaregression models using Hedges et al.'s (2010) corrections were run with ROBUMETA in Stata (Hedberg, 2011) to summarize correlation coefficients and to examine potential moderators. Specifically, we first estimated only the overall weighted mean correlation between WM and mathematics.

Then, subgroup analyses were used to examine the relation between WM and mathematics for each subcategory of each moderator. Metaregression analyses were used to examine whether domains of WM, types of mathematical skills, and sample type moderated the relation between WM and mathematics, and whether domains of WM and sample type moderate the relation between each type of mathematics skills and WM. For the moderation analysis, each moderator was examined with other moderators controlled in one metaregression model. For moderators that were dichotomous, we entered them directly into the metaregression model. For moderators with more than two categories, we created several sets of dummy coded variables to examine the comparisons among categories (Cohen, Cohen, West, & Aiken, 2013). Because we drew our sample cross the life span, we also controlled for age in all moderation analyses.

Moreover, publication bias (the problem of selective publication, in which the decision to publish a study is influenced by its results) was examined using the method of Egger, Smith, Schneider, and Minder (1997) and funnel plot. We did not find significant publication bias based on Egger et al.'s publication bias statistics (i.e., the standard errors of correlations did not significantly predict correlations among studies with ROBUMETA in Stata, $p = .34$), and funnel plot analyses showed reasonable symmetry in the reported correlations, suggesting that there was little influence of publication bias. Therefore, the original dataset was used in all reported analyses.

Results

The 110 studies included in the meta-analysis represent a total of 27,860 participants obtained from 132 independent samples and subsume 829 correlation coefficients that test the relation between WM and mathematics. Overall, the relation between WM and mathematics was medium ($r = .35$) and significant (95% confidence interval (CI) [.32, .37]; Cohen, 1988). Next, we examined the relation between WM and mathematics for each subcategory of each moderator, and whether domains of WM, types of mathematics skills, and sample type affected the relation between WM and mathematics.

The Moderation Effects of Domains of WM on Relation Between WM and Mathematics

We coded WM tasks as verbal WM (294 correlations), numerical WM (268 correlations), visuospatial WM (142 correlations), and composite WM (125 correlations; i.e., WM tasks involving two domains, or WM scores derived from WM tasks tapping at least two different domains). As Table 2 shows, the average correlation between WM and mathematics for each of the four types was significant: verbal WM ($r = .30$, 95% CI [.27, .33]), numerical WM ($r = .34$, 95% CI [.30, .37]), visuospatial WM ($r = .31$, 95% CI [.26, .35]), and composite WM ($r = .38$, 95% CI [.34, .40]). As Table 3 shows, after controlling for age, type of mathematics skills, and sample type, verbal WM, numerical WM, visuospatial WM, and composite WM all

Table 2
Relation Between Working Memory (WM) and Mathematics

Variables	No. of correlations	Correlation	Correlation 95% CI	Between-study sampling variance (τ^2)
Main average correlation	829	.35***	[.32, .37]	.03
Domains of WM				
1. Verbal WM	294	.30***	[.27, .33]	.01
2. Numerical WM	268	.34***	[.30, .37]	.04
3. Visuospatial WM	142	.31***	[.26, .35]	.01
4. Composite WM	125	.38***	[.34, .40]	.02
Types of mathematics skills				
1. Basic number knowledge	267	.31***	[.27, .35]	.02
2. Whole-number calculations	326	.35***	[.32, .39]	.05
2a. Single-digit calculations	85	.33***	[.28, .38]	.01
2b. Multidigit calculations	55	.27***	[.21, .33]	.003
3. Fractions	26	.30***	[.12, .46]	.03
4. Word-problem solving	143	.37***	[.34, .41]	.01
5. Geometry	40	.23***	[.17, .27]	.00
6. Algebra	27	.27*	[.09, .44]	.02
Sample type				
1. TD	589	.34***	[.30, .36]	.03
2. MD	50	.25**	[.08, .41]	.04
3. MD + DCD	29	.52***	[.39, .64]	.03

Note. Verbal WM = WM task that involves simultaneous verbal information storage and processing; Numerical WM = WM task that involves simultaneous numerical information storage and processing; Visuospatial WM = WM task that involves simultaneous visual or spatial information storage and processing; Composite WM = WM task that involves simultaneous storage and processing of information across at least two domains of verbal, numerical, and visuospatial domains, or composite scores derived from WM tasks tapping at least two domains of verbal, numerical, and visuospatial domains; TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits; CI = confidence interval.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3
Metaregression of the Moderation Analysis on the Relation Between Working Memory (WM) and Mathematics

Variables	Beta	*SE*	*t*	95% CI	*p*	Subgroup comparisons
Age	.001	.003	.44	[−.004, .008]	.66	
Domains of WM						
Verbal vs. numerical	.03	.03	.94	[−.03, .10]	.35	Composite = verbal = numerical = visuospatial
Verbal vs. visuospatial	.02	.03	.74	[−.03, .08]	.46	
Verbal vs. composite	.08	.04	2.00	[−.001, .17]	.05	
Numerical vs. visuospatial	−.01	.03	−.31	[−.07, .05]	.76	
Numerical vs. composite	.05	.04	1.23	[−.03, .14]	.22	
Visuospatial vs. composite	.06	.04	1.48	[−.02, −.15]	.14	
Types of mathematics skills						
Basic number knowledge vs. whole-number calculations	.02	.03	.56	[−.04, .08]	.58	Word-problem-solving > geometry whole-number calculations > geometry
Basic number knowledge vs. fractions	−.07	.07	−1.05	[−.21, .06]	.30	
Basic number knowledge vs. word-problem solving	.03	.05	.56	[−.07, .12]	.58	
Basic number knowledge vs. geometry	−.09	.05	−1.82	[−.18, −.01]	.07	
Basic number knowledge vs. algebra	−.08	.07	−1.22	[−.22, .05]	.23	
Whole-number calculations vs. fractions	−.09	.07	−1.31	[−.23, .05]	.19	
Whole-number calculations vs. word-problem solving	.01	.04	.21	[−.08, .10]	.83	
Whole-number calculations vs. geometry	−.10	.05	−2.34**	[−.19, −.02]	.02	
Whole-number calculations vs. algebra	−.10	.06	−1.57	[−.23, .03]	.12	
Fractions vs. word-problem solving	.10	.08	1.31	[−.05, .25]	.19	
Fractions vs. geometry	−.01	.08	−.17	[−.17, .14]	.87	
Fractions vs. algebra	−.01	.09	−.11	[−.19, .17]	.91	
Word-problem solving vs. geometry	−.11	.05	−2.13*	[−.22, −.01]	.04	
Word-problem solving vs. algebra	−.11	.07	−1.66	[−.24, .02]	.10	
Geometry vs. algebra	.003	.07	.04	[−.13, .14]	.97	
Sample type						
TD vs. MD	−.05	.08	−.65	[−.21, .11]	.52	MD + DCD > TD, MD
TD vs. MD + DCD	.19	.07	2.51*	[.04, .33]	.01	
MD vs. MD + DCD	.24	.11	2.21*	[.02, .45]	.03	

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than 2 categories. For the convenience of presentation, subgroup comparisons within domains of WM, types of mathematics skills, and sample type are all listed in the model. The first group in each group comparison variable is the reference group (e.g., in TD vs. MD, TD is the reference group in the dummy coding of sample type). Between-study sampling variance (τ^2) for this model is .02.Verbal WM = WM task that involves simultaneous verbal information storage and processing; Numerical WM = WM task that involves simultaneous numerical information storage and processing; Visuospatial WM = WM task that involves simultaneous visual or spatial information storage and processing; Composite WM = WM task that involves simultaneous storage and processing of information across at least two domains of verbal, numerical, and visuospatial domains, or composite scores derived from WM tasks tapping at least two domains of verbal, numerical, and visuospatial domains; CI = confidence interval; TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits.
* $p < .05$. ** $p < .01$.

correlate with mathematics skills to a similar degree ($\beta = -.01, -.08$, $t = -.31, -1.48$, ps $\geq .05$, $\tau^2 = .02$). In other words, there were no significant differences among verbal WM, numerical WM, and visuospatial WM regarding their relations with mathematics.

The Moderation Effects of Types of Mathematics Skills on Relation Between WM and Mathematics

The six categories of mathematics skills yielded the following data: basic number knowledge (267 correlations), whole-number calculations (326 correlations), fractions (26 correlations), word-problem solving (143 correlations), geometry (40 correlations), and algebra (27 correlations). As Table 2 shows, the average correlations between WM and mathematics for each of the six mathematics skills were significant: basic number knowledge ($r = .31$, 95% CI [.27, .35]), whole-number calculations ($r = .35$, 95% CI [.32, .39]), fractions ($r = .30$, 95% CI [.12, .46]), word-problem solving ($r = .37$, 95% CI [.34, .41]), geometry ($r = .23$, 95% CI [.17, .27]), and algebra ($r = .27$, 95% CI [.09, .44]). As Table 3 shows, after controlling for age, domains of WM, and sample type, geometry showed a significantly weaker relation with WM compared whole-number calculations and word-problem solving ($\beta = -.11, -.10$, $t = -2.13, -2.34$, ps $< .05$, $\tau^2 = .02$). In summary, the type of mathematics skills significantly affected the relation between WM and mathematics such that word-problem solving and whole-number calculations had the strongest relations with WM, whereas geometry showed the weakest relation with WM.

The Moderation Effects of Sample Type on Relation Between WM and Mathematics

We coded three sample types in the present study: typically developing individuals, individuals with MD, and individuals with MD + DCD (e.g., ADHD, intellectual disabilities, Turner syndrome, cerebral palsy, velo-cardio-facial syndromes, developmental coordination disorder, fetal alcohol syndrome). For this analysis, we did not include studies with a combined sample type (e.g., a combined sample of typically developing individuals and individuals with MD) that did not disaggregate results for the groups of interest. As Table 2 shows, the average correlations between WM and mathematics for each of the sample types were significant: typically developing (r = .34, 95% CI [.30, .36]; 589 correlations), MD (r = .25, 95% CI [.08, .41]; 50 correlations), MD + DCD (r = .52, 95% CI [.39, .64]; 29 correlations). As Table 3 shows, after controlling for age, domains of WM, and type of mathematics skills, sample type significantly affected the relation between WM and mathematics such that the relation is stronger among individuals with MD + DCD than among the typically developing and MD groups (β = .19, .24, t = 2.21, 2.51; ps < .05, τ^2 = .02).

The Moderation Effects of Domains of WM and Sample Type on Relation Between WM and Different Types of Mathematics Skills

Next, we examined whether the relations between WM and different types of mathematics skills were moderated by domains of WM or sample type. Also, for whole-number calculations, we examined whether there is a difference between single-digit and multidigit calculations regarding their relations with WM, and whether age interacts with the relations between whole-number calculations and verbal WM or visuospatial WM.

Given that we did not acquire a sufficient number of effect sizes examining the relation between WM and fractions and between WM and algebra (the number of effect sizes is less than 30, as shown in Table 4), we did not run the moderation analysis for these two mathematics skills. Tables 5, 6 and 7 show the results of these moderation analyses. Specifically, for the relation between basic number knowledge and WM, composite WM showed a significantly stronger relation with basic number knowledge than WM in other domains (β = .14, .22, t = 2.40, 3.61; ps < .05, τ^2 = .02). For the relation between WM and whole-number calculations, age did not interact with verbal WM or visuospatial WM (β = .24, t = .29, p = .42, τ^2 = .02). Single-digit calculations and multidigit calculations showed comparable relations with WM (β = −.02, t = −.39, p = .70, τ^2 = .02). However, age affected the relation between WM and whole-number calculations such that the relation was significantly stronger in younger than older individuals (β = −.01, t = −2.98; p = .01, τ^2 = .02). For the relation between WM and geometry, age also affected the relation such that the relation was stronger in younger than older individuals (β = −.01, t = −2.93; p = .04, τ^2 = .02). Sample type moderated the relation between WM and whole-number calculations such that the relation was stronger among the MD + DCD sample than the typically developing and MD groups (β = .19, .23, t = 1.95, 2.81; ps ≥ .05, τ^2 = .02).

Discussion

The present meta-analysis investigated the relation between WM and mathematics skills, to address questions related to whether domains of WM, types of mathematics skills, or sample type influences these relations. We found that the relation between WM and mathematics was medium (r = .35), and that this relation was significantly influenced by types of mathematics skills and sample type, but not by domains of WM, with one exception discussed below. Specifically, in terms of the type of mathematics skills, all types of mathematics skills showed significant relations with WM; however, word-problem solving and whole-number calculations had the strongest relations with WM (rs = .37 and .35), whereas WM and geometry were significantly more weakly related (r = .23). With respect to sample type, the relation between WM and mathematics was stronger among individuals with MD + DCD than it was for typically developing individuals or individuals with MD. With respect to domains of WM, verbal WM, numerical WM, and visuospatial WM and composite WM all showed comparable relations with mathematics with one exception: composite WM was significantly more strongly related to basic number knowledge than were other domains of WM.

Domains of WM

Whether different domains of WM influence the relation between WM and mathematics is relevant to the debate on the

Table 4
The Number of Effects Sizes on the Relation Between Working Memory (WM) and Different Types of Mathematics Skills Across Moderators

Variables	Basic number knowledge	Whole-number calculations	Fractions	Word-problem solving	Geometry	Algebra
Domains of WM						
Verbal WM	137	92	5	35	16	9
Numerical WM	78	102	20	53	7	8
Visuospatial WM	45	57	0	16	17	7
Composite WM	7	75	1	39	0	3
Sample type						
TD	164	241	6	111	40	27
MD	25	19	8	0	0	0
MD + CDC	3	19	0	7	0	0
Age (years)[a]	4.79–49.50	5.00–50.00	5.46–10.50	3.00–51.49	5.50–17.84	7.83–19.50

Note. TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits.
[a] Shows the range of age on the relation between WM and different types of mathematics skills.

Table 5
Metaregression of the Moderation Analysis on the Relation Between Working Memory (WM) and Basic Number Knowledge and Word-Problem Solving

Variables	Basic number knowledge					Word-problem solving[a]				
	Beta	*SE*	*t*	95% CI	*p*	Beta	*SE*	*t*	95% CI	*p*
Age	−.002	.004	−.63	[−.01, .01]	.54	.002	.01	.43	[−.01, .01]	.67
Domains of WM										
Verbal vs. numerical	−.02	.05	−.64	[−.12, .06]	.52	−.02	.06	−.26	[−.15, .11]	.79
Verbal vs. visuospatial	−.08	.05	−1.69	[−.18, .02]	.10	.02	.05	.39	[−.08, .12]	.70
Verbal vs. composite	.14	.06	2.40*	[.02, .26]	.02	.03	.10	.29	[−.17, .23]	.77
Numerical vs. visuospatial	−.05	.05	−1.02	[−.16, .12]	.53	.04	.04	.88	[−.05, .12]	.39
Numerical vs. composite	.17	.06	2.76*	[.04, .29]	.01	.05	.09	.52	[−.13, .22]	.61
Visuospatial vs. composite	.22	.06	3.61**	[.10, .35]	<.01	.01	.09	.11	[−.17, .19]	.92
Sample type										
TD vs. MD	−.03	.09	−.30	[−.21, .16]	.77	—	—	—	—	—
TD vs. MD + DCD	.22	.14	1.52	[−.08, .51]	.14	.02	.13	.12	[−.29, .26]	.90
MD vs. MD + DCD	.24	.17	1.47	[−.10, .58]	.15	—	—	—	—	—

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within domains of WM, types of mathematics skills, and sample type are all listed in the model. The first group in each group comparison variable is the reference group (e.g., in TD vs. MD, TD is the reference group in the dummy coding of sample type). Between-study sampling variance (τ^2) is .02 for models on both basic number knowledge and word-problem solving. Verbal WM = WM task that involves simultaneous verbal information storage and processing; Numerical WM = WM task that involves simultaneous numerical information storage and processing; Visuospatial WM = WM task that involves simultaneous visual or spatial information storage and processing; Composite WM = WM task that involves simultaneous storage and processing of information across at least two domains of verbal, numerical, and visuospatial domains, or composite scores derived from WM tasks tapping at least two domains of verbal, numerical, and visuospatial domains; CI = confidence interval; TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits. Dashes indicate data was not obtained.
[a] For the model of word-problem solving, there are no effect sizes for MD group.
* $p < .05$. ** $p < .01$.

domain-specificity of WM. Based on some WM models (e.g., Baddeley, 1986), WM is a domain-general construct, and so the relation of WM and other cognitive or academic skills such as mathematics should not be influenced by whether WM is measured using verbal, visuospatial or numerical materials. In contrast, according to domain-specific models of WM (e.g., Ericsson & Kintsch, 1995), WM is not a general capacity or domain general mechanism that supports different learning activities to a similar degree. In this view, the specific domain of WM (i.e., verbal, numerical, and visuospatial) is important for supporting performance on cognitive and academic tasks because WM is seen as the workspace for integrating domain-specific skills, knowledge, and procedures to meet the particular demands of learning tasks within a particular domain such as reading comprehension or mathematics. Thus, according to the domain-specific view, it might be expected that verbal WM and numerical WM would have a stronger relation to word-problem-solving, numerical WM to numerical-related mathematics skills (e.g., calculation) and visuospatial WM to visual-related mathematics skills (e.g., geometry).

We found that the relation between mathematics and WM was not affected by domains of WM after controlling for age, sample type, and types of mathematics skills. Nor were different domains of WM differentially related to particular mathematics skills; for example, verbal WM was not more related to word-problem solving than it was to other types of mathematics skills. The only exception to these findings is that composite WM measures tapping multiple domains had stronger relations with basic number knowledge than WM tapping only one domain. Taken together, these findings suggest that it is the domain-general central executive aspect of WM that drives the relation of WM and mathematics performance rather than domain-specific components of WM. Our findings also suggest that compared with WM tapping only one domain, composite WM measures may be more reliable measures of WM and may better tap the core construct of WM—the central executive. For example, according to domain-general models of WM, a composite WM measure would be expected to strongly tap central executive processes because the measures that form the composite have central executive components in common despite their differences in short-term storage components.

Types of Mathematics Skills

Because different mathematics skills may have different degrees of cognitive load, it is hypothesized that different types of mathematics skills may draw on WM resources to different degrees. In this meta-analysis, we investigated this hypothesis by examining the relations between WM and six mathematics skills based on Common Core State Standards: basic number knowledge, whole-number calculations, fractions, word-problem solving, geometry, and algebra. We found significant correlations of WM with all six mathematics skills, but the strength of the relation between WM and different mathematics skills was not invariant.

With respect to the relation between basic number knowledge and WM, our findings are consistent with previous studies, suggesting that although basic number knowledge tasks are not procedurally complicated, they are significantly correlated with WM (e.g., Morsanyi et al., 2013; Nunes et al., 2007). This finding, to some extent, supports the view that tasks that assess basic number knowledge draw on WM. For example, phonological coding in counting, visuospatial coding for mental number line activities,

Table 6
Metaregression of the Moderation Analysis on the Relation Between Working Memory (WM) and Whole-Number Calculations

	Whole-number calculations				
Variables	Beta	*SE*	*t*	95%CI	*p*
Age	−.01	.003	−2.98*	[−.02, −.003]	.01
Single-digit vs multidigit	−.02	.06	−.39	[−.15, .11]	.70
Domains of WM					
Verbal vs. numerical	−.03	.04	−.75	[−.11, .06]	.46
Verbal vs. visuospatial	.08	.07	1.17	[−.07, .23]	.26
Verbal vs. composite	−.01	.07	−.12	[−.15, .13]	.12
Numerical vs. visuospatial	.11	.08	1.49	[−.05, .28]	.16
Numerical vs. composite	.02	.07	.31	[−.14, .18]	.76
Visuospatial vs. composite	−.09	.08	−1.07	[−.27, .09]	.30
Age × Verbal vs. numerical	.01	.01	1.29	[−.01, .02]	.22
Age × Verbal vs. visuospatial	.24	.29	.83	[−.39, .87]	.42
Age × Verbal vs. composite	−.01	.01	−.61	[−.03, .01]	.56
Sample type					
TD vs. MD	−.04	.10	−.40	[−.24, .16]	.69
TD vs. MD + DCD	.19	.05	2.81*	[.05, .33]	.01
MD vs. MD + DCD	.23	.12	1.97	[−.003, .46]	.05

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within domains of WM, types of mathematics skills, and sample type are all listed in the model. The first group in each group comparison variable is the reference group (e.g., in TD vs. MD, TD is the reference group in the dummy coding of sample type). Between-study sampling variance (τ^2) is .02. Verbal WM = WM task that involves simultaneous verbal information storage and processing; Numerical WM = WM task that involves simultaneous numerical information storage and processing; Visuospatial WM = WM task that involves simultaneous visual or spatial information storage and processing; Composite WM = WM task that involves simultaneous storage and processing of information across at least two domains of verbal, numerical, and visuospatial domains, or composite scores derived from WM tasks tapping at least two domains of verbal, numerical, and visuospatial domains; CI = confidence interval; TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits; Age × Verbal vs. Numerical = the interaction term that indicates whether age affects the relation between WM and whole-number calculation differently between verbal WM and numerical WM; Age × Verbal vs. Visuospatial = the interaction term that indicates whether age affects the relation between WM and whole-number calculation differently between verbal WM and visuospatial WM; Age × Verbal vs. Composite = the interaction term that indicates whether age affects the relation between WM and whole-number calculation differently between verbal WM and composite WM.
* $p < .05$.

and facts retrieval from long-term memory in number naming and comparison tasks are thought to require coordination by the central executive of WM (e.g., Geary et al., 2008; Mazzocco et al., 2011).

Regarding whole-number calculations, previous studies have suggested that compared with single-digit calculations, multidigit calculations, which involve maintenance of intermediate sums and management of regrouping demands, may show a stronger relation with WM (e.g., DeStefano & LeFevre, 2004). However, we found that WM showed comparable strength of association with both single-digit and multidigit calculations. One possible explanation for these findings has to do with the fact that the single digit calculation studies in this meta-analysis typically involved younger children whereas the multidigit calculation studies were typically conducted with older children. It may be the case that young children in these studies were not fluent in single-digit calculations, and the older children were not fluent in multidigit calculation. Raghubar et al. (2010) suggested that WM resources may be recruited more often when new mathematics skills are being acquired regardless of age, and that age may simply be a proxy for familiarity or experience with certain mathematical concepts and procedures. For example, young children are more likely to solve single digit arithmetic problems using counting and decomposition strategies that likely require more WM resources than direct fact retrieval. Our findings are consistent with this hypothesis.

Contrary to what was predicted, we did not find an interaction between age and verbal or visuospatial WM for the relation between WM and whole-number calculations. Based on their findings from a dual task study, McKenzie et al. (2003) suggested that younger children use a combination of verbal and visual strategies to solve calculation problems whereas older children rely more on verbal strategies. The McKenzie et al. study employed a dual task paradigm in which the operation of the phonological loop and the visuospatial sketchpad (i.e., short-term storage components of WM models; Baddeley, 1986), were disrupted by secondary tasks. The current meta-analysis included only complex WM measures (storage plus concurrent processing), which may account for a failure to replicate age effects for the relation of mathematics and the phonological loop and the visuospatial sketchpad.

Geometry showed the weakest relation with WM and we did not find that domains of WM affected the relation between geometry and WM. This result is consistent with some previous studies showing that the relation between visuospatial WM and geometry is small (e.g., Giofrè et al., 2013) and the relation between WM and geometry

Table 7
Metaregression of the Moderation Analysis on the Relation Between Working Memory (WM) and Geometry

Variables	Geometry[a]				
	Beta	*SE*	*t*	95% CI	*p*
Age	−.01	.004	−2.93*	[−.02, .001]	.04
Domains of WM					
Verbal vs. numerical	−.10	.04	−2.40	[−.20, .01]	.07
Verbal vs. visuospatial	.04	.04	.89	[−.08, .15]	.42
Verbal vs. composite	—	—	—	—	—
Numerical vs. visuospatial	.13	.05	2.65	[−.01, .27]	.06
Numerical vs. composite	—	—	—	—	—
Visuospatial vs. composite	—	—	—	—	—
Sample type					
TD vs. MD	—	—	—	—	—
TD vs. MD + DCD	—	—	—	—	—
MD vs. MD + DCD	—	—	—	—	—

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within domains of WM, types of mathematics skills, and sample type are all listed in the model. The first group in each group comparison variable is the reference group (e.g., in TD vs. MD, TD is the reference group in the dummy coding of sample type). Between-study sampling variance (τ^2) is 0 for the model of geometry and .01 for the model of comprehensive mathematics skills. Verbal WM = WM task that involves simultaneous verbal information storage and processing; Numerical WM = WM task that involves simultaneous numerical information storage and processing; Visuospatial WM = WM task that involves simultaneous visual or spatial information storage and processing; Composite WM = WM task that involves simultaneous storage and processing of information across at least two domains of verbal, numerical, and visuospatial domains, or composite scores derived from WM tasks tapping at least two domains of verbal, numerical, and visuospatial domains; CI = confidence interval; TD = typically developing individuals; MD = individuals with mathematics difficulties; MD + DCD = individuals with mathematics difficulties that are associated with other disorders or cognitive deficits. Dashes indicate data was not obtained.
[a] For the model of geometry, there are no effect sizes for composite WM, MD, or MD + DCD.
* $p < .05$.

is not influenced by domains of WM (e.g., Giofre et al., 2014). That being said, the geometry tasks coded in this meta-analysis were mostly processing of simple two-dimensional objects (e.g., concepts of shapes and lines, Giofrè et al., 2013; Passolunghi et al., 2008; Giofrè et al., 2014). Future studies should explore the relation between WM and geometry tasks that involve more complex geometrical concepts (e.g., operating on and comparing two-dimensional shapes, processing three-dimensional objects).

Regarding word-problem solving, some research has shown that verbal WM, numerical WM, and visuospatial WM are all related to word-problem solving (Holmes & Adams, 2006) whereas other studies have found no relation between visuospatial WM and word-problem solving (Rasmussen & Bisanz, 2005). In this meta-analysis there was a significant relation between WM and word-problem solving and domains of WM did not moderate this relation. These findings are important because they suggest that word-problem solving, while requiring general and mathematics-specific language comprehension processes (Fuchs, Fuchs, Compton, Hamlett, & Wang, 2015), draws on domain-general WM resources that are not specifically language-based. These findings may indicate the important role of the central executive of WM in word-problem solving for directing attention to relevant information in word-problem solving, suppressing irrelevant information in word problems, and for the coordination of multiple cognitive processes simultaneously (e.g., number facts retrieval from long-term memory, calculations, text comprehension). In future research it would be of interest to determine whether WM resources are more strongly implicated in word problems that contain irrelevant information, that have more steps and/or missing values, in which critical mathematical information is presented out of order in the context of the word problem, and so forth. Findings from such studies might be of particularly relevant for aspects of instruction in word-problem solving.

Relatively few studies were found that focused on the relation between WM and algebra/fractions. Across the primary studies these relations are reported as being somewhat variable (r = .07–.30; Hecht et al., 2003; Hecht & Vagi, 2010; Lee et al., 2011; Tolar et al., 2009). The meta-analysis found the strength of the relation of WM to algebra and fractions to be small to medium, and significant (r = .27–.30). We did not run the moderation analyses on the relation between WM and those two mathematics skills because of the paucity of effect sizes in the literature. Thus, more studies are needed to investigate the relation between different domains of WM, sample type and algebra and fractions.

Sample Type

We focused on three types of populations in this study: typically developing individuals, individuals with MD, and individuals with MD + DCD. We found that the relation between WM and mathematics was stronger among individuals with MD + DCD than that among typically developing individuals or individuals with MD. One possible explanation for this finding is that individuals with MD + DCD often had comorbid neuro-cognitive disabilities/

genetic disorders and MD, which may lead to more severe MD as well as more impairment in domain-general cognitive resources such as WM than the individuals with MD. Individuals with severe MD may lack effective strategies or the ability to directly retrieve facts from long-term memory to help accomplish mathematics tasks, and thus they would, instead, rely more on their high-level cognitive skills, such as WM, to help them solve the problems (e.g., Geary et al., 2007; Klein & Bisanz, 2000). If this were the case, similar higher correlations of WM and mathematics should also be found in individuals with more severe MD compared with those with less severe MD regardless of the presence of other comorbid disorders. Additional studies would be needed to systematically examine this hypothesis by comparing mathematics performance between individuals with MD + DCD and individuals with MD who differ in the severity of their mathematics difficulties regardless of the presence of comorbid academic or neurodevelopmental disorders.

Because we drew our sample across the life span, we controlled for age in all moderation analyses. It is surprising that we found that the relation between WM and whole-number calculations and the relation between WM and geometry were stronger in younger individuals. We think this age effect on the relation between WM and a specific mathematics performance may be an artifact of the higher order reasoning requirements of the mathematics task itself, which is likely to vary with age and experience. Specifically, in a recent consideration of dual process theories in reasoning and decision-making, Evans and Stanovich (2013) distinguish between rapid autonomous processing that produces "default" responses and higher order reasoning processes that require WM resources. For young children, very little about mathematical symbols and operations are likely to be automated and therefore, mathematical performance on even simple arithmetic tasks may require WM resources. For older children, WM may be engaged less for those mathematical tasks in which mathematical routines are easily accessible and stored in long-term memory (e.g., arithmetic). Compared with basic number knowledge, young children may not have much experience with whole-number calculations and geometry and performance on these tasks may involve more WM resources. To sum up, our findings on the effect of types of mathematics skills, together with Evans and Stanovich (2013)'s findings, may suggest that not age but types of mathematics skills affect the relation between WM and mathematics. That being said, research is needed to further examine the interaction between WM and mathematics learning experiences on the WM involvement in different types of mathematics skills among populations with different ages.

Limitations and Implications

Our conclusions came from the combined results of 110 studies conducted with more than 27,000 individuals. Despite the scale of our literature search and the final sample size for our study, we note the following limitations. First, we only found a small number of studies reporting the relation between WM and algebra/fractions, and we did not run moderation analyses on these relations because of insufficient power. Second, although we searched for unpublished studies (e.g., dissertation and conference articles), most studies that met the inclusion criteria for the purpose of this present study were peer-reviewed journal articles. Thus, even though our funnel plot and publication bias test did not indicate publication bias, we cannot completely rule out publication bias as we may have missed studies that reported nonsignificant correlations between WM and different types of mathematics skills. Third, we did not index study quality mainly because of limited information provided in each study. For example, few studies provided reliability coefficients for their WM measures or mathematics measures, which could affect the results.

With these limitations in mind, like other narrative reviews and a previous meta-analysis, the present meta-analysis confirms the significant moderate relation of WM and mathematics. The unique contributions of the current meta-analysis are that (a) WM is a domain-general construct for mathematics performance, such that domains of WM did not affect the relation between WM and mathematics performance; (b) different types of mathematics performance involve WM to different degrees, such that word-problem solving and whole-number calculations involve more WM than geometry; and (c) the relation between mathematics and WM is stronger among individuals with mathematics difficulties accompanied by other learning, behavioral, or neurodevelopmental disorders.

Although the findings from this meta-analysis concern correlational data, they may have implications for thinking about intervention design and for whom different types of interventions might be most appropriate. Two recent studies have reported aptitude-by-treatment interactions involving WM and mathematics. Fuchs, Schumacher, et al. (2014) found that students with very weak WM learned fractions better with conceptual activities, but students with more adequate (but still low) WM learned fractions better with fluency activities. Swanson (2014) found that at-risk children with relatively higher WM were more likely to benefit from strategy training in a word-problem-solving intervention, whereas children with lower WM may have had their already low cognitive resources overtaxed by strategy training. These findings, together with those from the meta-analysis showing stronger relations of WM and mathematics for some individuals, suggest that there may be a need to consider WM status when designing mathematics interventions for individuals with mathematics difficulties, though clearly, more research is needed to investigate aptitude-by-treatment interactions for different types of mathematics and WM.

Our findings may also have implications for WM training research. Specifically, we found that although domains of WM did not affect the relation between WM and mathematics, WM tasks tapping multiple domains seemed to show stronger relations with mathematics than WM tasks tapping one domain. Potential implications for WM training research relate to the breadth of WM training (i.e., training that involves multiple domains) and to the measurement of WM outcomes (i.e., outcome measures that tap multiple domains). It is worth keeping in mind, however, that when one translates the correlations from the current meta-analysis into variances that WM can account for in mathematics performance, the range is 5% to 25%, with an average around 10%. These findings suggest that training WM alone is unlikely to be sufficient for improving mathematics performance (Jacob & Parkinson, 2015). The findings of the current meta-analysis may be relevant for informing the design of intervention studies that test combined WM and mathematics instructions. For example, based on the robust correlations between WM and word-problem solving and whole-number calculations, these two areas of mathematics may be particularly good candidates for such combined interventions. Moreover, the finding of a stronger relation of WM and mathematics for some individuals, suggests that it may be important to consider some of the person-related factors (e.g., severity of mathematics and/or WM difficulties, presence of other disorders) that might moderate the outcomes of these intervention performance.

References

References marked with an asterisk indicate studies included in the meta-analysis.

*Alloway, T. P., Gathercole, S. E., Adams, A-M., Willis, C., Eaglen, R., & Lamont, E. (2005). Working memory and phonological awareness as predictors of progress towards early learning goals at school entry. *British Journal of Developmental Psychology, 23,* 417–426. http://dx.doi.org/10.1348/026151005X26804

*Alloway, T. P., & Passolunghi, M. C. (2011). The relation between working memory, IQ, and mathematical skills in children. *Learning and Individual Differences, 21,* 133–137. http://dx.doi.org/10.1016/j.lindif.2010.09.013

*Andersson, U. (2007). The contribution of working memory to children's mathematical word problem solving. *Applied Cognitive Psychology, 21,* 1201–1216. http://dx.doi.org/10.1002/acp.1317

*Andersson, U. (2008). Working memory as a predictor of written arithmetical skills in children: The importance of central executive functions. *British Journal of Educational Psychology, 78,* 181–203. http://dx.doi.org/10.1348/000709907X209854

*Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal of Experimental Child Psychology, 96,* 197–228. http://dx.doi.org/10.1016/j.jecp.2006.10.001

*Andersson, U., & Ostergren, R. (2012). Number magnitude processing and basic cognitive functions in children with mathematical learning disabilities. *Learning and Individual Differences, 22,* 701–714. http://dx.doi.org/10.1016/j.lindif.2012.05.004

Baddeley, A. D. (1986). *Working memory*. New York, NY: Oxford University Press.

*Bailey, D. H., Littlefield, A., & Geary, D. C. (2012). The codevelopment of skill at and preference for use of retrieval-based processes for solving addition problems: Individual and sex differences from first to sixth grades. *Journal of Experimental Child Psychology, 113,* 78–92. http://dx.doi.org/10.1016/j.jecp.2012.04.014

Barnes, M. A., Raghubar, K. P., English, L., Williams, J. M., Taylor, H., & Landry, S. (2014). Longitudinal mediators of achievement in mathematics and reading in typical and atypical development. *Journal of Experimental Child Psychology, 119,* 1–16. http://dx.doi.org/10.1016/j.jecp.2013.09.006

*Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology, 91,* 183–204. http://dx.doi.org/10.1016/j.jecp.2005.03.002

*Berg, D. H. (2008). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology, 99,* 288–308. http://dx.doi.org/10.1016/j.jecp.2007.12.002

Borenstein, M., Hedges, L., Higgins, J., & Rothstein, H. (2005). *Comprehensive Meta-Analysis (Version 2)* [Computer software]. Englewood, NJ: Biostat.

*Buelow, M. T., & Frakey, L. L. (2013). Math anxiety differentially affects WAIS–IV arithmetic performance in undergraduates. *Archives of Clinical Neuropsychology, 28,* 356–362. http://dx.doi.org/10.1093/arclin/act006

*Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology, 19,* 273–293. http://dx.doi.org/10.1207/S15326942DN1903_3

*Burchinal, M., Vernon-Feagans, L., Vitiello, V., & Greenberg, M. (2014). Thresholds in the association between child care quality and child outcomes in rural preschool children. *Early Childhood Research Quarterly, 29,* 41–51. http://dx.doi.org/10.1016/j.ecresq.2013.09.004

*Campos, I. S., Almeida, L. S., Ferreira, A. I., Martinez, L. F., & Ramalho, G. (2013). Cognitive processes and math performance: A study with children at third grade of basic education. *European Journal of Psychology of Education, 28,* 421–436. http://dx.doi.org/10.1007/s10212-012-0121-x

Case, R., Okamoto, Y., Griffin, S., McKeough, A., Bleiker, C., Henderson, B., . . . Keating, D. P. (1996). The role of central conceptual structures in the development of children's thought. *Monographs of the Society for Research in Child Development, 61,* 1–295. http://dx.doi.org/10.2307/1166077

*Chan, B. M. Y., & Ho, C. S. H. (2010). The cognitive profile of Chinese children with mathematics difficulties. *Journal of Experimental Child Psychology, 107,* 260–279. http://dx.doi.org/10.1016/j.jecp.2010.04.016

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). *Applied multiple regression/correlation analysis for the behavioral sciences*. New York, NY: Routledge.

Common Core State Standards Initiative. (2010). *Common core state standards for mathematics*. Washington, DC: National Governors Association Center for Best Practices and the Council of Chief State School Officers. Retrieved from http://www.corestandards.org

Connolly, A. (1988). *Key Math—Revised*. Circle Pines, MN: American Guidance Service.

*Cormier, P., & Dea, S. (1997). Distinctive patterns of relation of phonological awareness and working memory with reading development. *Reading and Writing: An Interdisciplinary Journal, 9,* 193–206. http://dx.doi.org/10.1023/A:1007932721290

Cornoldi, C., Friso, G., & Pra Baldi, A. (2010). *Prove MT avanzate-2. Prove MT avanzate di lettura e matematica 2 per il biennio della scuola secondaria di II grado* [Advanced MT 2 test — Advanced MT test of reading and mathematics for 9th and 10th grades]. Florence, Italy: Organizzazioni Speciali.

*Cornoldi, C., Orsini, A., Cianci, L., Giofrè, D., & Pezzuti, L. (2013). Intelligence and working memory control: Evidence from the WISC–IV administration to Italian children. *Learning and Individual Differences, 26,* 9–14. http://dx.doi.org/10.1016/j.lindif.2013.04.005

*Cowan, R., Donlan, C., Shepherd, D.-L., Cole-Fletcher, R., Saxton, M., & Hurry, J. (2011). Basic calculation proficiency and mathematics achievement in elementary school children. *Journal of Educational Psychology, 103,* 786–803. http://dx.doi.org/10.1037/a0024556

*Cowan, R., & Powell, D. (2014). The contributions of domain-general and numerical factors to third-grade arithmetic skills and mathematical learning disability. *Journal of Educational Psychology, 106,* 214–229. http://dx.doi.org/10.1037/a0034097

Cummins, D. D., Kintsch, W., Reusser, K., & Weimer, R. (1988). The role of understanding in solving word problems. *Cognitive Psychology, 20,* 405–438. http://dx.doi.org/10.1016/0010-0285(88)90011-4

Dahlin, K. I. E. (2011). Effects of working memory training on reading in children with special needs. *Reading and Writing, 24,* 479–491. http://dx.doi.org/10.1007/s11145-010-9238-y

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466. http://dx.doi.org/10.1016/S0022-5371(80)90312-6

*De Smedt, B., Swillen, A., Devriendt, K., Fryns, J. P., Verschaffel, L., Boets, B., & Ghesquière, P. (2008). Cognitive correlates of mathematical disabilities in children with velo-cardio-facial syndrome. *Genetic Counseling, 19,* 71–94.

DeStefano, D., & LeFevre, J. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology, 16,* 353–386. http://dx.doi.org/10.1080/09541440244000328

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal, 315,* 629–634. http://dx.doi.org/10.1136/bmj.315.7109.629

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11,* 19–23. http://dx.doi.org/10.1111/1467-8721.00160

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The psychology of learning and motivation* (pp. 145–199). New York, NY: Academic Press.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102,* 211–245. http://dx.doi.org/10.1037/0033-295X.102.2.211

*Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Developmental Neuropsychology, 26,* 465–486. http://dx.doi.org/10.1207/s15326942dn2601_6

Evans, J. S. B., & Stanovich, K. E. (2013). Dual-process theories of higher cognition: Advancing the debate. *Perspectives on Psychological Science, 8,* 223–241. http://dx.doi.org/10.1177/1745691612460685

*Friso-van den Bos, I., Kroesbergen, E. H., & van Luit, J. E. (2014). Number sense in kindergarten children: Factor structure and working memory predictors. *Learning and Individual Differences, 33,* 23–29. http://dx.doi.org/10.1016/j.lindif.2014.05.003

Friso-van den Bos, I., van der Ven, S. H., Kroesbergen, E. H., & van Luit, J. E. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review, 10,* 29–44. http://dx.doi.org/10.1016/j.edurev.2013.05.003

*Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., & Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *Journal of Educational Psychology, 97,* 493–513. http://dx.doi.org/10.1037/0022-0663.97.3.493

Fuchs, L. S., Fuchs, D., Compton, D. L., Hamlett, C. L., & Wang, A. Y. (2015). Is word-problem solving a form of text comprehension? *Scientific Studies of Reading, 19,* 204–223. http://dx.doi.org/10.1080/10888438.2015.1005745

*Fuchs, L. S., Fuchs, D., Compton, D. L., Powell, S. R., Seethaler, P. M., Capizzi, A. M., . . . Fletcher, J. M. (2006). The cognitive correlates of third-grade skill in arithmetic, algorithmic calculation, and arithmetic word problems. *Journal of Educational Psychology, 98,* 29–43. http://dx.doi.org/10.1037/0022-0663.98.1.29

*Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., Seethaler, P. M., . . . Schatschneider, C. (2010). Do different types of school mathematics development depend on different constellations of numerical versus general cognitive abilities? *Developmental Psychology, 46,* 1731–1746. http://dx.doi.org/10.1037/a0020662

*Fuchs, L. S., Geary, D. C., Fuchs, D., Compton, D. L., & Hamlett, C. L. (2014). Sources of individual differences in emerging competence with numeration understanding versus multidigit calculation skill. *Journal of Educational Psychology, 106,* 482–498. http://dx.doi.org/10.1037/a0034444

Fuchs, L. S., Hamlett, C. L., & Fuchs, D. (1990). Curriculum-based math computation and concepts/applications. (Available from L. S. Fuchs, 328 Peabody, Vanderbilt University, Nashville, TN 37203).

*Fuchs, L. S., Schumacher, R. F., Long, J., Namkung, J., Hamlett, C. L., Cirino, P. T., . . . Changas, P. (2013). Improving at-risk learners' understanding of fractions. *Journal of Educational Psychology, 105,* 683–700. http://dx.doi.org/10.1037/a0032446

Fuchs, L. S., Schumacher, R. F., Sterba, S. K., Long, J., Namkung, J., Malone, A., . . . Changas, P. (2014). Does working memory moderate the effects of fraction intervention? An aptitude–treatment interaction. *Journal of Educational Psychology, 106,* 499–514. http://dx.doi.org/10.1037/a0034341

*Gathercole, S. E., Brown, L., & Pickering, S. J. (2003). Working memory assessments at school entry as longitudinal predictors of national curriculum attainment levels. *Educational and Child Psychology, 20,* 109–123.

*Gathercole, S. E., & Pickering, S. J. (2000). Assessment of working memory in six- and seven-year-old children. *Journal of Educational Psychology, 92,* 377–390. http://dx.doi.org/10.1037/0022-0663.92.2.377

Geary, D. C., & Hoard, M. K. (2005). Learning disabilities in arithmetic and mathematics. In J. I. D. Campbell (Ed.), *The handbook of mathematical cognition* (pp. 253–267). New York, NY: Psychology Press.

Geary, D. C., Hoard, M. K., Byrd-Craven, J., Nugent, L., & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development, 78,* 1343–1359. http://dx.doi.org/10.1111/j.1467-8624.2007.01069.x

Geary, D. C., Hoard, M. K., Nugent, L., & Byrd-Craven, J. (2008). Development of number line representations in children with mathematical learning disability. *Developmental Neuropsychology, 33,* 277–299. http://dx.doi.org/10.1080/87565640801982361

*Giofrè, D., Mammarella, I. C., & Cornoldi, C. (2014). The relationship among geometry, working memory, and intelligence in children. *Journal of Experimental Child Psychology, 123,* 112–128. http://dx.doi.org/10.1016/j.jecp.2014.01.002

*Giofrè, D., Mammarella, I. C., Ronconi, L., & Cornoldi, C. (2013). Visuospatial working memory in intuitive geometry, and in academic achievement in geometry. *Learning and Individual Differences, 23,* 114–122. http://dx.doi.org/10.1016/j.lindif.2012.09.012

*Göbel, S. M., Moeller, K., Pixner, S., Kaufmann, L., & Nuerk, H. C. (2014). Language affects symbolic arithmetic in children: The case of number word inversion. *Journal of Experimental Child Psychology, 119,* 17–25. http://dx.doi.org/10.1016/j.jecp.2013.10.001

*Gómez-Chacón, I. M., García-Madruga, J. A., Vila, J. O., Elosúa, M. R., & Rodríguez, R. (2014). The dual processes hypothesis in mathematics performance: Beliefs, cognitive reflection, working memory and reasoning. *Learning and Individual Differences, 29,* 67–73. http://dx.doi.org/10.1016/j.lindif.2013.10.001

Hecht, S. A. (1998). Toward an information-processing account of individual differences in fraction skills. *Journal of Educational Psychology, 90,* 545–559. http://dx.doi.org/10.1037/0022-0663.90.3.545

*Hecht, S. A., Close, L., & Santisi, M. (2003). Sources of individual differences in fraction skills. *Journal of Experimental Child Psychology, 86,* 277–302. http://dx.doi.org/10.1016/j.jecp.2003.08.003

*Hecht, S. A., & Vagi, K. J. (2010). Sources of group and individual differences in emerging fraction skills. *Journal of Educational Psychology, 102,* 843–859. http://dx.doi.org/10.1037/a0019824

Hedberg, E. C. (2011). *ROBUMETA: Stata module to perform robust variance estimation in meta-regression with dependent effect size estimates*. Boston, MA: Boston College, Department of Economics.

Hedges, L. V., Tipton, E., & Johnson, M. C. (2010). Robust variance estimation in meta-regression with dependent effect size estimates. *Research Synthesis Methods, 1,* 39–65. http://dx.doi.org/10.1002/jrsm.5

*Henry, L., & MacLean, M. (2003). Relations between working memory, expressive vocabulary and arithmetical reasoning in children with and without intellectual disabilities. *Educational and Child Psychology, 20,* 51–63.

*Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General, 130,* 184–198. http://dx.doi.org/10.1037/0096-3445.130.2.184

*Hoffman, B. (2010). "I think I can, but I'm afraid to try": The role of self-efficacy beliefs and mathematics anxiety in mathematics problem-solving efficiency. *Learning and Individual Differences, 20,* 276–283. http://dx.doi.org/10.1016/j.lindif.2010.02.001

*Hoffman, B., & Schraw, G. (2009). The influence of self-efficacy and working memory capacity on problem-solving efficiency. *Learning and Individual Differences, 19,* 91–100. http://dx.doi.org/10.1016/j.lindif.2008.08.001

Holmes, J., & Adams, J. W. (2006). Working memory and children's mathematical skills: Implications for mathematical development and mathematics curricula. *Educational Psychology, 26,* 339–366. http://dx.doi.org/10.1080/01443410500341056

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science, 12,* F9–F15. http://dx.doi.org/10.1111/j.1467-7687.2009.00848.x

*Imbo, I., & Vandierendonck, A. (2008). Effects of problem size, operation, and working-memory span on simple-arithmetic strategies: Differences between children and adults? *Psychological Research, 72,* 331–346. http://dx.doi.org/10.1007/s00426-007-0112-8

Jacob, R., & Parkinson, J. (2015). The potential for school-based interventions that target executive function to improve academic achievement: A review. *Review of Educational Research*. Advance online publication. http://dx.doi.org/10.3102/0034654314561338

*Jarvis, H. L., & Gathercole, S. E. (2003). Verbal and non-verbal working memory and achievements on national curriculum tests at 11 and 14 years of age. *Educational and Child Psychology, 20,* 123–140.

*Jenks, K. M., de Moor, J., & van Lieshout, E. C. D. M. (2009). Arithmetic difficulties in children with cerebral palsy are related to executive function and working memory. *Journal of Child Psychology and Psychiatry, 50,* 824–833. http://dx.doi.org/10.1111/j.1469-7610.2008.02031.x

*Jenks, K. M., de Moor, J., van Lieshout, E. C. D. M., Maathuis, K. G. B., Keus, I., & Gorter, J. W. (2007). The effect of cerebral palsy on arithmetic accuracy is mediated by working memory, intelligence, early numeracy, and instruction time. *Developmental Neuropsychology, 32,* 861–879. http://dx.doi.org/10.1080/87565640701539758

*Jordan, N. C., Hansen, N., Fuchs, L. S., Siegler, R. S., Gersten, R., & Micklos, D. (2013). Developmental predictors of fraction concepts and procedures. *Journal of Experimental Child Psychology, 116,* 45–58. http://dx.doi.org/10.1016/j.jecp.2013.02.001

*Keeler, M. L., & Swanson, H. L. (2001). Does strategy knowledge influence working memory in children with mathematical disabilities? *Journal of Learning Disabilities, 34,* 418–434. http://dx.doi.org/10.1177/002221940103400504

*Khanam, S. J., Ara, A., & Ahmad, R. (2011). Association of calculation ability and digit span in schizophrenia patients. *Pakistan Journal of Psychology, 42,* 93–100.

*Khng, K. H., & Lee, K. (2009). Inhibiting interference from prior knowledge: Arithmetic intrusions in algebra word problem solving. *Learning and Individual Differences, 19,* 262–268. http://dx.doi.org/10.1016/j.lindif.2009.01.004

*Kleemans, T., Segers, E., & Verhoeven, L. (2011). Precursors to numeracy in kindergartners with specific language impairment. *Research in Developmental Disabilities, 32,* 2901–2908. http://dx.doi.org/10.1016/j.ridd.2011.05.013

Klein, J. S., & Bisanz, J. (2000). Preschoolers doing arithmetic: The concepts are willing but the working memory is weak. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 54,* 105–116. http://dx.doi.org/10.1037/h0087333

*Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. M. (2014). Involvement of working memory in longitudinal development of number–magnitude skills. *Infant and Child Development, 23,* 36–50. http://dx.doi.org/10.1002/icd.1834

Kroesbergen, E. H., van't Noordende, J. E., & Kolkman, M. E. (2014). Training working memory in kindergarten children: Effects on working memory and early numeracy. *Child Neuropsychology, 20,* 23–37. http://dx.doi.org/10.1080/09297049.2012.736483

*Kyttälä, M., Aunio, P., & Hautamäki, J. (2010). Working memory resources in young children with mathematical difficulties. *Scandinavian Journal of Psychology, 51,* 1–15. http://dx.doi.org/10.1111/j.1467-9450.2009.00736.x

*Kyttälä, M., Aunio, P., Lehto, J. E., Luit, J. V., & Hautamäki, J. (2003). Visuospatial working memory and early numeracy. *Educational and Child Psychology, 20,* 65–77.

*Lan, X., Legare, C. H., Ponitz, C. C., Li, S., & Morrison, F. J. (2011). Investigating the links between the subcomponents of executive function and academic achievement: A cross-cultural analysis of Chinese and American preschoolers. *Journal of Experimental Child Psychology, 108,* 677–692. http://dx.doi.org/10.1016/j.jecp.2010.11.001

*Lee, K., Ng, E. L., & Ng, S. F. (2009). The contributions of working memory and executive functioning to problem representation and solution generation in algebraic word problems. *Journal of Educational Psychology, 101,* 373–387. http://dx.doi.org/10.1037/a0013843

*Lee, K., Ng, S. F., Bull, R., Pe, M. L., & Ho, R. H. M. (2011). Are patterns important? An investigation of the relations between proficiencies in patterns, calculation, executive functioning, and algebraic word problems. *Journal of Educational Psychology, 103,* 269–281. http://dx.doi.org/10.1037/a0023068

*Lee, K., Ng, S. F., Ng, E. L., & Lim, Z. Y. (2004). Working memory and literacy as predictors of performance on algebraic word problems. *Journal of Experimental Child Psychology, 89,* 140–158. http://dx.doi.org/10.1016/j.jecp.2004.07.001

*Lee, K., Ning, F., & Goh, H. C. (2014). Interaction between cognitive and non-cognitive factors the influences of academic goal orientation and working memory on mathematical performance. *Educational Psychology: An international Journal of Experimental Educational Psychology, 34,* 73–91. http://dx.doi.org/10.1080/01443410.2013.836158

*LeFevre, J. A., Berrigan, L., Vendetti, C., Kamawar, D., Bisanz, J., Skwarchuk, S.-L., & Smith-Chant, B. L. (2013). The role of executive attention in the acquisition of mathematical skills for children in Grades 2 through 4. *Journal of Experimental Child Psychology, 114,* 243–261. http://dx.doi.org/10.1016/j.jecp.2012.10.005

LeFevre, J. A., DeStefano, D., Coleman, B., & Shanahan, T. (2005). Mathematical cognition and working memory. In J. I. D. Campbell (Ed.), *The handbook of mathematical cognition* (pp. 361–378). New York, NY: Psychology Press.

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development, 81,* 1753–1767. http://dx.doi.org/10.1111/j.1467-8624.2010.01508.x

*Li, D. M., Liu, C., & Li, G. Y. (2001). The construction of basic cognitive capacity test and its standardization. *Acta Psychologica Sinica, 33,* 453–460.

*Li, Y., & Geary, D. C. (2013). Developmental gains in visuospatial memory predict gains in mathematics achievement. *PLoS ONE, 8,* e70160. http://dx.doi.org/10.1371/journal.pone.0070160

Lipsey, M. W., & Wilson, D. B. (2001). *Practical meta-analysis*. Thousand Oaks, CA: Sage.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory & Cognition, 22,* 395–410. http://dx.doi.org/10.3758/BF03200866

*Lundberg, I., & Sterner, G. (2006). Reading, arithmetic, and task orientation—How are they related? *Annals of Dyslexia, 56,* 361–377. http://dx.doi.org/10.1007/s11881-006-0016-0

*Mabbott, D. J., & Bisanz, J. (2003). Developmental change and individual differences in children's multiplication. *Child Development, 74,* 1091–1107. http://dx.doi.org/10.1111/1467-8624.00594

Martin, R. B., Cirino, P. T., Barnes, M. A., Ewing-Cobbs, L., Fuchs, L. S., Stuebing, K. K., & Fletcher, J. M. (2013). Prediction and stability of mathematics skill and difficulty. *Journal of Learning Disabilities, 46,* 428–443. http://dx.doi.org/10.1177/0022219411436214

*Martin, R. B., Cirino, P. T., Sharp, C., & Barnes, M. (2014). Number and Counting skills in kindergarten as predictors of grade 1 mathematical skills. *Learning and Individual Differences, 34,* 12–23. http://dx.doi.org/10.1016/j.lindif.2014.05.006

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development, 82,* 1224–1237. http://dx.doi.org/10.1111/j.1467-8624.2011.01608.x

McKenzie, B., Bull, R., & Gray, C. (2003). The effects of phonological and visuospatial interference on children's arithmetical performance. *Educational and Child Psychology, 20,* 93–108.

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology, 49,* 270–291. http://dx.doi.org/10.1037/a0028228

Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences, 20,* 101–109. http://dx.doi.org/10.1016/j.lindif.2009.08.004

Miyake, A., & Shah, P. (Eds.). (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. New York, NY: Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139174909

Morsanyi, K., Devine, A., Nobes, A., & Szűcs, D. (2013). The link between logic, mathematics and imagination: Evidence from children with developmental dyscalculia and mathematically gifted children. *Developmental Science, 16,* 542–553. http://dx.doi.org/10.1111/desc.12048

*Murphy, M. M., & Mazzocco, M. M. M. (2008). Mathematics learning disabilities in girls with Fragile X or Turner syndrome during late elementary school. *Journal of Learning Disabilities, 41,* 29–46. http://dx.doi.org/10.1177/0022219407311038

Nathan, M. J., Kintsch, W., & Young, E. (1992). A theory of algebra-word-problem comprehension and its implications for the design of learning environments. *Cognition and Instruction, 9,* 329–389. http://dx.doi.org/10.1207/s1532690xci0904_2

*Navarro, J. I., Aguilar, M., Alcalde, C., Ruiz, G., Marchena, E., & Menacho, I. (2011). Inhibitory processes, working memory, phonological awareness, naming speed, and early arithmetic achievement. *The Spanish Journal of Psychology, 14,* 580–588. http://dx.doi.org/10.5209/rev_SJOP.2011.v14.n2.6

*Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children's arithmetic competence. *PLoS ONE, 8,* e67918. http://dx.doi.org/10.1371/journal.pone.0067918

*Numminen, H., Service, E., Ahonen, T., Korhonen, T., Tolvanen, A., Patja, K., & Ruoppila, I. (2000). Working memory structure and intellectual disability. *Journal of Intellectual Disability Research, 44,* 579–590. http://dx.doi.org/10.1046/j.1365-2788.2000.00279.x

*Nunes, T., Bryant, P., Barros, R., & Sylva, K. (2012). The relative importance of two different mathematical abilities to mathematical achievement. *British Journal of Educational Psychology, 82,* 136–156. http://dx.doi.org/10.1111/j.2044-8279.2011.02033.x

*Nunes, T., Bryant, P., Evans, D., Bell, D., Gardner, S., Gardner, A., & Carraher, J. (2007). The contribution of logical reasoning to the learning of mathematics in primary school. *British Journal of Developmental Psychology, 25,* 147–166. http://dx.doi.org/10.1348/026151006X153127

*Nyroos, M., & Wiklund-Hornqvist, C. (2012). The association between working memory and educational attainment as measured in different mathematical subtopics in the Swedish national assessment: Primary education. *Educational Psychology: An international Journal of Experimental Educational Psychology, 32,* 239–256. http://dx.doi.org/10.1080/01443410.2011.643578

*Okamoto, Y., Curtis, R., Jabagchourian, J. J., & Weckbacher, L. M. (2006). Mathematical precocity in young children: A neo-Piagetian perspective. *High Ability Studies, 17,* 183–202. http://dx.doi.org/10.1080/13598130601121409

*Östergren, R., & Träff, U. (2013). Early number knowledge and cognitive ability affect early arithmetic ability. *Journal of Experimental Child Psychology, 115,* 405–421. http://dx.doi.org/10.1016/j.jecp.2013.03.007

*Passolunghi, M. C., & Lanfranchi, S. (2012). Domain-specific and domain-general precursors of mathematical achievement: A longitudinal study from kindergarten to first grade. *British Journal of Educational Psychology, 82,* 42–63. http://dx.doi.org/10.1111/j.2044-8279.2011.02039.x

*Passolunghi, M. C., Mammarella, I. C., & Altoè, G. (2008). Cognitive abilities as precursors of the early acquisition of mathematical skills during first through second grades. *Developmental Neuropsychology, 33,* 229–250. http://dx.doi.org/10.1080/87565640801982320

Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology, 80,* 44–57. http://dx.doi.org/10.1006/jecp.2000.2626

*Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology, 88,* 348–367. http://dx.doi.org/10.1016/j.jecp.2004.04.002

*Passolunghi, M. C., Vercelloni, B., & Schadee, H. (2007). The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development, 22,* 165–184. http://dx.doi.org/10.1016/j.cogdev.2006.09.001

Peng, P., & Fuchs, D. (2014). A meta-analysis of working memory deficits in children with learning difficulties: Is there a difference between verbal domain and numerical domain? *Journal of Learning Disabilities*. Advance online publication. http://dx.doi.org/10.1177/0022219414521667

*Pomplun, M., & Custer, M. (2005). The construct validity of the Stanford–Binet 5 measures of working memory. *Assessment, 12,* 338–346. http://dx.doi.org/10.1177/1073191105276796

Psychological Corporation. (1992). *Wechsler individual achievement test*. San Antonio, TX: Harcourt Brace & Co.

*Purpura, D. J., & Ganley, C. M. (2014). Working memory and language: Skill-specific or domain-general relations to mathematics? *Journal of Experimental Child Psychology, 122,* 104–121. http://dx.doi.org/10.1016/j.jecp.2013.12.009

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual differences and cognitive approaches. *Learning and Individual Differences, 20,* 110–122. http://dx.doi.org/10.1016/j.lindif.2009.10.005

*Rasmussen, C., & Bisanz, J. (2005). Representation and working memory in early arithmetic. *Journal of Experimental Child Psychology, 91,* 137–157. http://dx.doi.org/10.1016/j.jecp.2005.01.004

*Rasmussen, C., & Bisanz, J. (2011). The relation between mathematics and working memory in young children with Fetal Alcohol Spectrum Disorders. *The Journal of Special Education, 45,* 184–191. http://dx.doi.org/10.1177/0022466909356110

Redick, T. S., Shipstead, Z., Wiemers, E. A., Melby-Lervåg, M., & Hulme, C. (2015). What's working in working memory training? An educational perspective. *Educational Psychology Review*. Advance online publication. http://dx.doi.org/10.1007/s10648-015-9314-6

*Robinson, N. M., Abbott, R. D., Berninger, V. W., & Busse, J. (1996). The structure of abilities in math-precocious young children: Gender similarities and differences. *Journal of Educational Psychology, 88,* 341–352. http://dx.doi.org/10.1037/0022-0663.88.2.341

Roid, G. H. (2003a). *Stanford-Binet Intelligence Scales,* Fifth Edition, examiner manual. Itasca, IL: Riverside.

*Rose, S. A., Feldman, J. F., & Jankowski, J. J. (2011). Modeling a cascade of effects: The role of speed and executive functioning in preterm/full-term differences in academic achievement. *Developmental Science, 14,* 1161–1175. http://dx.doi.org/10.1111/j.1467-7687.2011.01068.x

*Royan, J., Tombaugh, T. N., Rees, L., & Francis, M. (2004). The Adjusting-Paced Serial Addition Test (Adjusting-PSAT): Thresholds for speed of information processing as a function of stimulus modality and problem complexity. *Archives of Clinical Neuropsychology, 19,* 131–143. http://dx.doi.org/10.1093/arclin/19.1.131

*Ryan, J. J., & Paolo, A. M. (2001). Exploratory factor analysis of the WAIS–III in a mixed patient sample. *Archives of Clinical Neuropsychology, 16,* 151–156. http://dx.doi.org/10.1093/arclin/16.2.151

*Salthouse, T. A., & Kersten, A. W. (1993). Decomposing adult age differences in symbol arithmetic. *Memory & Cognition, 21,* 699–710. http://dx.doi.org/10.3758/BF03197200

*Seethaler, P. M., & Fuchs, L. S. (2006). The cognitive correlates of computational estimation skill among third-grade students. *Learning Disabilities Research & Practice, 21,* 233–243. http://dx.doi.org/10.1111/j.1540-5826.2006.00220.x

*Sewell, R. D. (2008). *Cognitive and behavioral correlates in mathematical ability subtypes* (Doctoral dissertation). Available from ProQuest Dissertations and Theses database (UMI No. 3319343).

*Shelton, J. T., Elliott, E. M., Hill, B. D., Calamia, M. R., & Gouvier, W. D. (2009). A comparison of laboratory and clinical working memory tests and their prediction of fluid intelligence. *Intelligence, 37,* 283–293. http://dx.doi.org/10.1016/j.intell.2008.11.005

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin, 138,* 628–654. http://dx.doi.org/10.1037/a0027473

*Simmons, F. R., Willis, C., & Adams, A. M. (2012). Different components of working memory have different relationships with different mathematical skills. *Journal of Experimental Child Psychology, 111,* 139–155. http://dx.doi.org/10.1016/j.jecp.2011.08.011

*Spybrook, J. (2009). *The relation among working memory, mathematics anxiety, and mathematics achievement in developmental mathematics courses in community college* (Doctoral dissertation). Available from ProQuest Dissertations and Theses database (UMI No. 3345281)

*St. Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 59,* 745–759. http://dx.doi.org/10.1080/17470210500162854

*Swanson, H. L. (2004). Working memory and phonological processing as predictors of children's mathematical problem solving at different ages. *Memory & Cognition, 32,* 648–661. http://dx.doi.org/10.3758/BF03195856

*Swanson, H. L. (2006a). Cognitive processes that underlie mathematical precociousness in young children. *Journal of Experimental Child Psychology, 93,* 239–264. http://dx.doi.org/10.1016/j.jecp.2005.09.006

*Swanson, H. L. (2006b). Cross-sectional and incremental changes in working memory and mathematical problem solving. *Journal of Educational Psychology, 98,* 265–281. http://dx.doi.org/10.1037/0022-0663.98.2.265

*Swanson, H. L. (2011). Intellectual growth in children as a function of domain specific and domain general working memory subgroups. *Intelligence, 39,* 481–492. http://dx.doi.org/10.1016/j.intell.2011.10.001

Swanson, H. L. (2014). Does cognitive strategy training on word problems compensate for working memory capacity in children with math difficulties? *Journal of Educational Psychology, 106,* 831–848. http://dx.doi.org/10.1037/a0035838

*Swanson, H. L., & Beebe-Frankenberger, M. (2004). The relation between working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *Journal of Educational Psychology, 96,* 471–491. http://dx.doi.org/10.1037/0022-0663.96.3.471

*Swanson, H. L., & Howard, C. B. (2005). Children with reading disabilities: Does dynamic assessment help in the classification? *Learning Disability Quarterly, 28,* 17–34. http://dx.doi.org/10.2307/4126971

Swanson, H. L., & Jerman, O. (2006). Math disabilities: A selective meta-analysis of the literature. *Review of Educational Research, 76,* 249–274. http://dx.doi.org/10.3102/00346543076002249

Swanson, H. L., Jerman, O., & Zheng, X. (2008). Growth in working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *Journal of Educational Psychology, 100,* 343–379. http://dx.doi.org/10.1037/0022-0663.100.2.343

*Swanson, H. L., & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence, 35,* 151–168. http://dx.doi.org/10.1016/j.intell.2006.07.001

*Swanson, H. L., & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: Both executive and phonological processes are important. *Journal of Experimental Child Psychology, 79,* 294–321. http://dx.doi.org/10.1006/jecp.2000.2587

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction, 4,* 295–312. http://dx.doi.org/10.1016/0959-4752(94)90003-5

*Tirre, W. C., & Pena, C. M. (1993). Components of quantitative reasoning: General and group ability factors. *Intelligence, 17,* 501–521. http://dx.doi.org/10.1016/0160-2896(93)90015-W

*Tolar, T. D., Lederberg, A. R., & Fletcher, J. M. (2009). A structural model of algebra achievement: Computational fluency and spatial visualization as mediators of the effect of working memory on algebra achievement. *Educational Psychology: An international Journal of Experimental Educational Psychology, 29,* 239–266. http://dx.doi.org/10.1080/01443410802708903

*Toll, S. W. M., & Van Luit, J. E. H. (2014). Explaining numeracy development in weak performing kindergartners. *Journal of Experimental Child Psychology, 124,* 97–111. http://dx.doi.org/10.1016/j.jecp.2014.02.001

*Trezise, K., & Reeve, R. A. (2014). Working memory, worry, and algebraic ability. *Journal of Experimental Child Psychology, 121,* 120–136. http://dx.doi.org/10.1016/j.jecp.2013.12.001

U.S. Department of Education. (2013). National Assessment of Educational Progress (NAEP): NAEP questions tool. Retrieved from http://nces.ed.gov/nationsreportcard/itmrlsx/search.aspx?subjectmathematics

*Vallée-Tourangeau, F. (2013). Interactivity, efficiency, and individual differences in mental arithmetic. *Experimental Psychology, 60,* 302–311. http://dx.doi.org/10.1027/1618-3169/a000200

*van Rooijen, M., Verhoeven, L., Smits, D. W., Dallmeijer, A. J., Becher, J. G., & Steenbergen, B. (2014). Cognitive precursors of arithmetic development in primary school children with cerebral palsy. *Research in Developmental Disabilities, 35,* 826–832. http://dx.doi.org/10.1016/j.ridd.2014.01.016

*van Rooijen, M., Verhoeven, L., Smits, D.-W., Ketelaar, M., Becher, J. G., & Steenbergen, B. (2012). Arithmetic performance of children with cerebral palsy: The influence of cognitive and motor factors. *Research in Developmental Disabilities, 33,* 530–537. http://dx.doi.org/10.1016/j.ridd.2011.10.020

*Vukovic, R. K., Kieffer, M. J., Bailey, S. P., & Harari, R. R. (2013). Mathematics anxiety in young children: Concurrent and longitudinal associations with mathematical performance. *Contemporary Educa-*

tional Psychology, 38, 1–10. http://dx.doi.org/10.1016/j.cedpsych.2012.09.001

*Vukovic, R. K., & Lesaux, N. K. (2013). The language of mathematics: Investigating the ways language counts for children's mathematical development. *Journal of Experimental Child Psychology, 115,* 227–244. http://dx.doi.org/10.1016/j.jecp.2013.02.002

Wechsler, D. (2003). *Wechsler intelligence scale for children*—Fourth edition. San Antonio, TX: Psychological Corporation.

*Whitwer, L. E. (2004). *The effects of working memory capacity and task type on motor performance* (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses database (UMI No. 3126972)

Wilkinson, G. S., & Robertson, G. J. (2006). *Wide Range Achievement Test* (WRAT4). Lutz, FL: Psychological Assessment Resources.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock–Johnson III*. Itasca, IL: Riverside Publishing.

Woodcock, R. W., & Johnson, M. B. (1990). *Woodcock–Johnson Psycho-Educational Battery—Revised*. Allen, TX: DLM Teaching Resources.

*Xenidou-Dervou, I., De Smedt, B., van der Schoot, M., & van Lieshout, E. C. D. M. (2013). Individual differences in kindergarten math achievement: The integrative roles of approximation skills and working memory. *Learning and Individual Differences, 28,* 119–129. http://dx.doi.org/10.1016/j.lindif.2013.09.012

*Xin, Z. Q., & Liu, G. F. (2011). The development of children's non-symbolic calculation ability of whole-Number and fraction and its relation with number memory. *Journal of Psychological Science, 34,* 520–526.

*Zheng, X., Swanson, H. L., & Marcoulides, G. A. (2011). Working memory components as predictors of children's mathematical word problem solving. *Journal of Experimental Child Psychology, 110,* 481–498. http://dx.doi.org/10.1016/j.jecp.2011.06.001

Received February 2, 2015
Revision received June 11, 2015
Accepted July 22, 2015 ■