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A Meta-Analytical Review of the Genetic and Environmental Correlations between Reading and Attention-Deficit Hyperactivity Disorder Symptoms and Reading and Math

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Abstract

According to the Multiple Deficit Model, comorbidity results when the genetic and environmental risk factors that increase the liability for a disorder are domain-general. In order to explore the role of domain-general etiological risk factors in the co-occurrence of learning-related difficulties, the current meta-analysis compiled 38 studies of third through ninth-grade children to estimate the average genetic, shared environmental, and nonshared environmental correlations between reading and attention-deficit/hyperactivity disorder (ADHD) symptoms, and reading and math, as well as their potential moderators. Results revealed average genetic, shared and nonshared environmental correlations between reading and ADHD symptoms of .42, .64, and .20, and reading and math of .71, .90, and .56, suggesting that reading and math may have more domain-general risk factors than reading and ADHD symptoms. A number of significant sources of heterogeneity were also found and discussed. These results have important implications for both intervention and classification of learning disabilities.

Keywords

reading; math; Attention Deficit Hyperactivity Disorder; comorbidity; genetics

Decades of research demonstrates that learning disabilities are diverse and multi-dimensional with a number of domain-general and domain-specific genetic and environmental influences. Reading disability, which affects 5–10% of the school-age population and is characterized by significant underachievement in reading based on age and development (Compton et al., 2014), has been linked to deficits that are both domain-general, like poor working memory (Willcutt et al., 2013) or delayed processing speed

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

(Peterson et al., 2017), and domain-specific, like problems with phonological processing (Landerl, Fussenegger, Moll, & Willburger, 2009). Children with reading problems are more likely than typical readers to exhibit higher rates of externalizing problems, like Attention Deficit Hyperactivity-Impulsivity Disorder (ADHD; Willcutt & Pennington, 2000), and approximately 60% of those with reading difficulties also qualify for at least one additional learning disorder (Trzesniewski et al., 2006), like math disability. Accordingly, two of the most common and frequently studied disorders that co-occur with reading problems are ADHD symptoms and math difficulties (Willcutt et al., 2010, 2013). In fact, approximately 20 to 40% of individuals with reading problems demonstrate comorbid ADHD symptoms (Willcutt & Pennington, 2000), and 30–70% of those with difficulties in either reading or math also exhibit problems in the other domain (Landerl & Moll, 2010). However, comorbidity rates are less than 100%, demonstrating that domain-specific etiological factors also influence learning disorders. In this study we use meta-analytic methods to investigate the extent to which genetic and environmental (i.e., etiological) risk factors that underlie reading and ADHD symptoms and reading and math are domain-general versus domain-specific, to examine the role of overlapping etiological influences on their co-occurrences.

One potential explanation for the comorbidity of reading difficulties with ADHD symptoms and math difficulties is an overlap of genetic and environmental influences among disorders that manifest as general cognitive deficits. Accordingly, the Multiple Deficit Model (MDM) posits that learning-related disorders result from a combination of common and unique etiological risk factors, manifesting at the cognitive and/or neurological level and are either domain-general, underlying many learning disorders and resulting in comorbidity, or domain-specific, differentiating learning disorders from one another (Pennington, 2006). Supporting the role of common risk factors among learning-related disorders, there is building evidence of domain-general cognitive deficits that contribute to comorbid learning problems. For reading problems and ADHD symptoms, these deficits include poor cognitive impulsivity, deficient executive functions, and decreased verbal storage ability (Donfrancesco et al., 2005; Purvis & Tannock, 2000; Willcutt et al., 2001). For reading and math problems, they include deficient memory and slow processing speed (Geary & Hoard, 2001; Peterson et al., 2017). These domain-general cognitive deficits are likely driven by overlapping etiological risk factors, like common genetic influences (Greven et al., 2012; Wadsworth et al., 2015), and to a lesser extent, common environmental influences (Hart et al., 2010; Willcutt et al., 2010). The idea of common genetic risk factors linking learning-related disorders falls under the purview of the *generalist genes hypothesis*, which posits that the same genes underlie all cognitive abilities and disabilities both within and between academic domains (Plomin & Kovas, 2005). Domain-general environmental risk factors, like social disadvantage and large family size, have also been found among co-occurring learning problems (Light & DeFries, 1995).

There is also evidence of domain-specific cognitive deficits that contribute to specific learning-related disabilities. For example, phonological processing difficulties have been found in children with poor reading performance, whether or not they also exhibited problems with ADHD symptoms or math, but not in children with deficits in ADHD symptoms or math only (Landerl et al., 2009; Pennington et al., 1993). Similarly, both with and without a reading deficit, children with ADHD symptoms exhibit significantly impaired

object naming and behavioral inhibition, and math-disabled groups demonstrate visuospatial and numerical processing deficits, while those with only reading problems sometimes do not (Landerl et al., 2004; Landerl et al., 2009; Shafir & Siegel, 1994). From a behavioral genetic perspective, these domain-specific deficits would be measured as domain-specific etiological risk factors, or genetic and environmental influences which are modeled on reading only, and not on ADHD symptoms or math. This maps onto the MDM principle that domain-specific etiological risk factors differentiate learning-related disorders from one another (Pennington, 2006), and aligns with evidence from genetically-sensitive studies that find significant unique variance for each specific learning domain beyond the overlapping etiologies underlying learning-related abilities (Hart et al., 2010; Willcutt et al., 2013).

To quantify the common genetic and environmental influences on the co-occurrence of learning-related difficulties, and empirically test the principle of common and unique risk factors, we conducted a meta-analysis of all available genetically-sensitive studies examining the genetic and environmental correlations between reading and ADHD symptoms and reading and math. Genetic, shared environmental, and nonshared environmental correlations quantify the extent to which genetic, shared environmental, and nonshared environmental influences on one trait overlap with those influences on another trait. The extent to which these correlations are found to be greater than zero reflects the domain-general risk factors common between reading and ADHD symptoms and reading and math. The extent to which the correlations are less than 1.00 reflects the domain-specific etiological risk factors underlying each domain. Based on previous twin work and the generalist genes hypothesis, we expected mostly common genetic risk factors to account for comorbidity (Little et al., 2017), as well as common environmental risk factors between domains (Willcutt et al., 2010). Additionally, we expected genetic and environmental correlations between reading and math to be higher than reading and ADHD symptoms (Hart et al., 2010).

The large ranges in comorbidity rates between reading and ADHD symptoms and reading and math, along with the differences in samples and methodologies used across studies make a meta-analysis uniquely suited to provide a statistically-driven procedure for accounting for study heterogeneity. First, creating a pooled sample increased both power and sample diversity providing a more precise snapshot of the overall research area and enabling the calculation of more robust estimates. Second, moderator analyses allowed for testing varying study characteristics that may be influencing the strength of the genetic and/or environmental correlations found between reading and ADHD symptoms and reading and math to pinpoint the sources of differences across study results.

In examining the literature on reading and ADHD symptoms and reading and math, it was important to consider the variability in defining reading and math disability (Spencer et al., 2014; Watson & Gable, 2013), as well as the application of the label “ADHD” when symptoms exist below the threshold for clinical ADHD diagnosis. The diagnostic method utilized by the DSM-V (American Psychiatric Association, 2013) for all three disorders aligns with the MDM framework. First, all three disorders are based on a checklist of possible symptoms, mapping onto the MDM principle that learning-related disorders result from multiple interacting risk factors that manifest as cognitive and behavioral symptoms

(Pennington, 2006). Second, both reading and math fall under the same diagnostic category of Specific Learning Disorder, which coincides with the MDM principle of domain-general risk factors among learning disorders. Finally, a Specific Learning Disorder diagnosis requires the inclusion of a severity rating, which supports the idea in the genetically-sensitive literature that learning disorders are dimensional, and any cutoff criteria used to group children into single-deficit and comorbid groups simply creates arbitrary categories (Pennington, 2006). Accordingly, we included studies that had participants with normally-varying traits, as well as studies with subsamples selected based on learning-related disability cutoffs in our final study sample. This decision was supported by a substantial literature demonstrating that individual differences in reading, ADHD symptoms, and math represent a normal distribution of genetic and environmental influences, where reading disability, clinical ADHD diagnosis, and math disability are simply at the quantitative extreme of the same genetic and environmental factors responsible for typical variation (Kovas et al., 2005).

The present work contributes to the field by providing empirical support for the use of the MDM framework. In addition to theory building, evidence from the present report also provides applied benefits. For example, evidence for the existence of domain-general risk factors among disorders empirically supports the need for the consideration of different learning domains during learning disability assessment, especially in reading disorders where co-occurring deficits are common. Alternatively, empirical support for domain-specific risk factors encourages careful scrutiny when choosing measures to capture a specific domain, to avoid using assessments that may tap into other domains due to shared method variance. The evidence gleaned from the present analysis provides strong generalizable results that guide future decisions to use both domain-general and domain-specific screening tools to pinpoint children's specific learning disability classification(s) and fully capture their general and specific learning needs.

Moderators

A number of moderators were chosen based on the significant moderators found in a previous genetically-sensitive meta-analysis on reading (Little et al., 2017) and on the sample and methodological characteristics that varied between studies.

Sample Characteristic Moderators.

Twin project.—Typically, each twin project utilizes measures that are specific to its country or region to assess learning domains and has its own method of twin recruitment that may cause heterogeneity. Since many of these differences may be project-specific, we accounted for twin project as a potential moderator.

Age and grade-level.—We included both a continuous and categorical indicator of the study sample's point in development: reported age and grade-level. Prior investigations have shown that as children advance in school, reading-ADHD symptom relations are highly stable (Greven et al., 2012), while reading-math relations tend to strengthen (Koponen et al., 2018), so we expected there may be moderation by age and/or grade-level.

Race.—Race-related gaps in achievement have been found in which Caucasian students perform higher than minority students (Roscigno & Ainsworth-Darnell, 1999). Thus, we tested for moderation by race to examine its impact on the correlations found.

Nationality.—We included the nationality of the study sample as a potential moderator based on recent meta-analyses that found significant between-country differences in genetic influences on achievement (de Zeeuw et al., 2014).

Clinical status.—Even though ability and disability are not etiologically distinct (Plomin & Kovas, 2005), some work has found that the genetic correlations between reading and ADHD symptoms (Willcutt et al., 2007) and reading and math (Knopik et al., 1997) may be stronger in reading-disabled children than typically-developing children. Therefore, we included a moderator which represented whether the sample recruited was typically-developing, had a learning-disability (reading, math, ADHD, or comorbid disability diagnosis), or both.

Methodological Moderators.

Reading and math assessments, formats, and domains.—High variability in comorbidity rates among reading and math may reflect the different measures and subskills used for assessment (Moll, Kunze, Neuhoﬀ, Bruder, & Schulte-Körne, 2014; Moll, Landerl, Snowling, & Schulte-Körne, 2018). This is supported by previous genetically-sensitive work showing different genetic and environmental correlations, depending on the reading or math measure used and/or domain assessed (Hart et al., 2009). Therefore, we coded for specific reading and math assessments (e.g., WJ-Reading, WJ-Math), assessment format (e.g., cloze test), and the domain captured by the assessment (e.g., reading comprehension, quantitative concepts). This also allowed us to account for the potential impact of shared method variance (i.e., a math measure that requires reading probably draws on reading and math skills).

ADHD assessment, reliability, and component measured.—Given that the wide range of comorbidity rates between reading and ADHD symptoms found across studies may be due to differences between ADHD measures (Naglieri et al, 2005; Swanson et al., 2012), we accounted for the ADHD assessment used in each study. Whenever the reliability was calculated for the present study's sample, we also tested for the moderating effects of the ADHD assessment's reliability. Based on the differences in the association between reading and ADHD symptoms found for different ADHD components, we also accounted for whether inattention, hyperactivity/impulsivity or overall ADHD was modeled. Estimates typically show higher and more significant genetic and/or environmental correlations between reading and inattention symptoms or overall ADHD compared to reading and hyperactivity/impulsivity symptoms (Chhabildas et al., 2001; Willcutt & Pennington, 2000), although that is not always the case (Hart et al., 2010).

Analysis used.—Although a majority of the study samples used Cholesky decompositions to estimate the genetic and environmental correlations on the full distribution of behavior (Plomin et al., 2013), the DeFries-Fulker (DF; DeFries & Fulker, 1985) method of analysis

was also used in our study sample. The DF method applies a cut-point to continuous learning-related abilities in order to calculate group heritability for the individuals below the cut. Based on behavioral literature showing that the cutoff criteria used for disability diagnosis can affect comorbidity estimates (Moll et al., 2014), we accounted for whether or not the DF method was used.

Methods

Search Strategy and Coding

Studies were included in the present meta-analysis based on the inclusionary criteria presented in Table 1. To identify articles, we conducted literature searches using the PsycINFO, ERIC, PubMed and Google Scholar databases during the fall of 2018. Peer-reviewed articles, theses, and dissertations were queried. Search terms included a combination of phrases related to reading (read*, reading comprehension, reading difficulties, dyslexia), phrases related to ADHD symptoms (ADHD, ADD, inattention, inattentiveness, hyperactivity, attention difficulties, attention deficit), phrases related to math (math*, math difficulties, dyscalculia), and phrases related to genetically-sensitive analyses (twin, twins, genes, etiology, genetic). Finally, a combination term was added (i.e., AND, OR, or terms were presented “in quotes”) to generate genetically-sensitive studies assessing the covariance between reading and ADHD symptoms and reading and math. Studies were evaluated for inclusion based first on title relevance, and then by reviewing abstracts and, if needed, complete manuscripts. The references of each relevant article were also examined for additional studies to be included. In an effort to find grey literature, the Google scholar results were reviewed beyond page 35 (Haddaway et al., 2015), however no additional grey literature was found. Additionally, authors who have published in this field (Coventry, Kovas, Petrill, van Bergen, and Willcutt) were emailed directly and asked to provide any (un)published data related to the present study and to check the final list of references to be included for any omissions. Willcutt provided unpublished data from two subsequent data collection waves for a paper already included in the final study sample (Willcutt et al., 2007), which were added to the data used for analysis. Unpublished data from the Florida Twin Project on Reading, Behavior, and Environment (FTP; Taylor et al., 2013) were also included. Figure 1 depicts a flow chart of the article selection process.

Our search yielded 83 articles for review and coding, 45 of which were excluded for the following reasons: the study did not use genetically-sensitive analyses ($n=15$), the study did not assess the appropriate covariates (e.g., analyzed reading and ADHD separately; $n=13$), the study used a genetically-sensitive analysis that did not allow us to extract the information we needed (e.g., common pathway model; $n=2$) the study was a review or the data were already represented in a separate article ($n=4$), the study utilized the DF method of analysis and did not report enough information for conversion to the covariances necessary for the present investigation ($n=5$), the study was a duplicate ($n=6$), or the study was a molecular genetic investigation ($n=5$). There were 38 studies remaining, which included 17 published articles and 3 unpublished waves of data assessing the covariance between reading and ADHD symptoms and 20 articles assessing the covariance between reading and math. These studies were coded at three different levels: study, sample, and methodology. Coded study

characteristics included: genetic and environmental correlations, sample size (number of individuals), and twin project. Coded sample characteristics included: age (the midpoint was reported for age ranges), grade-level, clinical status¹, race reported, race inferred², and nationality. Coded methodological characteristics included: assessment types for reading, ADHD symptoms, and math, assessment reliability for ADHD, ADHD component assessed, assessment format for reading and math, and domain assessed for reading and math. A detailed codebook is presented in Supplemental Materials (including some information that was collected but not reported here). A codebook legend is provided in Table 2, and descriptions of all 9 included twin projects and all reading, ADHD symptom, and math assessments in the final study sample are presented in Table 3.

Coding was split evenly between two trained researchers, with an additional outside individual serving as the reliability coder. Once the researchers had coded their assigned studies, 20% of the studies were re-coded by the reliability coder to assess inter-coder reliability. Coding discrepancies were discussed and resolved between the coders; subsequent inter-coder reliability was 0.97.

Analyses

A meta-analysis of genetically-sensitive studies was conducted to estimate the average magnitude of genetic and environmental correlations between reading and ADHD symptoms ($k=20$) and reading and math ($k=20$). Given that the explanatory power of genetic and environmental correlations is limited to the extent to which two traits are correlated phenotypically, a meta-analysis of the phenotypic correlations for each bivariate correlation was conducted first. Corresponding authors were contacted for eight studies that either did not report phenotypic correlations or reported correlations for variables that differed from those used in the genetically-sensitive analyses (Plourde et al., 2017; Rosenberg et al., 2012; Stevenson et al., 1993; Thompson et al., 1991; Willcutt et al., 2010, unpublished), and authors from two of the studies provided the unpublished phenotypic correlations in time to include them (Hart et al., 2009b; Little et al., 2016), resulting in a sample of 32 studies for the phenotypic meta-analyses. Although four studies reported phenotypic correlations separately for disabled and control groups (Knopik & DeFries, 1999; Knopik et al., 1997; Kovas et al., 2007; Light et al., 1998), there were not enough data to warrant running separate analyses for disabled samples, so in these four cases, both correlation coefficients were included.

For the genetically-sensitive analyses, effect sizes were obtained from reported genetic (r_A), shared environmental (r_C), and nonshared environmental (r_E) correlations, or calculated

¹For the clinical status moderator we accounted for whether 75% or more of the study sample was selected for reading deficits, ADHD symptoms, or math deficits or was typically-developing. We also included a category that captured mixed samples in which both typically-developing children and children with a learning disability were included, due to the inclusion of a number of studies that utilized proband analyses to calculate DF estimates. Typically, such analyses require the selection of twin pairs in which at least one twin is considered learning-disabled and the other may or may not be, so the inclusion of an additional category helped us account for studies that used such samples.

²Race-reported and race-inferred were both included as moderators because many of the manuscripts included in the current analyses did not directly report the racial composition of their study samples, which led to a lot of missing data. We chose to overcome this issue by filling in missing data based on our knowledge of the twin projects. Thus, race-reported versus -inferred refers to whether the racial composition of the sample was directly reported in the manuscript or inferred based on our personal knowledge of the research area.

using path estimates from bivariate Cholesky decompositions or DF group heritabilities reported in the studies. Before analyses were conducted, effect sizes were all converted to positive values and standardized using Fisher's z -transformation (Lipsey & Wilson, 2001) but then re-transformed into r_A , r_C , and r_E values for ease of interpretation (Hedges & Olkin, 1985; Little et al., 2017). Individual effect sizes were analyzed using random-effects models to estimate the weighted average effect sizes for r_A , r_C , and r_E (Hedges, 1983). Forest plots were then created to depict the average effect size from each random-effects model, along with the effect sizes extracted from each study, in order to display the full distribution of effect sizes that comprised our weighted averages. After the primary analyses with all effect sizes, follow-up analyses to account for data dependence were conducted using robust variance estimation (RVE; Hedges et al., 2010). RVE handles dependent effect sizes without using effect size covariance structures or averages, by clustering the effect sizes by a given control variable and weighting them based on correlated effects in order to provide unbiased estimates of the standard errors. Two sets of RVE analyses were conducted: study-level influences and project-level influences. Study-level RVE analyses were conducted due to the large number of studies that reported multiple effect sizes, and project-level RVE analyses were conducted to control for study differences that may be attributable to twin project samples and the different measures and methodologies utilized by each twin project. Importantly, due to the small study sample, all RVE analyses were conducted using a small-sample adjustment to minimize the risk for alpha-inflation (Tipton & Pustejovsky, 2015).

Potential moderators of the bivariate correlations were assessed using a two-level mixed-effects model, controlling for study (Borenstein et al., 2009). We elected to not include twin project as control for the moderator analyses because it removed a substantial portion of heterogeneity that we were interested in explaining. Nonshared environmental correlations were excluded from moderator analyses because the presence of error within these estimates may bias estimates of heterogeneity. The Q , I^2 , and τ^2 statistics were used to examine the presence and magnitude of heterogeneity among effect sizes due to moderator variables (Q_M ; Borenstein et al., 2009; Higgins et al., 2003). The Q statistic and corresponding p -value indicates the presence or absence of significant heterogeneity among effect sizes (Borenstein et al., 2009), while I^2 represents the proportion of variance, ranging from 0–100%, that is due to heterogeneity (Higgins et al., 2003). The τ^2 statistic represents the true variance from the observed studies (Borenstein et al., 2009).

Results

Phenotypic Correlations Between Reading and Math and Reading and ADHD Symptoms.

Results of the random-effects analysis of the phenotypic correlations between reading and ADHD yielded an average weighted correlation of .24[.21–.27], $SE=.00$. For the phenotypic correlations between reading and math the random-effects analysis indicated an average weighted correlation of .52[.49–.56], $SE=.00$. Results of RVE analyses indicated a slightly higher average weighted correlation for reading and ADHD .26[.20–.32], $SE=.03$, and for reading and math .54[.49–.60], $SE=.04$. Sensitivity analyses were conducted across varying values of within-study correlations, or ρ (0.0, 0.2, 0.4, 0.6, & 0.8), and results indicated that

the effect sizes, standard errors, and τ^2 values were robust to p value fluctuations for both random effects and RVE analyses.

Genetic and Shared Environmental Correlations Between Reading and ADHD Symptoms.

Starting with the genetic correlation between reading and ADHD symptoms, random-effects analysis was conducted to determine the nature of the variance between studies ($Q_M(90) = 42825.37$, $p < .01$), which indicated an average genetic correlation between reading and ADHD symptoms of $.42$ [$.35-.49$], $SE = .00$. These steps were repeated for environmental estimates revealing an average shared environmental correlation of $.64$ [$.47-.76$], $SE = .12$; $Q_M(54) = 250845.99$, $p < .01$ and an average nonshared environmental correlation of $.20$ [$.10-.30$], $SE = .04$; $Q_M(61) = 8568.47$, $p < .01$. Figures 2–4 present forest plots for each random-effects analysis.

Next, two sets of RVE analyses were conducted to account for multiple effect sizes from within the same study or within the same project. For the study-level bivariate correlations of reading with ADHD symptoms, the RVE-generated effect sizes were similar, up to the 100th decimal place, to effect sizes generated from the analyses utilizing all available effect sizes, with the exception of the bivariate shared environmental correlation ($.012$; see Table 4). At the project-level, the RVE-generated effect sizes were similar at the 10th decimal place for r_A , but not for r_C ($.010$) or r_E ($.018$), see Table 4. The similar magnitudes found between the two sets of generated correlations, along with sensitivity analyses showing consistent results across many values of ρ , indicated that estimates were robust.

Following RVE analyses, moderator analyses were conducted to determine which study features contributed to heterogeneity among the bivariate correlations. Studies were analyzed at the moderator level using a mixed model approach. Age and ADHD reliability were entered as continuous moderators and all other moderators were entered as categorical (Table 5). For reading and ADHD symptoms, age was a significant source of heterogeneity with a $.03$ [$.005 - .063$] unit increase in r_A for every 1-year increase in age. No significant heterogeneity was found for ADHD reliability. Among the categorical moderators, race inferred, project, nationality, clinical status of the sample, ADHD assessment, and the use of the DF method of analysis were significant sources of heterogeneity. Table 6 presents the results of bivariate genetic correlations with a 95% confidence interval, corresponding p -values, and standard errors for significant categorical moderators.

Results of moderator analyses for the shared environmental correlations of reading with ADHD symptoms are presented in Table 7. Age was again a significant source of heterogeneity with a $.09$ [$.022 - .156$] unit increase in r_C for every 1-year increase in age. Race inferred, grade-level, project, nationality, reading assessment, and ADHD assessment were significant categorical moderators for shared environmental correlations between reading and ADHD symptoms (Table 7). Table 8 shows the correlations, with a 95% confidence interval, corresponding p -values and standard errors for the significant categorical moderators.

Genetic and Shared Environmental Correlations Between Reading and Math

The same set of analyses was conducted for the genetic and environmental correlations between reading and math. Results indicated an average genetic correlation of .71[.64–.77], $SE=.07$, $Q_M(62)=22399.10$, $p<.01$, an average shared environmental correlation of .90[.85–.94], $SE=.11$, $Q_M(58)=122737.60$, $p<.01$, and an average nonshared environmental correlation of .56[.40–.69], $SE=.11$, $Q_M(60)=44393.60$, $p<.01$. Forest plots of effect sizes for each random-effects analysis are presented in Figures 5–7. Follow-up RVE analyses indicated, at the study-level, differences between RVE-generated estimates and estimates using all available effect sizes were small, for r_A (< 0.05), r_C (< 0.02) and r_E (< 0.04 ; see Table 9). For project-level, differences between the RVE-generated estimates and estimates using all available effect sizes were also small (see Table 9) and similar in magnitude to study-level RVE estimates. For both study-level and project-level, sensitivity analyses indicated the effect sizes, standard errors, and τ^2 values were robust to ρ value fluctuations.

Moderator analyses (Table 10) revealed grade-level, project, reading assessment, and reading assessment format were significant sources of heterogeneity for the genetic correlations between reading and math. Table 11 displays the correlations, with a 95% confidence interval, corresponding p -values and standard errors. For shared environmental correlations between reading and math, race (reported and inferred), clinical status of the sample, math domain, and math assessment format were significant sources of heterogeneity (Table 12). The correlations for these significant moderators, with a 95% confidence interval, corresponding p -values and standard errors are displayed in Table 13.

Discussion

Results of the current study supported the theory that common, domain-general risk factors underlie the co-occurrence of reading and math but not necessarily the co-occurrence of reading and ADHD symptoms. Although the comorbidity rates of RD and ADHD are higher than chance (20–40%; Willcutt & Pennington, 2000), our results implied that genetic influences on reading are largely distinct from those on ADHD symptoms. Conversely, the higher magnitude genetic correlations found between reading and math align with the higher epidemiological rates of comorbid reading and math disabilities (Trzesniewski et al., 2006). The lesser degree of etiological overlap between reading and ADHD symptoms compared to reading and math was echoed in our phenotypic results, showing the average correlation between reading and ADHD symptoms was about half as large as the magnitude of the correlation between reading and math ($r=.24$ versus $r=.52$). Practically speaking, our results suggest that children with reading difficulties may be at a higher risk for exhibiting comorbid math difficulties than comorbid ADHD symptoms (and vice versa) and that mostly domain-specific risk factors should be considered in cases of co-occurring difficulties with reading and ADHD symptoms.

Across all analyses, the average shared environmental correlations were higher than the average genetic correlations. This pattern of results, supported by the MDM, suggests that shared environmental influences such as home and school contexts, like a poor home literacy environment (LeFevre et al., 2009), serve as general risk factors for learning disabilities.

However, caution should be taken in over-interpreting the genetically-sensitive results because the shared environmental correlations only explain the extent to which shared environmental influences are common between two domains, which is limited by the phenotypic correlation. Specifically, our phenotypic results show that, despite being large, the shared environmental overlap between reading and ADHD symptoms is only explaining a small effect (6% common variance). Conversely, the overlapping shared environmental influences between reading and math are explaining a larger effect (27% common variance). The same logic applies to the genetic correlation.

Based on the large between-study differences, depicted in the forest plots, we investigated the extent to which certain moderators were driving the high variability in the magnitude of the genetic and environmental correlations. In general, we found that specific moderator effects were unique to each bivariate relation, but in general, the differences in effect sizes seemed to be driven by the characteristics of the assessment used to measure reading, ADHD symptoms, and math but not the domain measured. The non-significant moderation by domain was surprising, especially for the overlap of reading and math, because previous work has shown that the comorbidity rates for reading and math disability vary based on the reading and/or math domain measured (Landerl & Moll, 2010; Moll et al., 2018). However, our findings suggest that domain-specific comorbidity rates are likely not driven by domain-specific etiological influences. Instead, the use of specific assessments and response formats appears to influence the degree of etiological overlap between reading and ADHD symptoms and reading and math more than domain.

Another noteworthy and unexpected finding for the reading and ADHD symptom model was that the ADHD component measured was not a significant moderator of the genetic and environmental correlations found. This means that, although the common risk factors across ADHD components may not represent the *same* genetic and environmental risk factors, the degree of common risk factors between reading and ADHD symptoms is the same whether attention, hyperactivity/impulsivity, or overall ADHD is measured. Although the behavioral and genetically-sensitive literatures have provided considerable evidence for a stronger role for attention, in comparison to hyperactivity/impulsivity symptoms, on the association between reading and ADHD symptoms (Masseti et al., 2008; Willcutt et al., 2000, 2007), it appears that even if inattention is more related to reading problems at the behavioral level, it is not driven by a higher degree of overlapping genetic risk factors.

Age was a significant moderator of the genetic and shared environmental associations between reading and ADHD symptoms (but not reading and math), with both genetic and shared environmental influences increasing with age. Although a more pronounced role for genetic effects and diminished role for environmental effects across the lifespan is supported by previous behavioral genetic studies (Little et al., 2017), the increase observed in the current study for the shared environmental influences was unexpected. Since our moderation analyses for grade-level did not follow a logical pattern, the reason behind the differences in magnitude due to age remains unclear.

Our findings for moderation by race also failed to follow a logical pattern. Given the close link between race and SES (McDermott, 1995), we expected that if race were a significant

moderator it would follow the same pattern as high versus low SES, with lower genetic and higher shared environmental correlations for races most commonly associated with low SES (i.e., minorities) and higher genetic and lower shared environmental correlations for races linked to high SES (i.e., Caucasian), but no such pattern emerged. However, the significant moderation by race, in which majority-Caucasian samples showed different correlations than mixed race samples, is worth noting due to the lack of diversity in most twin projects. With the exception of the FTP, most twin project samples are homogenous, with over 90% Caucasian participants. Future twin work should recruit more heterogeneous samples in order to conduct studies that may generalize to more racially-diverse populations and capture differences in genetic and/or environmental influences associated with factors related to race.

A final noteworthy finding was the significant moderation by twin project and nationality for both reading and ADHD symptoms and reading and math. Specifically, U.S.-based samples demonstrated the highest genetic correlations for reading and ADHD symptoms but not for reading and math. In line with this finding, we also found a higher magnitude genetic correlation between reading and ADHD symptoms due to sample and methodological characteristics that were U.S.-specific (e.g., use of the DF method). Notably, the FTP and the FTP-specific assessments (i.e., FCAT and FAIR) also showed the highest magnitude shared environmental correlations between reading and ADHD symptoms, which may be driven by the relatively higher shared environmental variance for achievement measures found in the FTP than in less diverse twin samples (Taylor et al., 2010).

Overall, the significant moderation by project, as well as the other significant moderators that appear to be confounded by project, means that future decisions in the clinical and educational fields should be made across twin projects. For example, the Colorado sample has produced an influential body of work that has driven the general consensus within the field, showing significant differences in the genetic and environmental correlations between reading and ADHD symptoms based on the ADHD component measured. However, our meta-analytic results across all twin projects did not support this finding, potentially due to differences in sample and methodological characteristics (e.g., sample diversity, use of DF analyses), including their selection of twins with clinical reading deficits or ADHD. These results demonstrate that no one twin project should be relied upon as the deciding factor for the genetic and environmental influences on learning disabilities.

This work should be viewed in the context of some limitations. First, there were only a few twin projects that were included in the examination of the association between reading and ADHD symptoms. This is potentially problematic, as it may mean that the current results are biased by unknown factors. Second, although our study sample aggregated all available genetically-sensitive data on the associations studied here, mostly English-speaking children were included and only a handful of countries were represented. This also limits the generalizability of our phenotypic results (Joyner & Wagner, 2019), which only represent a meta-analysis of the phenotypic correlations drawn from the behavioral genetic literature and do not include all non-twin work conducted on the relations examined here. Twin samples are rare and may not be representative of the general population. Our limited sample of genetically-sensitive studies may also be related to the relatively small overlap

found for reading and ADHD symptoms. Samples with clinical levels of ADHD symptoms may have shown different results than our examination of ADHD symptoms on a continuum. Third, there has been recent interest in the overlap of all three skills: reading, math, and ADHD symptoms. Although the results of such an analysis would have been interesting and would have further expanded on the role of etiology in co-occurring learning-related disorders, we were not aware of more than one study that has examined this (Hart et al., 2010). Finally, genetic and environmental correlations do not account for the extent to which the two traits themselves are influenced by genetic and environmental effects. A different statistic, the bivariate heritability, is available which accounts for this, as well as the extent to which the two traits are phenotypically correlated. Future work may find it interesting to meta-analyze this other approach to understanding how traits covary.

Conclusion

Our meta-analytic results are broadly informative for how we study, identify, and treat learning-related deficits moving forward. Based on the small degree of overlap on both the phenotypic and etiological levels, reading and ADHD symptoms appear to be distinct disorders driven by domain-specific risk factors. In contrast, the higher magnitude phenotypic and etiological overlaps between reading and math suggest that their co-occurrences are driven by some common risk factors, in addition to domain-specific influences. Overall, this variability in the estimates of etiological overlap between different assessments, highlights the importance of paying careful attention when choosing screener and diagnostic assessments to identify learning problems. Specifically, efforts to pinpoint and intervene on the sources of children's co-occurring reading and ADHD symptom deficits should focus on domain-specific items, as cross-domain transfer is not likely (Tamm et al., 2017), but measures to identify co-occurring reading and math deficits should include both domain-general and domain-specific skills, as early math skills have been strongly linked to later reading skills (Duncan et al., 2007). Future work should examine if there is a causal connection between difficulties with reading and math.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

*Denotes articles that were coded and included in the present meta-analysis.

ACARA (2016). National assessment program. Australian Curriculum, Assessment and Reporting Authority <http://www.nap.edu.au/>

Achenbach TM, & Edelbrock C (1991). Child behavior checklist. Burlington (Vt), 7.

Adey P, Robertson A, & Venville G (2001). Let's think Windsor: NFER Nelson.

American Psychiatric Association. (2013). Diagnostic and statistical manual of mental disorders (DSM-5®) American Psychiatric Pub.

Beck MD (1974). Achievement test reliability as a function of pupil-response procedures. *Journal of Educational Measurement*, 11(2), 109–114.

- Bennett KS, Hay DA, Piek J, Pearsall-Jones J, Levy F, & Martin N (2006). The Australian Twin ADHD Project: Current status and future directions. *Twin Research and Human Genetics*, 9(6), 718–726. [PubMed: 17254397]
- Boivin M, Brendgen M, Dionne G, Dubois L, Pérusse D, Robaey P, & Vitaro F (2013). The Quebec newborn twin study into adolescence: 15 years later. *Twin Research and Human Genetics*, 16(1), 64–69. [PubMed: 23200437]
- Boomsma DI, De Geus EJ, Vink JM, Stubbe JH, Distel MA, Hottenga JJ, ... & Willemsen G (2006). Netherlands Twin Register: From twins to twin families. *Twin Research and Human Genetics*, 9(6), 849–857. [PubMed: 17254420]
- Borenstein M, Hedges LV, Higgins JPT, & Rothstein HR (2009). *Introduction to Meta-analysis* West Sussex, UK: Wiley
- Byrne B, Delaland C, Fielding-Barnsley R, Quain P, Samuelsson S, Høien T, Corley R, DeFries JC, Wadsworth S, Willcutt E and Olson RK, (2002). Longitudinal twin study of early reading development in three countries: Preliminary results. *Annals of Dyslexia*, 52(1), 47–73.
- *Cheung CH, Wood AC, Paloyelis Y, Arias-Vasquez A, Buitelaar JK, Franke B, ... & Sonuga-Barke EJ (2012). Aetiology for the covariation between combined type ADHD and reading difficulties in a family study: the role of IQ. *Journal of Child Psychology and Psychiatry*, 53(8), 864–873. [PubMed: 22324316]
- Chhabildas N, Pennington BF, & Willcutt EG (2001). A comparison of the neuropsychological profiles of the DSM-IV subtypes of ADHD. *Journal of Abnormal Child Psychology*, 29(6), 529–540. [PubMed: 11761286]
- Compton DL, Miller AC, Elleman AM, & Steacy LM (2014). Have we forsaken reading theory in the name of “quick fix” interventions for children with reading disability?. *Scientific Studies of Reading*, 18(1), 55–73.
- Conners CK, Sitarenios G, Parker JD, & Epstein JN (1998). The revised Conners' Parent Rating Scale (CPRS-R): Factor structure, reliability, and criterion validity. *Journal of Abnormal Child Psychology*, 26(4), 257–268. [PubMed: 9700518]
- Cunningham AE, & Stanovich KE (1990). Assessing print exposure and orthographic processing skill in children: A quick measure of reading experience. *Journal of Educational Psychology*, 82(4), 733.
- *Davis OSP, Kovas Y, Harlaar N, Busfield P, McMillan A, Frances J, Petrill SA, Dale PS and Plomin R, (2008). Generalist genes and the Internet generation: Etiology of learning abilities by web testing at age 10. *Genes, Brain and Behavior*, 7(4), 455–462.
- *Davis OS, Haworth CM, & Plomin R (2009). Learning abilities and disabilities: Generalist genes in early adolescence. *Cognitive neuropsychiatry*, 14(4–5), 312–331. [PubMed: 19634033]
- *Davis OSP, Kovas Y, Harlaar N, Busfield P, McMillan A, Frances J, ... & Plomin R (2008). Generalist genes and the Internet generation: etiology of learning abilities by web testing at age 10. *Genes, Brain and Behavior*, 7(4), 455–462.
- DeFries JC (1997). Colorado learning disabilities research center. *Learning Disabilities: A Multidisciplinary Journal*, 8(1), 7–19.
- DeFries JC, & Fulker DW (1985). Multiple regression analysis of twin data. *Behavior Genetics*, 15(5), 467–473. [PubMed: 4074272]
- de Zeeuw EL, de Geus EJ, & Boomsma DI (2015). Meta-analysis of twin studies highlights the importance of genetic variation in primary school educational achievement. *Trends in Neuroscience Education*, 4(3):69–76.
- Donfrancesco R, Mugnaini D, & Dell'Uomo A (2005). Cognitive impulsivity in specific learning disabilities. *European Child & Adolescent Psychiatry*, 14(5), 270–275. [PubMed: 15981139]
- Dumont R, Willis JO, Veizel K, & Zibulsky J (2013). Wechsler Individual Achievement Test—third edition. In Reynolds CR, Vannest KJ, & Fletcher-Janzen E (Eds.), *Encyclopedia of special education: a reference for the education of children, adolescents, and adults with disabilities and other exceptional individuals* (4th ed.). Hoboken, NJ: Wiley.
- Duncan GJ, Dowsett CJ, Claessens A, Magnuson K, Huston AC, Klebanov P, ... & Sexton H (2007). School readiness and later achievement. *Developmental psychology*, 43(6), 1428–1446. [PubMed: 18020822]

- Dunn LM, & Markwardt FC (1970). Peabody Individual Achievement Test Circle Pines, MN: American Guidance Service.
- DuPaul GJ, Anastopoulos AD, Power TJ, Reid R, Ikeda MJ, & McGoey KE (1998). Parent ratings of attention-deficit/hyperactivity disorder symptoms: Factor structure and normative data. *Journal of Psychopathology and Behavioral Assessment*, 20(1), 83–102.
- Durost WN, Bixler H, Wrightstone GA, Prescott GA, & Balow I (1970). Metropolitan Achievement Test New York.
- Florida Department of Education (2009–2014). Florida Assessments for Instruction in Reading (FAIR) Tallahassee, FL: Author.
- Gathercole SE, & Pickering SJ (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology*, 70(2), 177–194. [PubMed: 10900777]
- Geary DC, & Hoard MK (2001). Numerical and arithmetical deficits in learning-disabled children: Relation to dyscalculia and dyslexia. *Aphasiology*, 15(7), 635–647.
- *Gillis JJ, Gilger JW, Pennington BF, & DeFries JC (1992). Attention deficit disorder in reading-disabled twins: Evidence for a genetic etiology. *Journal of Abnormal Child Psychology*, 20(3), 303–315. [PubMed: 1377727]
- Grasby KL, Byrne B, & Olson RK (2015). Validity of large-scale reading tests: A phenotypic and behavior-genetic analysis. *Australian Journal of Education*, 59(1), 5–21. [PubMed: 27721516]
- *Grasby KL, Coventry WL, Byrne B, Olson RK, & Medland SE (2016). Genetic and environmental influences on literacy and numeracy performance in Australian school children in Grades 3, 5, 7, and 9. *Behavior Genetics*, 46(5), 627–648. [PubMed: 27276978]
- Grenwelle CH (2009). Test Review: Woodcock, RW, Schrank, FA, Mather, N., & McGrew, KS (2007). Woodcock-Johnson III Tests of Achievement, Form C/Brief Battery. Rolling Meadows, IL: Riverside. *Journal of Psychoeducational Assessment*, 27(4), 345–350.
- *Greven CU, Harlaar N, Dale PS, & Plomin R (2011). Genetic overlap between ADHD symptoms and reading is largely driven by inattentiveness rather than hyperactivity/impulsivity. *Journal of the Canadian Academy of Child and Adolescent Psychiatry*, 20(1), 6–14. [PubMed: 21286364]
- *Greven CU, Kovas Y, Willcutt EG, Petrill SA, & Plomin R (2014). Evidence for shared genetic risk between ADHD symptoms and reduced mathematics ability: A twin study. *Journal of Child Psychology and Psychiatry*, 55(1), 39–48. [PubMed: 23731013]
- *Greven CU, Rijdsdijk FV, Asherson P, & Plomin R (2012). A longitudinal twin study on the association between ADHD symptoms and reading. *Journal of Child Psychology and Psychiatry*, 53(3), 234–242. [PubMed: 21819398]
- Haddaway NR, Collins AM, Coughlin D, & Kirk S (2015). The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *PloS one*, 10(9), e0138237. [PubMed: 26379270]
- *Harlaar N, Kovas Y, Dale PS, Petrill SA, & Plomin R (2012). Mathematics is differentially related to reading comprehension and word decoding: Evidence from a genetically sensitive design. *Journal of Educational Psychology*, 104(3), 622–648.
- Hart SA, Logan JA, Thompson L, Kovas Y, McLoughlin G, & Petrill SA (2016). A latent profile analysis of math achievement, numerosity, and math anxiety in twins. *Journal of Educational Psychology*, 108(2), 181–193. [PubMed: 26957650]
- *Hart SA, Petrill SA, Thompson LA, & Plomin R (2009). The ABCs of math: A genetic analysis of mathematics and its links with reading ability and general cognitive ability. *Journal of Educational Psychology*, 101(2), 388–418. [PubMed: 20157630]
- *Hart SA, Petrill SA, & Thompson LA (2010a). A factorial analysis of timed and untimed measures of mathematics and reading abilities in school aged twins. *Learning and Individual Differences*, 20(2), 63–69. [PubMed: 20161680]
- *Hart SA, Petrill SA, Willcutt E, Thompson LA, Schatschneider C, Deater-Deckard K, & Cutting LE (2010b). Exploring how symptoms of attention-deficit/hyperactivity disorder are related to reading and mathematics performance: General genes, general environments. *Psychological Science*, 21(11), 1708–1715. [PubMed: 20966487]

- Haworth C, Harlaar N, Kovas Y, Davis OS, Oliver BR, Hayiou-Thomas ME, Frances J, Busfield P, McMillan A, Dale PS, & Plomin R (2007). Internet cognitive testing of large samples needed in genetic research. *Twin Research and Human Genetics*, 10, 554–563.
- *Haworth CM, Dale PS, & Plomin R (2009). Generalist genes and high cognitive abilities. *Behavior Genetics*, 39(4), 437–445. [PubMed: 19377870]
- *Haworth C, Kovas Y, Harlaar N, Hayiou-Thomas ME, Petrill SA, Dale PS, & Plomin R (2009b). Generalist genes and learning disabilities: A multivariate genetic analysis of low performance in reading, mathematics, language and general cognitive ability in a sample of 8000 12-year-old twins. *Journal of Child Psychology and Psychiatry*, 50(10), 1318–1325. [PubMed: 19573035]
- Hedges LV (1983). A random effects model for effect sizes. *Psychological Bulletin*, 93(2), 388–395.
- Hedges LV, & Olkin I (1985). *Statistical methods for meta-analysis* Orlando: Academic Press.
- Hedges LV, Tipton E, & Johnson MC (2010). Robust variance estimation in meta-regression with dependent effect size estimates. *Research Synthesis Methods*, 1(1), 39–65. [PubMed: 26056092]
- Higgins JP, Thompson SG, Deeks JJ, & Altman DG (2003). Measuring inconsistency in meta-analyses. *BMJ: British Medical Journal*, 327(7414), 557. [PubMed: 12958120]
- Hopper JL (2002). The Australian twin registry. *Twin Research and Human Genetics*, 5(5), 329–336.
- Joyner RE & Wagner RK (2019). Co-Occurrence of reading disabilities and math disabilities: A meta-analysis. *Scientific Studies of Reading*, DOI: 10.1080/10888438.2019.1593420
- Knight BA, & Galletly SA (2006). The Test of Word Reading Efficiency (TOWRE) used in an Australian context. *Australian Journal of Learning Disabilities*, 11(3), 139–146.
- *Knopik VS, Alarcón M, & DeFries JC (1997). Comorbidity of mathematics and reading deficits: Evidence for a genetic etiology. *Behavior Genetics*, 27(5), 447–453. [PubMed: 9336081]
- *Knopik VS, & DeFries JC (1999). Etiology of covariation between reading and mathematics performance: A twin study. *Twin Research and Human Genetics*, 2(3), 226–234.
- Koponen T, Aro M, Poikkeus AM, Niemi P, Lerkkanen MK, Ahonen T, & Nurmi JE (2018). Comorbid fluency difficulties in reading and math: Longitudinal stability across early grades. *Exceptional Children*, 84(3), 298–311.
- *Kovas Y, Harlaar N, Petrill SA, & Plomin R (2005). ‘Generalist genes’ and mathematics in 7-year-old twins. *Intelligence*, 33(5), 473–489. [PubMed: 19319204]
- *Kovas Y, Haworth CMA, Harlaar N, Petrill SA, Dale PS, & Plomin R (2007). Overlap and specificity of genetic and environmental influences on mathematics and reading disability in 10-year-old twins. *Journal of Child Psychology and Psychiatry*, 48(9), 914–922. [PubMed: 17714376]
- Lakes KD, Swanson JM, & Riggs M (2012). The reliability and validity of the English and Spanish Strengths and Weaknesses of ADHD and Normal behavior rating scales in a preschool sample: Continuum measures of hyperactivity and inattention. *Journal of Attention Disorders*, 16(6), 510–516. [PubMed: 21807955]
- Landerl K, Bevan A, & Butterworth B (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition*, 93(2), 99–125. [PubMed: 15147931]
- Landerl K, Fussenegger B, Moll K, & Willburger E (2009). Dyslexia and dyscalculia: Two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology*, 103(3), 309–324. [PubMed: 19398112]
- Landerl K, & Moll K (2010). Comorbidity of learning disorders: prevalence and familial transmission. *Journal of Child Psychology and Psychiatry*, 51(3), 287–294. [PubMed: 19788550]
- Lefavrais P (2006). *Alouette R: test d’analyse de la vitesse de lecture à partir d’un texte*. [Alouette R: analysis test of text-reading speed] Paris, France: Les Editions du Centre de Psychologie Appliquée.
- LeFevre J, Skwarchuck S, Smith-Chant BL, Fast L, Kamawar D, & Bisanz J (2009). Home Numeracy Experiences and Children’s Math Performance in the Early School Years. *Canadian Journal of Behavioural Science*, 41, 55–66.
- Levy F, Hay DA, Bennett KS, & McStephen M (2005). Gender differences in ADHD subtype comorbidity. *Journal of the American Academy of Child & Adolescent Psychiatry*, 44(4), 368–376. [PubMed: 15782084]

- Light JG, & DeFries JC (1995). Comorbidity of reading and mathematics disabilities: Genetic and environmental etiologies. *Journal of Learning Disabilities*, 28(2), 96–106. [PubMed: 7884303]
- *Light JG, DeFries JC, & Olson RK (1998). Multivariate behavioral genetic analysis of achievement and cognitive measures in reading-disabled and control twin pairs. *Human Biology*, 70(2), 215–237. [PubMed: 9549237]
- Lipsey MW, & Wilson DB (2001). *Practical meta-analysis Applied Social Research Methods Series* (Vol. 49). Thousand Oaks, CA: SAGE Publications.
- *Little CW, Hart SA, Schatschneider C, & Taylor J (2016). Examining associations among ADHD, homework behavior, and reading comprehension: A twin study. *Journal of Learning Disabilities*, 49(4), 410–423. [PubMed: 25349092]
- Little CW, Haughbrook R, & Hart SA (2017). Cross-study differences in the etiology of reading comprehension: A meta-analytical review of twin studies. *Behavior Genetics*, 47(1), 52–76. [PubMed: 27630039]
- *Markowitz EM, Willemsen G, Trumbetta SL, van Beijsterveldt TC, & Boomsma DI (2005). The etiology of mathematical and reading (dis)ability covariation in a sample of Dutch twins. *Twin Research and Human Genetics*, 8(6), 585–593. [PubMed: 16354500]
- Markwardt FC (1989). *Peabody individual achievement test-revised: PIAT-R* Circle Pines: American Guidance Service.
- Massetti GM, Lahey BB, Pelham WE, Loney J, Ehrhardt A, Lee SS, & Kipp H (2008). Academic achievement over 8 years among children who met modified criteria for attention-deficit/hyperactivity disorder at 4–6 years of age. *Journal of Abnormal Child Psychology*, 36(3), 399–410. [PubMed: 17940863]
- McDermott PA (1995). Sex, race, class, and other demographics as explanations for children's ability and adjustment: A national appraisal. *Journal of School Psychology*, 33(1), 75–91.
- Moffitt TE, & E-Risk Study Team. (2002). Teen-aged mothers in contemporary Britain. *Journal of Child Psychology and Psychiatry*, 43(6), 727–742. [PubMed: 12236608]
- Moll K, Kunze S, Neuhoﬀ N, Bruder J, & Schulte-Körne G (2014). Specific learning disorder: Prevalence and gender differences. *PLoS one*, 9(7), e103537. [PubMed: 25072465]
- Moll K, Landerl K, Snowling MJ, & Schulte-Körne G (2018). Understanding comorbidity of learning disorders: Task-dependent estimates of prevalence. *Journal of Child Psychology and Psychiatry*
- Naglieri JA, Goldstein S, Delauder BY, & Schwebach A (2005). Relationships between the WISC-III and the Cognitive Assessment System with Conners' rating scales and continuous performance tests. *Archives of Clinical Neuropsychology*, 20(3), 385–401. [PubMed: 15797174]
- Nanda AO, Greenberg D, & Morris RD (2014). Reliability and validity of the CTOPP Elision and Blending Words subtests for struggling adult readers. *Reading and Writing*, 27(9), 1603–1618.
- Newton PE (2009). The reliability of results from national curriculum testing in England. *Educational Research*, 51(2), 181–212.
- Oliver BR, & Plomin R (2007). Twins' Early Development Study (TEDS): A multivariate, longitudinal genetic investigation of language, cognition and behavior problems from childhood through adolescence. *Twin Research and Human Genetics*, 10(1), 96–105. [PubMed: 17539369]
- *Paloyelis Y, Rijdsdijk F, Wood AC, Asherson P, & Kuntsi J (2010). The genetic association between ADHD symptoms and reading difficulties: The role of inattentiveness and IQ. *Journal of Abnormal Child Psychology*, 38(8), 1083–1095. [PubMed: 20556504]
- Pelham WE Jr., Fabiano GA, & Massetti GM (2005). Evidence-based assessment of attention deficit hyperactivity disorder in children and adolescents. *Journal of Clinical Child and Adolescent Psychology*, 34(3), 449–476. [PubMed: 16026214]
- Pelham WE Jr., Gnagy EM, Greenslade KE, & Milich R (1992). Teacher ratings of DSM-III-R symptoms for the disruptive behavior disorders. *Journal of the American Academy of Child & Adolescent Psychiatry*, 31(2), 210–218. [PubMed: 1564021]
- Pennington BF (2006). From single to multiple deficit models of developmental disorders. *Cognition*, 101(2), 385–413. [PubMed: 16844106]
- Pennington BF, Groisser D, & Welsh MC (1993). Contrasting cognitive deficits in attention deficit hyperactivity disorder versus reading disability. *Developmental Psychology*, 29(3), 511.
- Pépin M, & Loranger M (1999). Test d'habiletés en lecture (THAL) Le Réseau Psychotech..

- Peterson RL, Boada R, McGrath LM, Willcutt EG, Olson RK, & Pennington BF (2017). Cognitive prediction of reading, math, and attention: Shared and unique influences. *Journal of Learning Disabilities*, 50(4), 408–421. [PubMed: 26825667]
- Plomin R, DeFries JC, Knopik VS, & Neiderhiser JM (2013). *Behavioral Genetics (6th Ed.)*. New York, New York: Worth Publishers.
- Plomin R, & Kovas Y (2005). Generalist genes and learning disabilities. *Psychological Bulletin*, 131(4), 592–617. [PubMed: 16060804]
- *Plourde V, Boivin M, Forget-Dubois N, Brendgen M, Vitaro F, Marino C, ... & Dionne G (2015). Phenotypic and genetic associations between reading comprehension, decoding skills, and ADHD dimensions: Evidence from two population-based studies. *Journal of Child Psychology and Psychiatry*, 56(10), 1074–1082. [PubMed: 25683090]
- *Plourde V, Boivin M, Brendgen M, Vitaro F, & Dionne G (2017). Phenotypic and genetic associations between reading and attention-deficit/hyperactivity disorder dimensions in adolescence. *Development and Psychopathology*, 29(4), 1215–1226. [PubMed: 28031065]
- Polderman TJC, Derks EM, Hudziak JJ, Verhulst FC, Posthuma D, & Boomsma DI (2007). Across the continuum of attention skills: A twin study of the SWAN ADHD rating scale. *Journal of Child Psychology & Psychiatry*, 48(11), 1080–1087. [PubMed: 17995483]
- *Polderman TJ, Huizink AC, Verhulst FC, van Beijsterveldt CE, Boomsma DI, & Bartels M (2011). A genetic study on attention problems and academic skills: Results of a longitudinal study in twins. *Journal of the Canadian Academy of Child and Adolescent Psychiatry*, 20(1), 22–34. [PubMed: 21286366]
- Purvis KL, & Tannock R (2000). Phonological processing, not inhibitory control, differentiates ADHD and reading disability. *Journal of the American Academy of Child & Adolescent Psychiatry*, 39(4), 485–494. [PubMed: 10761351]
- Reich W (2000). Diagnostic interview for children and adolescents (DICA). *Journal of the American Academy of Child & Adolescent Psychiatry*, 39(1), 59–66. [PubMed: 10638068]
- Roscigno VJ, & Ainsworth-Darnell JW (1999). Race, cultural capital, and educational resources: Persistent inequalities and achievement returns. *Sociology of Education*, 72(3), 158–178.
- *Rosenberg J, Pennington BF, Willcutt EG, & Olson RK (2012). Gene by environment interactions influencing reading disability and the inattentive symptom dimension of attention deficit/hyperactivity disorder. *Journal of Child Psychology and Psychiatry*, 53(3), 243–251. [PubMed: 21884522]
- Samuelsson S, Byrne B, Olson RK, Hulslander J, Wadsworth S, Corley R, ... & DeFries JC (2008). Response to early literacy instruction in the United States, Australia, and Scandinavia: A behavioral-genetic analysis. *Learning and Individual Differences*, 18(3), 289–295. [PubMed: 19122888]
- Shaffer D, Fisher P, Lucas CP, Dulcan MK, & Schwab-Stone ME (2000). NIMH Diagnostic Interview Schedule for Children Version IV (NIMH DISC-IV): Description, differences from previous versions, and reliability of some common diagnoses. *Journal of the American Academy of Child & Adolescent Psychiatry*, 39(1), 28–38. [PubMed: 10638065]
- Shafir U, & Siegel LS (1994). Subtypes of learning disabilities in adolescents and adults. *Journal of Learning Disabilities*, 27(2), 123–124. [PubMed: 8195688]
- Spencer M, Wagner RK, Schatschneider C, Quinn JM, Lopez D, & Petscher Y (2014). Incorporating RTI in a hybrid model of reading disability. *Learning Disability Quarterly*, 37(3), 161–171. [PubMed: 25422531]
- Sprenger-Charolles L, Colé P, Kipffer-Piquard A, Pinton F, & Billard C (2009). Reliability and prevalence of an atypical development of phonological skills in French-speaking dyslexics. *Reading and Writing*, 22(7), 811–842.
- *Stevenson J, Pennington BF, Gilger JW, DeFries JC, & Gillis JJ (1993). Hyperactivity and spelling disability: Testing for shared genetic aetiology. *Journal of Child Psychology and Psychiatry*, 34(7), 1137–1152. [PubMed: 8245138]
- Swanson J, Schuck S, Mann M, Carlson C, Hartman C, & Sergeant J (2001). Over-identification of extreme behavior in the evaluation and diagnosis of ADHD/HKD Available at <http://www.adhd.net>.

- Swanson JM, Schuck S, Porter MM, Carlson C, Hartman CA, Sergeant JA, ... & Wigal T (2012). Categorical and Dimensional Definitions and Evaluations of Symptoms of ADHD: History of the SNAP and the SWAN Rating Scales. *The International journal of Educational and Psychological Assessment*, 10(1), 51–70. [PubMed: 26504617]
- Tamm L, Denton CA, Epstein JN, Schatschneider C, Taylor H, Arnold LE, ... & Maltinsky J (2017). Comparing treatments for children with ADHD and word reading difficulties: A randomized clinical trial. *Journal of consulting and clinical psychology*, 85(5), 434–446. [PubMed: 28333510]
- Taylor JE, Hart SA, Mikolajewski AJ, & Schatschneider C (2013). An update on the Florida state twin registry. *Twin Research and Human Genetics*, 16(1), 471–475. [PubMed: 23067863]
- Taylor J, Roehrig AD, Hensler BS, Connor CM, & Schatschneider C (2010). Teacher quality moderates the genetic effects on early reading. *Science*, 328(5977), 512–514. [PubMed: 20413504]
- *Thompson LA, Detterman DK, & Plomin R (1991). Associations between cognitive abilities and scholastic achievement: Genetic overlap but environmental differences. *Psychological Science*, 2(3), 158–165.
- Tipton E, & Pustejovsky JE (2015). Small-sample adjustments for tests of moderators and model fit using robust variance estimation in meta-regression. *Journal of Educational and Behavioral Statistics*, 40(6), 604–634.
- Torgesen JK, Rashotte CA, & Wagner RK (1999). *TOWRE: Test of word reading efficiency* Austin, TX: Pro-ed.
- Treloar JM (1994). Wechsler individual achievement test (WIAT). *Intervention in School and Clinic*, 29(4), 242–246.
- Tremblay RE, Desmarais-Gervais L, Gagnon C, & Charlebois P (1987). The Preschool Behaviour Questionnaire: Stability of its factor structure between cultures, sexes, ages and socioeconomic classes. *International Journal of Behavioral Development*, 10(4), 467–484.
- *Trzesniewski KH, Moffitt TE, Caspi A, Taylor A, & Maughan B (2006). Revisiting the association between reading achievement and antisocial behavior: New evidence of an environmental explanation from a twin study. *Child Development*, 77(1), 72–88. [PubMed: 16460526]
- Tucker-Drob EM, & Bates TC (2016). Large cross-national differences in gene $\times$ socioeconomic status interaction on intelligence. *Psychological Science*, 27(2), 138–149. [PubMed: 26671911]
- Vargas I, Friedman NP, & Drake CL (2015). Vulnerability to stress-related sleep disturbance and insomnia: Investigating the link with comorbid depressive symptoms. *Translational Issues in Psychological Science*, 1(1), 57–66. [PubMed: 25914895]
- Vlug KF (1997). Because every pupil counts: The success of the pupil monitoring system in The Netherlands. *Education and Information Technologies*, 2(4), 287–306.
- *Wadsworth SJ, DeFries JC, Fulker DW, & Plomin R (1995). Cognitive ability and academic achievement in the Colorado Adoption Project: A multivariate genetic analysis of parent-offspring and sibling data. *Behavior Genetics*, 25(1), 1–15. [PubMed: 7755514]
- Wadsworth SJ, DeFries JC, Willcutt EG, Pennington BF, & Olson RK (2015). The Colorado longitudinal twin study of reading difficulties and ADHD: Etiologies of comorbidity and stability. *Twin Research and Human Genetics*, 18(6), 755–761. [PubMed: 26537134]
- Wagner RK, Torgesen JK, & Rashotte CA (1999). *Comprehensive Test of Phonological Processing (CTOPP)* Austin, TX: PRO-ED, Inc.
- Watson SM, & Gable RA (2013). Unraveling the complex nature of mathematics learning disability: Implications for research and practice. *Learning Disability Quarterly*, 36(3), 178–187.
- Wendling BJ, Schrank FA, & Schmitt AJ (2007). *Educational Interventions Related to the Woodcock-Johnson III Tests of Achievement (Assessment Service Bulletin No. 8)* Rolling Meadows, IL: Riverside Publishing.
- *Willcutt EG, Betjemann RS, McGrath LM, Chhabildas NA, Olson RK, DeFries JC, & Pennington BF (2010). Etiology and neuropsychology of comorbidity between RD and ADHD: The case for multiple-deficit models. *Cortex*, 46(10), 1345–1361. [PubMed: 20828676]

- *Willcutt EG, Betjemann RS, Wadsworth SJ, Samuelsson S, Corley R, DeFries JC, ... & Olson RK (2007a). Preschool twin study of the relation between attention-deficit/hyperactivity disorder and prereading skills. *Reading and Writing*, 20(1–2), 103–125.
- Willcutt EG, Boada R, Riddle MW, Chhabildas N, DeFries JC, & Pennington BF (2011). Colorado Learning Difficulties Questionnaire: validation of a parent-report screening measure. *Psychological Assessment*, 23(3), 778–791. [PubMed: 21574721]
- Willcutt EG, & Pennington BF (2000). Psychiatric comorbidity in children and adolescents with reading disability. *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, 41(8), 1039–1048.
- Willcutt EG, Pennington BF, Boada R, Ogline JS, Tunick RA, Chhabildas NA, & Olson RK (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology*, 110(1), 157–172. [PubMed: 11261391]
- *Willcutt EG, Pennington BF, & DeFries JC (2000). Etiology of inattention and hyperactivity/impulsivity in a community sample of twins with learning difficulties. *Journal of Abnormal Child Psychology*, 28(2), 149–159. [PubMed: 10834767]
- *Willcutt EG, Pennington BF, Olson RK, & DeFries JC (2007b). Understanding comorbidity: A twin study of reading disability and attention-deficit/hyperactivity disorder. *American Journal of Medical Genetics Part B: Neuropsychiatric Genetics*, 144(6), 709–714.
- Willcutt EG, Petrill SA, Wu S, Boada R, DeFries JC, Olson RK, & Pennington BF (2013). Comorbidity between reading disability and math disability: Concurrent psychopathology, functional impairment, and neuropsychological functioning. *Journal of Learning Disabilities*, 46(6), 500–516. [PubMed: 23449727]
- Woodcock RW, Mather N, McGrew KS, & Wendling BJ (2001). *Woodcock-Johnson III Tests of Cognitive Abilities* Ithasca, IL: Riverside Publishing Company.

Figure 1.
Article selection flow chart.

Figure 2. Forest plot of bivariate genetic correlations (r_A) between reading and ADHD symptoms.

Figure 3.
Forest plot of bivariate shared environmental correlations (r_C) between reading and ADHD symptoms.

Figure 4.
Forest plot of bivariate nonshared environmental correlations (r_E) between reading and ADHD symptoms.

Figure 5.
Forest plot of bivariate genetic correlations (r_A) between reading and math.

Figure 6.

Forest plot of bivariate shared environmental correlations (r_C) between reading and math.

Figure 7.
Forest plot of bivariate nonshared environmental correlations (r_E) between reading and math.

Table 1.

Inclusionary criteria for article selection and coding

1. The study must use a genetically-sensitive (i.e., twin or family) research design.
2. The study must either directly report the genetic and/or environmental correlation between reading and ADHD symptoms and/or reading and math, or: <div><div>a. Provide path estimates that can be converted into correlations with the formula: $r_g = \frac{a_{21}a_{11}}{\sqrt{a_{11}^2 * (a_{21}^2 + a_{22}^2)}}$, or</div><div>b. Report DeFries-Fulker estimates that can be converted with the formula: $r_g = \sqrt{\frac{B_{2(xy)}B_{2(yx)}}{B_{2(x)}B_{2(y)}}}$</div></div>
3. When a study uses a model comparison approach and reports the results of several models that may be relevant to the present study, only the chosen final model will be coded.
4. The assessment used for reading, ADHD symptoms, or math will be coded as a reading, ADHD symptom, or math composite when many different assessments were used, but not when multiple subtests from the same assessment were included.

Table 2.

Article coding key

Category	Value Description
Publication Type	1 = peer reviewed journal article 2 = thesis or dissertation 3 = unpublished data
Study Type	1 = twins 2 = twins and siblings 3 = twins and adoption 4 = nontwins and parents 5 = family design
Twin Project	1 = FTP 2 = TEDS (E-risk) 3 = CLDRC 4 = WRRMP 5 = ILTS 6 = MISTRA 7 = NLSY 8 = Other 9 = LTS 10 = NTR 11 = ATP 12 = QTS
Clinical Status	0 = 75% or more typically-developing 1 = 75% or more had reading disability 2 = 75% or more had math disability 3 = mix of typically-developing students and students with a learning disability 4 = 75% or more comorbid reading and math disability 5 = Other
Race (Reported/Inferred)	0 = 75% or more Caucasian 1 = 75% or more Black/African American 2 = 75% or more Hispanic 3 = 75% or more Asian 4 = Other 5 = Mixed (more than one race) 6 = Not Reported
Nationality	1 = USA 2 = Australian 3 = Scandinavian 4 = UK 5 = More than one nationality 6 = Canadian

Category	Value Description
Grade-Level	7 = Dutch
	8 = Other
	9 = Not Applicable
	0 = Preschool/Kindergarten
	1 = 1 st grade
	2 = 2 nd grade
	3 = 3 rd grade
	4 = 4 th grade
	5 = 5 th grade
	6 = 6 th grade
	7 = 7 th grade
	8 = 8 th grade
	9 = 9 th grade
	10 = 10 th grade
	11 = 11 th grade
	12 = 12 th grade
	13 = Mixed elementary
ADHD Assessment	14 = Mixed middle school
	15 = Mixed high school
	16 = Undergraduates
	17 = Not Applicable
	1 = DBRS
	2 = DICA
	3 = Revised Conner's
	4 = DCB
	5 = SWAN
	6 = Other
	7 = ATBRS
	8 = DBD
	9 = ADHD composite (more than one ADHD assessment)
	10 = Not Applicable
	11 = CBCL
	12 = SBQ
Reading Assessment	1 = PIAT reading subtest
	2 = WJ-Reading subtest
	3 = Reading Composite (more than one reading assessment)
	4 = Netherlands PMS reading subtest
	5 = UKNC reading subtest
	6 = Other
	7 = FCAT reading subtest
	8 = FAIR

Category	Value Description
Reading Domain	9 = GOAL reading subtest
	10 = TOWRE
	11 = Alouette-R reading subtest
	12 = WIAT reading subtest
	14 = Reading Difficulties Questionnaire
	15 = CTOPP RAN
	16 = NAPLAN
	17 = OCT
	18 = THAL
	1 = Reading Comprehension
Reading Assessment Format	2 = Reading Fluency
	3 = Spelling (includes Orthographic Choice, Print Knowledge)
	4 = Phonological Awareness
	5 = Decoding
	6 = Other (includes Vocab, Grammar, Syntax, RAN)
	7 = Multiple (more than one reading domain)
	8 = Not Applicable
	9 = Difficulties with Reading
	1 = Cloze/Short Answer
	2 = Multiple Choice
Math Assessment	3 = Mixed (more than one format)
	4 = Rating Scale
	5 = Retell (includes spoken/oral response)
	6 = Timed
	7 = True/False
	8 = Other
	9 = Not Applicable
	1 = PIAT math subtest
	2 = WJ-Math subtest
	3 = Netherlands PMS math subtest
Math Domain	4 = Math Composite (more than one math assessment)
	5 = UKNC math subtest
	6 = Other
	7 = GOAL math subtest
	8 = MAT math subtest
	9 = WIAT math subtest
	10 = Not Applicable
	11 = NFER 5–14 Mathematics Series
	12 = NAPLAN
	1 = Math fluency
	2 = Calculation
	3 = Spatial Ability

Category	Value Description
Math Assessment Format	4 = Problem Solving
	5 = Quantitative Concepts (includes Numeracy, Number Line, Dots Task)
	6 = Other
	7 = Multiple (more than one math domain)
	8 = Not Applicable
	9 = Math Difficulties
	1 = Cloze/Short Answer
	2 = Multiple Choice
	3 = Mixed (more than one format)
	4 = Rating Scale
DeFries-Fulker Method	5 = Timed
	6 = True/False
	7 = Other
	8 = Not Applicable
	9 = Parent-Report
	10 = Teacher-Report
	1 = Yes
	2 = No
ADHD Component	1 = Overall ADHD
	2 = Hyperactivity/Impulsivity
	3 = Inattention
	4 = Not Applicable

Note. For Reading Assessment, the value “13” was unintentionally skipped in the coding scheme used.

Table 3.**Descriptions of Twin Projects and Reading, ADHD symptom, and Math Assessments**

Description	
Twin Projects	
Florida Twin Project on Reading, (FTP)	FTP is a cohort-sequential longitudinal twin study, with data on achievement, behavior, and the home and school environments for 5200 ethnically- and racially-diverse school-aged twins across Florida ¹ .
Twins Early Development Study (TEDS)	TEDS is a UK-based longitudinal twin study with over 13,000 twin-pairs, 90% of which identify as Caucasian, which includes data on health, behavior, and cognitive abilities ² .
Colorado Longitudinal Twin Study of Reading Disability (CLTSRD)	The CLTSRD is a longitudinal study on a subset of twins and siblings from the Colorado Learning Disabilities Research Center (CLDRC) ³ . It includes diagnostic, behavioral, cognitive and achievement data on roughly 2330 predominantly Caucasian (>90%) twins ⁴ .
Western Reserve Reading and Math Project (WRRMP)	The WRRMP is an Ohio-based longitudinal twin project with more than 400 twin family participants ⁵ . It spans 7 years, with data on reading, math, and other cognitive outcomes for a predominantly Caucasian (>90%) and socioeconomically diverse sample ⁶ .
International Longitudinal Twin Study (ILTS)	The ILTS is a longitudinal twin study that recruited participants in preschool and followed their development through the first three years of formal schooling in the US, Australia, Norway, and Sweden ^{7,8} . It includes data on reading, and its related skills, as well as other cognitive and achievement outcomes ⁹ .
Netherlands Twin Register (NTR)	The NTR is comprised of two groups of twins: young twins (YNTR) and adolescent and young adult twins (ANTR) ¹⁰ . The NTR includes over 50,000 twins and their families' data on cognitive skills, brain imaging, ADHD, and other outcomes ¹⁰ .
Australian Twin ADHD Project (ATAP)	ATAP is a cohort-sequential longitudinal twin project aimed at understanding the development of ADHD and related factors in twins and their siblings ¹¹ . The ATAP includes parent- and child-reported data on behavior, development, and education for over 6,000 twin families ¹¹ .
Environmental Risk Longitudinal Twin Study (E-risk)	E-risk is a cohort-sequential longitudinal twin study following an epidemiological sample of 1116 twin families that were drawn from TEDS at two consecutive birth cohorts (1994 and 1995) ¹¹ . It includes parent- and teacher-reported data on child health and behavior, cognitive development, family structure, and mental health ¹² .
Quebec Newborn Twin Study (QNTS)	QNTS is a longitudinal follow-up study on twin cohorts born from 1995–1998 in Canada ¹³ . The sample includes 662 twin families with data on individual differences in cognition, behavior, socio-emotional development, school achievement, health outcomes, child environments (i.e. family-SES, parent- and peer-relationships), brain imaging, and nutrition, among other variables ¹³ .
Australian Twin Registry (ATR)	ATR is a large volunteer twin registry established in the 1970s, with more than 30,000 registered twins of all ages ¹⁴ . The ATR includes basic demographic and family health data on registrants ¹⁴ .
Reading Assessments	
Peabody Individual Achievement Test (PIAT)	The PIAT is a US nationally norm-referenced assessment that measures many achievement domains, including reading comprehension and word recognition ¹⁵ . The reading comprehension subtest is comprised of 82 items and assesses literal comprehension of sentences using multiple-choice picture format ¹⁶ . Test-retest reliability is reported at .64 ¹⁵ and .86–.94 for the revised version ¹⁶ .
Netherlands Pupil Monitoring System (PMS)	The PMS is an assessment used by almost 95% of Netherlands schools ¹⁷ , which was created by the National Institute for Educational Measurement and tracks student progress from 4–12 years old to determine if student performance and teacher instruction meet national standards ¹⁸ . This tracking system utilizes student portfolios for each primary school subject, including reading comprehension, decoding, and math ¹⁸ .
United Kingdom National Curriculum reading test (UKNC Reading)	The UK National Curriculum uses teacher ratings of students' English, science, and mathematics skills at 7, 11, and 14 years-old to compare student performance based on their age to nationally expected performance levels outlined in the UK National Curriculum on a 4-point Likert scale that ranges from below to above average ¹⁹ . The decision consistency for each level (i.e., test-retest reliability) is 80–98% ²⁰ .

	Description
Comprehensive Test of Phonological Processing Rapid Automatized Naming (CTOPP RAN)	The CTOPP ²¹ is comprised of seven core subtests, which combine to produce three composite scores: the phonological awareness composite score, the phonological memory composite score, and the rapid automatized naming (RAN) composite score. The RAN composite score is calculated from four subtests, which measure the ability to rapidly name digits, letters, colors and objects, respectively. Average internal reliability and alternate forms reliability exceeds 0.80, with test-retest reliability ranging between .70 and .92 ²² .
Florida Comprehensive Assessment Test (FCAT)	The FCAT is an annual standardized achievement test in Florida that measures reading comprehension using multiple choice questions based on narrative and expository text passages ²³ . Alpha reliability is reported at .90 ²³ .
Florida Assessment for Instruction in Reading (FAIR)	The FAIR is a system of computer-based assessments designed to support reading instruction in Florida ²⁴ . The Maze task is the reading fluency subtest, which requires students to choose, from a list, which three words are best to fill in blanks within a passage. Alpha reliability is reported to be .77–.90 ²⁴ . The Reading Comprehension assessment requires students to answer questions related to text passages that vary in length and difficulty ²³ . Alpha reliability is reported to be .88–.92 ²⁴ .
Global Online Assessment for Learning (GOAL)	The GOAL Formative Assessment in Literacy Key Stage 3 is a UK-based reading comprehension assessment that captures both literal and inferential comprehension skills in multiple-choice format, using prompts made up of words, sentences, and short paragraphs ²⁵ . The GOAL has a reported alpha reliability of .91 ²⁶ .
Test d'habilités en lecture (THAL; "Reading skills test")	THAL ²⁷ is a computerized French-language standardized reading skills test with subtests for phonetic decoding and reading comprehension. The phonetic decoding subtest is comprised of 50 items that require a child to indicate whether or not a phoneme presented in a stimulus word is also found in a comparison word and shows an internal consistency of .93 ²⁸ . The reading comprehension subtest includes 40 items that require children to choose the best missing words to complete a silently read short text and has a reported internal consistency of .98 ²⁸ .
Test of Word Reading Efficiency (TOWRE)	The TOWRE is a norm-referenced reading assessment comprised of two subtests: The Sight Word Efficiency (SWE) subtest and the Phonemic Decoding Efficiency (PDE) subtest ²⁹ . They both measure how efficiently participants read mono- and multi-syllabic words in a maximum of 3 minutes, with the SWE using a list containing 104 real words ³¹ and the PDE using a list of 63 nonwords ³⁰ . The TOWRE is normed for US readers 6–24 years of age and has reported reliability >.94 ³⁰ .
Woodcock Johnson-III Tests of Achievement reading subtest (WJ-Reading)	The WJ is a standardized achievement measure comprised of 22 separate tests of cognitive performance ³¹ . Subtests identified in the current study sample included: Passage Comprehension, which measures reading comprehension using 43 items by presenting students with a series of short passages and requiring them to fill in missing words within the text ³¹ and Letter Word Identification, which requires students to read a list of increasingly difficult words aloud out of 76 total items until six consecutive errors are made ³² . Split-half reliabilities for these measures range between .88 and .96 ³³ .
Alouette-R	The Alouette-R ³⁴ is a standardized French reading fluency measure for ages 6–16 that requires participants to read connected text as quickly and accurately as possible in a maximum of 3 minutes ³⁴ . It is often used to group children into reading levels and to diagnose dyslexia ³⁵ .
Wechsler Individual Achievement Test (WIAT)	The WIAT is a norm-referenced achievement measure for children 4–19 years of old ³⁶ that assesses four content areas, including reading and math. Reading subtests include Early Reading Skills (i.e., letter naming and phonological skills), Word Reading, Pseudo-word Decoding, Reading Comprehension, and Oral Reading Fluency ³⁷ . Subscales can be scored independently or combined to calculate composite reading and math scores. Reported inter-item reliability ranges between .69 and .97 ³⁷ .
National Assessment Program, Literacy and Numeracy (NAPLAN Reading)	The NAPLAN is an Australian standardized assessment that tests both literacy and numeracy skills in the third, fifth, seventh, and ninth years of school based on national benchmarks set by the Australian Curriculum and Assessment Authority ³⁸ . The literacy assessments measure student performance in reading, writing, spelling, grammar and punctuation in paper-and-pencil format. Alpha reliability for literacy and numeracy subtests range between .84 and .93 ³⁸ .
Reading Difficulties Questionnaire (RDQ)	The RDQ ³⁹ is a 6-item measure that asks parents to report on a 5-point Likert scale, ranging from "never/not at all" to "always/a great deal", the extent to which their child reads slowly and below expectancy level, and requires extra help at school, and the degree of difficulty their child has with spelling and sounding out words. The scale shows excellent internal consistency (alpha = .90) and high inter-rater and test-retest reliabilities (.83 and .81, respectively) ³⁹ .

	Description
Orthographic Choice Task (OCT)	The OCT uses 25 items to measure students' spelling ability by requiring them to choose the correct letter string out of two choices that sound alike (e.g., bote vs. boat), one correct and one nonsense alternative. It has a split-half reliability of .93 ⁴⁰ .
ADHD symptom Assessments	
Direct Behavior Rating Scale (DBRS)	The DBRS measures ADHD based on the 18 ADHD symptoms outlined in the <i>DSM-V</i> , with 9 items corresponding to inattention and 9 that correspond to hyperactivity/impulsivity ⁴¹ . It can be parent-, teacher-, or practitioner-administered and asks students to rate their experience of ADHD symptoms over the last 6 months on a 4-point Likert scale ⁴² . The internal reliability for the Inattention and Hyperactivity/Impulsivity subscales is reported to be approximately .90 ⁴¹ .
Diagnostic Interview for Children and Adolescents (DICA)	The DICA is an ADHD measure that can be administered as a semi-structured interview or via computer. It includes three versions: one for 6–12 year-olds, one for 13–18 year-olds, and a parent-interview version. Reliability for symptom count on the ADHD scale has been reported at 0.65 for student respondents, and .84 for parent respondents ⁴³ .
Revised Conner's Parent Rating Scale (Revised Conner's)	The Revised Conner's is a North American-normed comprehensive assessment of child behavior ⁴⁴ . The Revised Conner's measures 7 separate factors, including a hyperactivity/impulsivity factor. Alpha reliability ranges between .73 and .95 ⁴⁵ .
Strengths and Weaknesses of ADHD-Symptoms and Normal Behavior Scale (SWAN)	The SWAN ⁴⁶ is a 30-item measure, informed by the 18 ADHD symptoms listed in the <i>DSM-V</i> . It is scored on a 7-point Likert scale, with nine of the scale items corresponding to Inattention and nine items corresponding to Hyperactivity/Impulsivity ⁴⁷ . Higher scores on the SWAN indicate more problems with attention. Cronbach's alpha reliability for SWAN-Attention is reported at .92 and .94 for SWAN-Hyperactivity ⁴⁸ .
Disruptive Behavior Disorder scale (DBD)	The DBD scale ⁴⁹ is a diagnostic checklist for <i>DSM-V</i> symptoms of ADHD and other behavior disorders made up of 42 total items, 18 of which correspond to ADHD symptoms. Parents or teachers rate child behavior on a 4-point Likert scale, with higher scores corresponding to more ADHD symptoms. Alpha reliability for the DBD is reported to be .91–.96 ⁴⁹ .
Child Behavior Check List (CBCL)	The CBCL ⁵⁰ Attention Problem Scale is a 20-item measure that asks parents to report on a 3-point Likert scale on the amount and quality of child participation in sports, hobbies, games, activities, jobs, chores, and friendships, performance at school, and how well child plays and works alone and with others ⁵⁰ .
Social Behavioral Questionnaire (SBQ)	The SBQ is a parent-report ADHD instrument used for children and adolescents that rates child ADHD dimensions over the past 6 months on a 3-point Likert scale (very true to not true at all) ⁵¹ . It includes 3 items for inattention, which have a reported alpha of .84 and 5 items for hyperactivity/impulsivity, which have a reported alpha of .77 ⁵² .
Math Assessments	
United Kingdom National Curriculum math test (UKNC Math)	The UK National Curriculum uses teacher ratings of students' English, science, and mathematics skills at 7, 11, and 14 years-old to compare student performance based on their age to nationally expected performance levels outlined in the UK National Curriculum on a 4-point Likert scale that ranges from below to above average ¹⁹ . The decision consistency for each level (i.e., test-retest reliability) is 80–98% ²⁰ .
Metropolitan Achievement Test (MAT)	The MAT is a norm-referenced achievement test with diagnostic math subtests for arithmetic, math concepts and problem solving, and math communication ⁵³ . Reliability is reported between .87 and .95 for these subtests ⁵⁴ .
Woodcock Johnson Tests of Achievement-III math subtest (WJ-Math)	The WJ is a standardized achievement measure comprised of 22 separate tests of cognitive performance ³¹ . The math subtests in the present sample include Quantitative Concepts, which measures student knowledge of mathematical concepts with orally presented questions on math facts ³² ; Math Fluency, which assesses children's ability to correctly answer as many addition, subtraction, and multiplication problems out of 160 as possible within a three minute limit; Applied Problems, which includes 63 items that measure students' ability to solve orally-presented items on counting objects, probability, and algebra; and Calculation, which includes 45 items on math calculations, that range from writing single numbers to performing calculus operations ³² . Split-half reliabilities for these measures range between .88 and .96 ³³ .

	Description
National Foundation for Educational Research 5–14 Mathematics Series (NFER 5–14)	The NFER 5–14 Mathematics Series is a UK computer- or paper-administered math assessment that is based on UK curriculum requirements ⁵⁵ . Subtests include Understanding Numbers, which uses 33 items to assess students' ability to solve problems requiring numeric and algebraic processes and has an alpha reliability of .90; Numerical Processes, which includes 25 items assessing non-numerical concepts, like rotational symmetry and has an alpha reliability of .87; and Computation and Knowledge, which includes 37 items on students' ability to recall math facts and terms and perform simple calculations, with an alpha reliability of .93 ⁵⁶ .
National Assessment Program, Literacy and Numeracy (NAPLAN Math)	The NAPLAN is an annual Australian standardized measure of both literacy and numeracy skills ³⁸ . The Numeracy assessment tests children's knowledge and application of mathematical concepts, such as algebra, functions, patterns, space, measurement, probability, and data. This assessment is traditionally a paper and pencil assessment, given in the third, fifth, seventh, and ninth years of school in Australia and is based on national benchmarks set by the Australian Curriculum and Assessment Authority ⁴¹ . Alpha reliability for literacy and numeracy subtests range between .84 and .93 ³⁸ .

Note.

¹Taylor, Hart, Mikolajewski, & Schatschneider, 2013;

²Oliver & Plomin, 2007;

³DeFries, 1997;

⁴Vargas, Friedman, & Drake, 2015;

⁵Hart et al., 2009;

⁶Hart et al., 2016;

⁷Byrne et al., 2002;

⁸Grasby et al., 2015;

⁹Samuelsson et al., 2008;

¹⁰Boomsma et al., 2006;

¹¹Bennett et al., 2006;

¹²Moffit & the E-Risk Study Team, 2002;

¹³Boivin et al., 2013;

¹⁴Hopper, 2002;

¹⁵Dunn & Markwardt, 1970;

¹⁶Markwardt, 1989;

¹⁷Polderman et al., 2011;

¹⁸Vlug, 1997;

¹⁹Gathercole & Pickering, 2000;

²⁰Newton, 2009;

²¹Wagner, Torgesen, & Rashotte, 1999;

²²Nanda, Greenberg, & Morris, 2014;

²³Florida Department of Education, 2001;

- ²⁴Florida Department of Education, 2009;
- ²⁵Harlaar, Kovas, Dale, Petrill, & Plomin, 2012;
- ²⁶Haworth et al., 2007;
- ²⁷Pépin & Loranger, 1999;
- ²⁸Plourde et al., 2015;
- ²⁹Torgesen, Rashotte, & Wagner, 1999;
- ³⁰Knight & Galletly, 2006;
- ³¹Woodcock, Mather, McGrew, & Wendling, 2001;
- ³²Wendling, Schrank, & Schmitt, 2007;
- ³³Grenwelge, 2009;
- ³⁴Lefavrais, 2006;
- ³⁵Sprenger-Charolles, Colé, Kipffer-Piquard, Pinton, & Billard, 2009;
- ³⁶Treloar, 1994;
- ³⁷Dumont et al., 2013;
- ³⁸ACARA, 2016;
- ³⁹Willcutt, Boada, Riddle, Chhabildas, DeFries, & Pennington, 2010;
- ⁴⁰Cunningham & Stanovich, 1990;
- ⁴¹DuPaul et al., 1998;
- ⁴²Reich, 2000;
- ⁴³Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000;
- ⁴⁴Conners, Sitarenios, Parker, & Epstein, 1998;
- ⁴⁵Pelham, Fabiano, & Massetti, 2005;
- ⁴⁶Swanson, Schuck, Mann, Carlson, Hartman, & Sergeant, 2001;
- ⁴⁷Polderman et al., 2007;
- ⁴⁸Lakes, Swanson, & Riggs, 2012;
- ⁴⁹Pelham, Gnagy, Greenslade, & Milich, 1992;
- ⁵⁰Achenbach, 1991;
- ⁵¹Tremblay, Desmarais-Gervais, Gagnon, & Charlebois, 1987;
- ⁵²Plourde, Boivin, Brendgen, Vitaro, & Dionne, 2017;
- ⁵³Durost, Bixler, Wrightstone, Prescott, & Balow, 1970;
- ⁵⁴Beck, 1974;
- ⁵⁵Adey, Robertson, & Venville, 2001;
- ⁵⁶Davis et al., 2008;

⁵⁶Levy et al., 2005.

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Table 4.

Results of RVE analyses for genetic, shared environmental, and nonshared environmental bivariate correlations between reading and ADHD.

Study-level	ES	SE	<i>p</i>	Lower CI	Upper CI	τ^2
<i>r</i> A	0.49	0.12	<.01	0.27	0.66	0.12
<i>r</i> C	0.52	0.15	.005	0.19	0.85	0.57
<i>r</i> E	0.27	0.12	.046	0.01	0.53	0.04
Project-level	ES	SE	<i>p</i>	Lower CI	Upper CI	τ^2
<i>r</i> A	0.44	0.07	<.01	0.29	0.60	0.33
<i>r</i> C	0.54	0.15	.015	0.16	0.92	0.99
<i>r</i> E	0.38	0.25	.180	−0.23	0.98	0.16

Note. ES = effect size, *SE* = standard error, CI = 95% confidence interval.

Table 5.

Moderators of bivariate genetic correlations for reading and ADHD symptoms.

Moderator	<i>k</i>	<i>Q_M</i> (df)	<i>p</i>	τ^2	<i>I</i> ² (%)	<i>R</i> ² (%)
Age	74	5.34(1)	.02	0.19	99.9	5.64
ADHD Reliability	35	0.08(1)	.78	0.04	99.7	0.00
Race Reported	31	2.68(1)	.10	0.23	99.9	5.30
Race Inferred	91	6.45(1)	.01	0.16	99.8	5.80
Grade-Level	23	2.74(3)	.43	0.04	98.5	0.00
Project	85	16.96(7)	.02	0.16	99.8	10.68
Nationality	91	16.44(4)	<.01	0.15	99.8	12.21
Clinical Status	91	4.37(1)	.04	0.17	99.8	3.60
Read Assessment	91	20.08(14)	.13	0.16	99.8	1.46
Reading Domain	91	5.98(7)	.54	0.17	99.8	0.00
Reading Assessment Format	91	6.30(5)	.28	0.17	99.8	1.46
ADHD Assessment	88	48.06(8)	<.01	0.12	99.8	31.78
ADHD Component	91	3.58(2)	.17	0.17	99.8	1.71
DeFries-Fulker	83	5.83(1)	.02	0.18	99.9	5.60

Note. Significant ($p < .05$) moderators are indicated in bold. *k* represents the number of studies included in the analysis. R^2 indicates the total amount of heterogeneity accounted for by the specified moderator. SES reported did not show sufficient variability for moderator analyses.

Table 6.

Bivariate genetic correlations by moderators for reading and ADHD symptoms.

Race Inferred	<i>r</i>A	<i>SE</i>	<i>p</i>	Lower CI	Upper CI
Caucasian	0.38	0.05	<.001	0.30	0.45
Multiple	0.60	0.10	<.001	0.45	0.72
Project					
FTP	0.66	0.13	<.001	0.48	0.78
TEDS	0.27	0.09	.003	0.10	0.44
CLDRC	0.54	0.09	<.001	0.41	0.66
WRRMP	0.47	0.23	.023	0.06	0.75
ILTS	0.31	0.09	<.001	0.14	0.47
Other	0.30	0.40	.458	−0.45	0.80
NTR	0.27	0.13	.032	0.02	0.48
QNTS	0.43	0.18	.010	0.11	0.67
Nationality					
USA	0.57	0.06	<.001	0.47	0.64
UK	0.27	0.09	.001	0.11	0.43
Multiple	0.31	0.09	<.001	0.14	0.46
Canadian	0.43	0.17	.008	0.12	0.66
Dutch	0.26	0.12	.027	0.03	0.47
Clinical Status					
Typically Developing	0.38	0.05	<.001	0.30	0.46
Mixed	0.54	0.09	<.001	0.41	0.66
ADHD Assessment					
DBRS	0.40	0.06	<.001	0.29	0.49
DICA	0.42	0.35	.210	−0.25	0.80
Revised Conner's	0.26	0.08	.002	0.10	0.41
SWAN	0.81	0.14	<.001	0.69	0.89
Other	0.90	0.25	<.001	0.76	0.96
DBD	0.33	0.14	.018	0.06	0.54
ADHD Composite	0.45	0.11	<.001	0.26	0.61
CBCL	0.22	0.13	.093	−0.04	0.45
SBQ	0.43	0.16	.003	0.15	0.64
DeFries-Fulker					
Yes	0.62	0.12	<.001	0.45	0.74
No	0.39	0.05	<.001	0.30	0.46

Note. Typically-Developing = 75% or more of the sample qualified as typically-developing in the domains assessed; Mixed = the sample included a mixture of students with a learning disability and typically-developing students; DBRS = Disruptive Behavior Rating Scale, DICA = Diagnostic

Interview for Children and Adolescents, Revised Conner's = Revised Conner's Parent Rating Scale, SWAN = Strengths and Weaknesses of ADHD-symptoms and Normal behavior scale, Other = composite of Strengths and Weaknesses of ADHD symptoms and Normal behavior scale and Bayley Behavior Rating Scale, CBCL = Child Behavior Checklist, SBQ = Social Behavioral Questionnaire.

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Table 7.

Moderators of bivariate shared environmental correlations for reading and ADHD symptoms.

Moderator	<i>k</i>	<i>Q_M</i> (df)	<i>p</i>	τ^2	<i>I</i> ² (%)	<i>R</i> ² (%)
Age	55	6.70(1)	.01	0.73	100.0	9.56
ADHD Reliability	34	0.45(1)	.50	0.27	100.0	0.00
Race Reported	25	3.85(1)	.05	1.12	100.0	10.60
Race Inferred	55	27.82(1)	<.01	0.54	100.0	33.19
Grade-Level	5	44.69(1)	<.01	0.00	52.1	97.21
Project	49	13.02(5)	.02	0.42	100.0	14.33
Nationality	55	14.78(3)	<.01	0.66	100.0	17.92
Clinical Status	55	0.12(1)	.73	0.82	100.0	0.00
Reading Assessment	55	53.34(9)	<.01	0.44	100.0	45.11
Reading Domain	55	10.52(6)	.11	0.74	100.0	7.73
Reading Assessment Format	91	6.30(5)	.28	0.17	99.8	1.46
ADHD Assessment	88	48.06(8)	<.01	0.12	99.8	31.78
ADHD Component	91	3.58(2)	.17	0.17	99.8	1.71

Note. Significant ($p < .05$) moderators are indicated in bold. *k* represents the number of studies included in the analysis. R^2 indicates the total amount of heterogeneity accounted for by the specified moderator. SES reported did not show sufficient variability for moderator analyses. No r_C between reading and ADHD were calculated for studies using the DeFries-Fulker method.

Table 8.

Bivariate shared environmental correlations by moderators for reading and ADHD symptoms.

Grade-Level	<i>rC</i>	<i>SE</i>	<i>p</i>	Lower CI	Upper CI
Grade 5	0.33	0.01	<.001	0.31	0.35
Mixed elementary	0.49	0.03	<.001	0.45	0.52
Race Inferred					
Caucasian	0.41	0.12	<.001	0.21	0.58
Multiple	0.92	0.19	<.001	0.84	0.96
Project					
FTP	0.83	0.22	<.001	0.65	0.92
TEDS	0.51	0.16	<.001	0.65	0.71
CLDRC	0.56	0.26	.02	0.11	0.82
WRRMP	0.38	0.37	.29	−0.15	0.37
ILTS	0.23	0.20	.27	−0.18	0.56
QNTS	0.23	0.29	.42	−0.33	0.66
Nationality					
USA	0.84	0.17	<.001	0.71	0.91
UK	0.51	0.20	.006	0.16	0.74
Multiple	0.23	0.26	.38	−0.27	0.62
Canadian	0.23	0.36	.52	−0.45	0.74
Reading Assessment					
WJ-Reading	0.38	0.38	.30	−0.35	0.82
Reading Composite	0.37	0.13	.003	0.13	0.57
NCUK	0.74	0.27	<.001	0.38	0.91
FCAT	0.97	0.33	<.001	0.91	0.99
FAIR	0.95	0.24	<.001	0.89	0.98
TOWRE	0.00	0.67	.99	−0.86	0.86
Alouette-R	0.05	0.47	.73	−0.70	0.75
WIAT	0.00	0.67	.99	−0.86	0.86
CTOPP RAN	0.16	0.47	.73	−0.64	0.80
THAL	0.49	0.47	.26	−0.37	0.91
ADHD Assessment					
DBRS	0.36	0.14	.01	0.10	0.57
Revised Conner's	0.54	0.15	<.001	0.30	0.71
SWAN	0.83	0.23	<.001	0.64	0.93
DBD	0.99	0.23	<.001	0.98	0.99
ADHD Composite	0.31	0.23	.14	−0.10	0.62

Grade-Level	<i>rC</i>	<i>SE</i>	<i>p</i>	Lower CI	Upper CI
SBQ	0.23	0.25	.36	−0.26	0.62

Note. NCUK = National Curriculum United Kingdom reading subtest; FCAT = Florida Comprehensive Assessment Test, FAIR = Florida Assessment for Instruction in Reading, TOWRE = Test of Silent Word Reading Efficiency, WIAT = Wechsler Individual Achievement Test reading subtest, CTOPP RAN = Comprehensive Test of Phonological Processing Rapid Automatized Naming composite, THAL = Test d'habiletés en lecture (Reading skills test). DBRS = Disruptive Behavior Rating Scale, Revised Conner's = Revised Conner's Parent Rating Scale, SWAN = Strengths and Weaknesses of ADHD-symptoms and Normal behavior scale, SBQ=Social Behavioral Questionnaire.

Table 9.

Results of RVE analyses for genetic, shared environmental, and nonshared environmental bivariate correlations between reading and math.

Study-level	ES	SE	<i>p</i>	Lower CI	Upper CI	τ^2
<i>r</i> A	0.66	0.09	<.01	0.58	0.76	0.06
<i>r</i> C	0.92	0.17	<.01	0.84	0.96	0.54
<i>r</i> E	0.60	0.17	<.01	0.33	0.79	0.18
Project-level	ES	SE	<i>p</i>	Lower CI	Upper CI	τ^2
<i>r</i> A	0.74	0.17	<.01	0.49	0.88	0.18
<i>r</i> C	0.92	0.24	<.01	0.73	0.98	1.00
<i>r</i> E	0.63	0.23	.02	0.15	0.87	0.44

Note. ES = effect size, SE = standard error, CI = 95% confidence interval

Table 10.

Moderators of bivariate genetic correlations for reading and math.

Moderator	<i>k</i>	<i>Q_M</i> (df)	<i>p</i>	τ^2	<i>I</i> ² (%)	<i>R</i> ² (%)
Age	63	2.75(1)	.10	0.27	99.9	2.76
Race Reported	10	1.25(1)	.26	0.12	99.7	2.58
Race Inferred	63	0.04(1)	.85	0.28	99.9	0.00
Grade-Level	13	28.18(4)	<.01	0.05	99.1	67.28
Project	60	12.42(5)	.03	0.25	99.9	11.24
Nationality	63	4.48(3)	.21	0.27	99.9	2.35
Clinical Status	63	0.46(1)	.50	0.28	99.9	0.00
Reading Assessment	63	19.93(9)	.02	0.23	99.9	15.00
Reading Domain	63	3.94(6)	.68	0.28	99.9	0.00
Reading Assessment Format	63	11.39(4)	.02	0.24	99.9	10.70
Math Assessment	63	12.31(6)	.06	0.25	99.9	9.31
Math Domain	63	12.42(6)	.05	0.25	99.9	9.41
Math Assessment Format	63	4.27(5)	.51	0.28	99.9	0.00
DeFries-Fulker	63	0.41(1)	.52	0.28	99.9	0.00

Note. Significant ($p < .05$) moderators are indicated in bold. *k* represents the number of studies included in the analysis. *R*² indicates the total amount of heterogeneity accounted for by the specified moderator.

Table 11.

Bivariate genetic correlations by moderators for reading and math.

Grade-Level	<i>rA</i>	<i>SE</i>	<i>p</i>	Lower CI	Upper CI
Grade 3	0.80	0.13	<.001	0.68	0.87
Grade 5	0.80	0.13	<.001	0.70	0.88
Grade 7	0.77	0.13	<.001	0.65	0.86
Grade 9	0.75	0.13	<.001	0.62	0.84
Mixed Elementary	0.98	0.23	<.001	0.95	0.99
Project					
TEDS	0.62	0.10	<.001	0.47	0.73
CLDRC	0.51	0.22	.01	0.13	0.76
WRRMP	0.76	0.12	<.001	0.64	0.83
Other	0.94	0.35	<.001	0.76	0.98
NTR	0.61	0.35	.04	0.02	0.86
ATP	0.80	0.14	<.001	0.65	0.86
Reading Assessment					
PIAT	0.63	0.14	<.001	0.44	0.77
WJ-Reading	0.56	0.18	<.001	0.27	0.76
Reading Composite	0.82	0.12	<.001	0.72	0.89
Other	0.85	0.28	<.001	0.60	0.95
FCAT	0.44	0.48	.32	-0.44	0.89
FAIR	0.82	0.34	<.001	0.46	0.95
GOAL	0.67	0.28	.004	0.26	0.88
TOWRE	0.43	0.28	.12	-0.12	0.75
CTOPP RAN	0.38	0.22	.07	-0.03	0.68
NAPLAN	0.78	0.14	<.001	0.65	0.87
Reading Assessment Format					
Cloze	0.90	0.49	.003	0.46	0.99
Multiple Choice	0.73	0.14	<.001	0.57	0.83
Mixed	0.77	0.08	<.001	0.69	0.82
Rating Scale	0.61	0.35	.04	0.03	0.89
Retell	0.48	0.13	<.001	0.25	0.65

Note. TEDS = , CLDRC = Colorado Learning Disability Research Center, WRRMP = Western Reserve Reading M Project, NTR = National Twin Registry, ATP = Australia Twin Project; PIAT= Peabody Individual Achievement Test, WJ-Reading=Woodcock Johnson Tests of Achievement-III reading subtest. FCAT=Florida Comprehensive Assessment Test, FAIR=Florida Assessment for Instruction in Reading, GOAL= Global Online Assessment for Learning—Formative Assessment in Literacy for Key Stage 3, TOWRE=Test of Silent Word Reading Efficiency, WIAT=Wechsler Individual Achievement Test, CTOPP RAN = Comprehensive Test of Phonological Processing—Rapid Automatized Naming composite, NAPLAN = National Assessment Program—Literacy and Numeracy.

Table 12.

Moderators of bivariate shared environmental correlations for reading and math.

Moderator	<i>k</i>	<i>Q_M</i> (df)	<i>p</i>	τ^2	<i>I</i> ² (%)	<i>R</i> ² (%)
Age	59	0.04(1)	.83	0.79	100.0	0.00
Race Reported	9	20.52(1)	<.01	0.23	99.8	70.99
Race Inferred	59	7.23(1)	<.01	0.70	100.0	9.72
Grade-Level	13	6.92(4)	.14	0.23	99.8	19.64
Nationality	59	0.13(2)	.94	0.80	100.0	0.00
Project	56	4.96(4)	.29	0.71	100.0	1.71
Clinical Status	59	4.08(1)	.04	0.73	100.0	5.06
Reading Assessment	59	9.30(9)	.41	0.77	100.0	0.52
Reading Domain	59	3.97(5)	.55	0.79	100.0	0.00
Reading Assessment Format	59	5.49(3)	.14	0.74	100.0	4.12
Math Assessment	59	11.19(6)	.08	0.71	100.0	8.23
Math Domain	59	28.87(5)	<.01	0.55	100.0	29.18
Math Assessment Format	59	15.41(4)	<.01	0.65	100.0	16.45
DeFries-Fulker	59	0.47(1)	.49	0.78	100.0	0.00

Note. Significant ($p < .05$) moderators are indicated in bold. *k* represents the number of studies included in the analysis. R^2 indicates the total amount of heterogeneity accounted for by the specified moderator. SES reported did not show sufficient variability for moderator analyses.

Table 13.

Bivariate shared environmental correlations by moderators for reading and math.

Race Reported	<i>r</i>C	<i>SE</i>	<i>p</i>	Lower CI	Upper CI
Caucasian	0.95	0.20	<.001	0.88	0.97
Multiple	0.23	0.28	.41	−0.30	0.65
Race Inferred					
Caucasian	0.92	0.11	<.001	0.87	0.95
Multiple	0.23	0.48	.63	−0.62	0.83
Clinical Status					
Typically-Developing	0.89	0.12	<.001	0.84	0.93
Mixed	0.98	0.43	<.001	0.90	0.99
Math Domain					
Fluency	0.59	0.33	.04	0.02	0.87
Calculation	0.99	0.52	<.001	0.93	0.99
Spatial Ability	0.90	0.37	<.001	0.62	0.98
Problem Solving	0.64	0.29	.01	0.16	0.87
Quantitative Concepts	0.65	0.30	.01	0.18	0.88
Multiple Domains	0.95	0.12	<.001	0.92	0.97
Math Assessment Format					
Cloze	0.75	0.47	.03	0.07	0.96
Multiple Choice	0.71	0.33	.01	0.24	0.91
Mixed	0.94	0.12	<.001	0.90	0.96
Timed	0.23	0.46	.62	−0.59	0.81
Teacher-Report	0.87	0.46	<.001	0.41	0.98

Note. Bolded estimates indicate $p < .05$. Typically-Developing = 75% or more of the sample qualified as typically-developing in the domains assessed, Mixed = the sample included a mixture of students with a learning disability and typically-developing students.