American Psychological Association

Psychological Bulletin

0033-2909/19/$12.00

2019, Vol. 145, No. 2, 189–236
http://dx.doi.org/10.1037/bul0000182

A Meta-Analysis on the Relation Between Fluid Intelligence and Reading/ Mathematics: Effects of Tasks, Age, and Social Economics Status

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This study aimed to determine the relations between fluid intelligence (*Gf*) and reading/mathematics and possible moderators. A meta-analysis of 680 studies involving 793 independent samples and more than 370,000 participants found that *Gf* was moderately related to reading, r = .38, 95% CI [.36, .39], and mathematics, r = .41, 95% CI [.39, 44]. Synthesis on the longitudinal correlations showed that *Gf* and reading/mathematics predicted each other in the development even after controlling for initial performance. Moderation analyses revealed the following findings: (a) *Gf* showed stronger relations to mathematics than to reading, (b) within reading or mathematics, *Gf* showed stronger relations to complex skills than to foundational skills, (c) the relations between *Gf* and reading/mathematics increased with age, and (d) family social economic status (SES) mostly affected the relations between *Gf* and reading/mathematics in the early development stage. These findings, taken together, are partially in line with the investment theory but are more in line with the intrinsic cognitive load theory, mutualism theory, and the gene–SES interaction hypothesis of cognition and learning. More importantly, these findings imply an integration model of these theories from an educational and developmental perspective: Children may rely on *Gf* to learn reading and mathematics early on, when high family SES can boost the effects of *Gf* on reading/mathematics performance. As children receive more formal schooling and gain more learning experiences, their reading and mathematics improvement may promote their *Gf* development. During development, the negative effects of low family SES on the relations between *Gf* and reading/mathematics may be offset by education/learning experiences.

Public Significance Statement

Gf has moderate relations with reading and mathematics, with stronger relations with mathematics. The relations between *Gf* and reading/mathematics are stronger when involving complex reading/mathematics skills and composite nonverbal reasoning tasks. *Gf* and reading/mathematics predict each other in the development and their relations increase with age, suggesting a reciprocity between *Gf* and reading/mathematics. Compared with country SES, family SES is more important to the relations between *Gf* and reading/mathematics and the family SES effect is most obvious early on.

Keywords: age, fluid intelligence, mutualism theory, reading/mathematics, SES

Supplemental materials: http://dx.doi.org/10.1037/bul0000182.supp

Teachers often comment on a student saying "He/she is smart!", which usually means the student is capable of learning and performing academic tasks well at school. There are many cognitive abilities underlying "being smart" at school, but it is fluid intelligence (*Gf*), the capacity to reason and solve novel problems independent of any knowledge from the past (Cattell, 1963), that is

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We thank Ron Nelson at University of Nebraska, Lincoln for his suggestions on the this article.

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often considered as the cognitive hub for academic performance (Deary, Strand, Smith, & Fernandes, 2007; Gustafsson, 1984; Lynn & Vanhanen, 2012; Primi, Ferrão, & Almeida, 2010; Rohde & Thompson, 2007; Soares, Lemos, Primi, & Almeida, 2015). However, empirical evidence on the size of the relation between *Gf* and academic performance is mixed (Mackintosh & Mackintosh, 2011), with some studies indicating a low-moderate relation ($r <$ .30; e.g., Kaplan, 1993; Konold, 1999; Lassiter, Leverett, & Safa, 2000; Lynn & Hampson, 1985) and others reporting a very high relation ($r >$ .80; e.g., Brown & Ryan, 2004; Deary et al., 2007; Wechsler et al., 2014). It is necessary to gain a better insight into the degree to which *Gf* is related to academic performance and the factors that influence this relation. Answers to these questions are important not only to theorists of human cognition and learning, but also important to educators, policymakers, and others who wish to make informed decisions that will both maximize individual potential and make the most effective use of limited education resources (Connell, Sheridan, & Gardner, 2003).

In the past several decades, there are many studies on the structure of human cognitions involving *Gf* and academic performance (Carroll, 1993; Floyd, Evans, & McGrew, 2003; Kaufman, Reynolds, Liu, Kaufman, & McGrew, 2012; McGrew, 2009) and several reviews on the relations between *Gf* and education (e.g., education level and years of schooling; e.g., Ceci, 1991; Ceci & Williams, 1997; Herrnstein & Murray, 1994; Neisser et al., 1996; Strenze, 2007). However, only one meta-analysis, to our knowledge, specifically investigated the relation between *Gf* and academic performance. Specifically, Postlethwaite (2011) based on Cattell-Horn model of fluid (*Gf*) and crystallized intelligence (*Gc*) and explored the relations between *Gf*/*Gc* and academic performance. The author included 132 studies that reported the relations between *Gf*/*Gc* and academic performance coming from a "representative sample." Results showed that compared with *Gc* ($r =$ .36), *Gf* showed a weaker relation with academic performance ($r =$ .26). Postlethwaite (2011) study is a valuable contribution to our understanding on the relations between *Gf* and academic performance, but the results should be interpreted with several limitations. First, the *Gc* defined by Postlethwaite (2011) also included different reading, vocabulary, and calculation skills, which are usually categorized as academic performance. Second, the author defined academic performance as GPA and grades in general, which is subjective to students' course choice and grading idiosyncrasies between instructors and unable to reflect the fine-grained relations between *Gf* and a specific subject domain (e.g., reading and mathematics). Third, the author only included high school students and undergraduate students, limiting the generalizability of the findings. Fourth, important factors such as age and social economic status (SES) that may influence the relations between *Gf* and academic performance were not considered. Last, this study did not differentiate concurrent correlations from longitudinal correlations. Longitudinal correlations between *Gf* and academic performance should be analyzed independently to further reveal a possible causal impact of *Gf* on academic performance and vice versa (Strenze, 2007).

We think the relations between *Gf* and academic achievement rely on how *Gf* and academic achievement are measured, at what developmental stage these relations are investigated, and how a third variable such as SES that influences both *Gf* and academic achievement can influence their relations. Meta-analysis is useful in this regard because it can clarify these possibilities. Thus, the present study aims to replicate Postlethwaite's (2011) finding with an updated corpus of studies as well as address the questions mentioned above the review did not/was unable to answer. Specifically, the present meta-analysis systematically investigates the relations between *Gf* and academic performance with a focus on reading and mathematics among unselected samples (typically developing and atypically developing individuals) from a wide range of ages. In addition, we investigate several moderators that can potentially explain variations in these relations. The moderators include types of *Gf* tasks (i.e., matrix reasoning, nonmatrix reasoning, visuospatial reasoning, and composite nonverbal reasoning), types of reading (i.e., code skills and comprehension skills), types of mathematics (i.e., numerical knowledge, calculation, word problems, and fraction and algebra), age, and SES (country SES and family SES). Besides the concurrent relations between *Gf* and reading/mathematics, we also synthesize their longitudinal correlations to examine whether *Gf* predicts later reading/mathematics partialing out initial reading/mathematics and vice versa as to further detect a potential reciprocal effect (e.g., Kievit et al., 2017; McArdle, Hamagami, Meredith, & Bradway, 2000; Rindermann, Flores-Mendoza, & Mansur-Alves, 2010; Van Der Maas et al., 2006).

Theoretical Framework and Practice Consideration

The moderators included in the current meta-analysis are guided by several contemporary cognitive theories: intrinsic cognitive load theory, investment theory versus mutualism theory, and gene–SES interaction hypothesis. First, previous research involving *Gf* and reading/mathematics (categorized as part of *Gc*) mostly relied on the factor analytic approach to test the structure of intelligence or the relations between *Gf* and academic performance on a broad level (Carroll, 1993; Kaufman et al., 2012; Keith & Reynolds, 2010). Meta-analysis not only can investigate the general relations between *Gf* and reading/mathematics, but also can investigate the fine-grained relations between different types of *Gf* and different reading/mathematics skills, which takes into consideration of the task complexity effects. According to the intrinsic cognitive load theory, there is an inherent level of difficulty associated with a specific task (Chandler & Sweller, 1991; Sweller, 1994). Tasks with multiple interactive steps and sequential thinking are assumed to be more difficult than tasks involving fewer noninteractive steps. Based on the intrinsic cognitive load theory, complex *Gf* and academic tasks may increase the relations between *Gf* and academic performance, whereas relatively simple *Gf* and academic tasks may decrease the relations between *Gf* and academic performance.

Second, by considering the possible moderating effects of age from a lifelong span, we can examine the developmental nature of the relations between *Gf* and reading/mathematics in the context of two developmental cognitive theories. Specifically, based on the Investment theory, initial *Gf* contributes to the development of reading/mathematics but this effect decreases gradually (e.g., Cattell, 1987; Kvist & Gustafsson, 2008). In contrast, according to the Mutualism theory, the relations between *Gf* and reading/mathematics are small early on, but becoming stronger due to reciprocal influences (e.g., Kievit et al., 2017; McArdle et al., 2000; Van Der Maas et al., 2006).

Third, the gene–SES interaction hypothesis can help explore the effects of SES and the interaction between age and SES on the relations between *Gf* and academic performance. According to this hypothesis, SES may modify the heritability of *Gf*, which results in stronger relations between *Gf* and reading/mathematics in a high SES background and lower relations in a low SES background (e.g., Bronfenbrenner & Ceci, 1994; Turkheimer, Haley, Waldron, d'Onofrio, & Gottesman, 2003). The gene–SES interaction may also be time sensitive such that SES affects the relations between *Gf* and reading/mathematics mostly in early development but not so in later development due to the compensatory effects of schooling (Ceci, & Williams, 1997; Herrnstein & Murray, 1994; Ladd, 2012) and the accumulative heritability effect (e.g., Johnson, Deary, & Iacono, 2009; Kovas, Haworth, Dale, & Plomin, 2007; Kovas et al., 2013; Krapohl et al., 2014).

From a practical perspective, findings from the present meta-analysis may have important implications for education practice. An increasing number of studies in recent years have examined whether training high-level cognitive skills (e.g., working memory) could improve *Gf* and academic outcomes (e.g., Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Titz & Karbach, 2014), although there are mixed findings on this approach (Harrison et al., 2013; Melby-Lervåg & Hulme, 2013; Redick et al., 2013; Shipstead, Redick, Hicks, & Engle, 2012). One important characteristic (caveat) of cognitive training is the relatively intensive practice on abstract cognitive tasks (e.g., dual *n*-back tasks and complex working memory span tasks; Shipstead et al., 2012; Wang, Zhou, & Shah, 2014), which is often criticized for having low feasibility in school instruction and being educationally irrelevant (Peng & Fuchs, 2017). Investigating the developmental nature of the relations between *Gf* and reading/mathematics may provide evidence on whether and how cognitive training should be implemented in the school setting. If *Gf* influences reading/mathematics but not vice versa, it is worth exploring the feasibility of cognitive training or the combination of academic instruction and cognitive training at school, especially for children with boarder-line *Gf* or severe learning disabilities (Peng & Fuchs, 2017). If, however, *Gf* and reading/mathematics mutually predict each other, then focusing on instruction at school may suffice to improve both reading/mathematics and *Gf*, adding evidence to the importance of schooling for individual development (Ceci & Williams, 1997). In other words, increasing reading/mathematics instructional quality and time at school may be the most efficient way to improve students' domain-knowledge and general abilities. In the following sections, we describe the theoretical framework of the relations between *Gf* and reading/mathematics and the moderators in detail.

Gf and Reading/Mathematics: Effects of Tasks

The relations between *Gf* and academic performance are often researched and interpreted in the context of intelligence theories. Among many contemporary intelligence theories, the Cattell–Horn–Carroll (CHC) theory is a most influential one. Specifically, the CHC theory of intelligence is a synthesis of Cattell and Horn's *Gf-Gc* model (Cattell, 1963; Horn, 1968) and Carroll's (1993) *Three-Stratum* model (McGrew, 2005, 2009). This model assumes that human intelligence can be represented by a three-stratum structure. There are more than 80 narrow or specific abilities at stratum one, nine primary second-order abilities at stratum two, and an overall *g* ability (general intelligence) at stratum three. The primary CHC abilities that relate to the content of contemporary intelligence batteries are mainly represented by the stratum two: fluid intelligence (*Gf*), crystallized intelligence (*Gc*), short-term memory (STM; *Gsm*), visual processing (*Gv*), auditory processing (*Ga*), long-term storage and retrieval (*Glr*), cognitive processing speed (*Gs*), reading and writing (*Grw*), and quantitative knowledge (*Gq*). Among these, *Gf* and *Gc* are especially prominent, primarily because of the influence of Cattell and Horn's *Gf-Gc* model (Cattell, 1963; Horn, 1968) and that these two abilities have higher *g*-factor loadings than the others as shown by empirical studies (Carroll, 1993; Gignac, 2006).

Gf

Gf has been conceptualized as the capacity to solve novel and complex problems by means of mental operations such as drawing inferences, concept formation, classification, identifying relations, problem solving, and so forth (Cattell, 1963; Newton & Mcgrew, 2010). Therefore, reasoning (inductive and deductive) is generally considered as the hallmark indicator of *Gf* (Carroll, 1993; McGrew, 2009). However, how reasoning tasks are conceptualized and measured may influence their predictive power of academic performance (Lohman & Lakin, 2011). Specifically, task modality and task complexity of reasoning tasks are two major factors that may influence the relations between reasoning tasks and academic performance.

On one hand, reasoning tasks often vary on the modality of materials, including verbal, numerical and nonverbal tasks (Beauducel, Brocke, & Liepmann, 2001; Carroll, 1993; Csapó, 1997; Wilhelm, 2005). Verbal reasoning often taps inductive reasoning such as detecting generalizations or regularities that underlie a specific verbal problem (e.g., A, C, E, __) or deductive reasoning as in drawing a logical conclusion from verbally stated general conditions or premises (e.g., "fruits have some property X, all grapes are fruits, do grapes have property X?"; Johnson-Laird, 1999; Polk & Newell, 1995). Numerical reasoning is measured with quantitative elements, including inductive numerical reasoning tasks that require one to find rules for a series of numerical items (e.g., 2, 4, 6, __) and deductive numerical reasoning tasks similar to verbal deductive reasoning tasks (e.g., fill out blanks in a square/matrix based on two properties in a numerical Latin Square task: a row or column never contains the same number twice and every row and column contains the same numbers; Birney, Halford, & Andrews, 2006). Nonverbal reasoning is often assessed with figural/visual materials, tapping inductive reasoning that requires one to find rules underlying a series of figural/visual items (e.g., □, ○, □, __) or tapping the inductive and deductive reasoning simultaneously that requires one to find rules based on existing items and apply the rules to a new set of items at the same time (e.g., matrix reasoning; Primi, 2002; Klauer, Willmes, & Phye, 2002). In comparison with the verbal and numerical reasoning, nonverbal reasoning tasks are mostly used to represent *Gf* because they are culture-free and minimally influenced by prior knowledge, experience, or skills (Gustafsson, 1984).

Indeed, one important explanation for the mixed findings of the relations between *Gf* and academic performance is that most previous research did not consider the modality of materials in *Gf*, often using either verbal reasoning, numerical reasoning, or nonverbal reasoning (or all of them) to indicate *Gf* (e.g., Ackerman & Lohman, 2003; Deary et al., 2007; Primi et al., 2010), which would inflate the relations between *Gf* and academic performance. For example, *Gf* measured by the composite of verbal reasoning, numerical reasoning, and nonverbal reasoning tasks per se involves academic skills thus often shows stronger relations to reading and mathematics tasks than that of *Gf* measured only by nonverbal reasoning tasks (e.g., Deary et al., 2007; Kanerva & Kalakoski, 2016; Lu, Weber, Spinath, & Shi, 2011). In the present meta-analysis, we focus on *Gf* that taps only nonverbal reasoning to reduce or eliminate the "contamination" of knowledge/experiences.

On the other hand, reasoning tasks vary on complexity. From an educational research and practice perspective, we focused on four types of commonly used nonverbal reasoning tasks to examine whether complexity of these tasks affect *Gf*'s relations to academic performance. The first is matrix reasoning, which has been consistently considered as the most classic/pure measure of *Gf* (Carpenter, Just, & Shell, 1990; Gray & Thompson, 2004; Jaeggi et al., 2010; Lichtenberger & Kaufman, 2009). For each matrix reasoning item, the subject looks at an incomplete matrix and selects the missing portion from several response alternatives. In this study we treat it separately from the other types of nonverbal reasoning tasks because it has been included in most established standardized intelligence scales and used most widely (e.g., Raven's Matrices, Cattell's Culture Fair Test, the Wechsler Intelligence Scales for Adults and Children, and the Stanford-Binet Intelligence Scales). The second type of *Gf* measures is nonmatrix reasoning tasks that are similar to matrix reasoning except that those tasks were not in the form of matrix, but in the form of series, analogies, and classifications (e.g., analysis-synthesis, concept formation, topology, and series completion; Goldman & Pellegrino, 1984; Klauer et al., 2002). The third type of *Gf* measures is a mixture of nonverbal reasoning and visual processing (i.e., visuospatial reasoning; e.g., block design, picture completion, and object assembly). Several studies have indicated that these tasks load on both *Gf* and *Gv* factors in the analysis of empirical data (Keith, Fine, Taub, Reynolds, & Kranzler, 2006; Reynolds & Keith, 2017). Although these tasks are not considered as the most pure measure of *Gf*, they have often been used to index *Gf* in educational studies and practice (Alloway & Alloway, 2010; Hagborg & Wachman, 1992; Lakin & Lohman, 2011). The fourth type is composite nonverbal reasoning, the composite/factor score derived from a series of nonverbal reasoning tasks. This category primarily includes the composite nonverbal reasoning scores (e.g., performance IQ and perceptual organization) from popular IQ test battery such as Wechsler Intelligence Scales and Stanford-Binet Intelligence Scale (Gustafsson, 1984; Keith, 2005). Based on the intrinsic cognitive load theory, the composite nonverbal reasoning is more likely to sample various reasoning skills and thus is assumed to have stronger relations with academic achievement than a specific nonverbal reasoning measure. Among specific nonverbal reasoning measures, matrix reasoning and nonmatrix reasoning tasks, in comparison with visuospatial reasoning tasks, are more reasoning-loaded and complex, and thus may be more related to academic performance (Lohman & Lakin, 2011).

Reading/Mathematics

In contrast to *Gf*, academic performance is categorized as part of the *Gc* in the *Gf-Gc* model and the *Three-Stratum* model (Carroll, 1993) or as primary abilities independent of *Gc* in the CHC model (*Grw* and *Gq*, Horn & Blankson, 2005; Horn, & Noll, 1997). Based on these models, we used reading and mathematics as two main indices of academic performance. We choose reading and mathematics also because they are the most important academic skills emphasized at school and are taught more systematically in school across most cultures in comparison to other domains of knowledge (Organization for Economic Cooperation and Development, 2006). Unlike the *Gf-Gc* model, the *Three-Stratum* model, or the CHC model that considers reading and mathematics as a broad construct(s) (*Gc,* or *Grw* and *Gq*; McGrew, 2009), we treat reading (and different reading skills) and mathematics (and different mathematics skills) as relatively independent academic skills to study the fine-grained difference on their relations to *Gf*. Such categorization is important for instruction/intervention at school where different reading and mathematics skills are sequentially and systematically taught or emphasized at different grades (Common Core State Standards Initiative, 2010).

Reading and mathematics may involve *Gf* to varying degrees. A popular view, from a broad perspective, is that mathematics may involve more *Gf* than reading (Sternberg, Kaufman, & Grigorenko, 2008). This is possibly because there is more learning and applications of abstract rules in mathematics than in reading (Ackerman & Lohman, 2003; Blair, Gamson, Thorne, & Baker, 2005; Geary, 2011). Also, individuals often have more exposure to reading (e.g., exposures to language and books) in daily life than to mathematics (Barbarin et al., 2008), which can facilitate the use of background knowledge in reducing the cognitive load (e.g., *Gf*) during reading tasks than during mathematics tasks (Peng et al., 2018). In the current study, we examine whether *Gf* relates to reading and mathematics differently.

Based on the intrinsic cognitive load theory, different reading and mathematics tasks vary on complexity, which may contribute to the relations between *Gf* and reading/mathematics. Complex academic tasks such as reading comprehension and word problems that have multiple and sequential processing features may draw more *Gf* than foundational reading/mathematics tasks such as word reading and calculation. However, unlike *Gf* tasks, the complexity of a reading/mathematics task may change based on individuals' knowledge development for that task (Paas, Renkl, & Sweller, 2003). Thus, from the curriculum (i.e., learning progression) perspective, different skills within reading/mathematics may involve *Gf* to different degrees depending on age/grade.

In most reading curricula, instruction/learning is focused on two major components: code skills including word reading and word reading related metalinguistic skills (e.g., phonological and orthographic awareness), and comprehension skills including vocabulary, language comprehension, and reading comprehension (Hoover & Gough, 1990). The focus of reading instruction/learning is on code skills early on (i.e., before 4th grade) and gradually shifts to comprehension (Hoover & Gough, 1990; Peng et al., 2018). With the reading curriculum sequence, *Gf* is first involved in learning the letter-sound correspondence rules for word reading in alphabetic languages (e.g., English; e.g., Tiu, Thompson, & Lewis, 2003; Levy, 2011) and orthographic rules in nonalphabetic languages (e.g., Chinese; Ho, Wong, & Chan, 1999), but the involvement of *Gf* in these code-skills decreases as older children can read words based on the direct retrieval of words from the long-term memory (Peng et al., 2018). In contrast, *Gf* is supposed to closely relate to comprehension skills across grades, and this relation may become even stronger in later grades and life when expository texts are the major reading materials that involve much more reasoning (e.g., inferencing) than narrative texts encountered early on (e.g., Etmanskie, Partanen, & Siegel, 2016; Nation, Clarke, & Snowling, 2002; Tiu et al., 2003).

For most mathematics curricula, several major skills are sequentially taught at school, including (but not limited to) numerical knowledge, calculation, word problems, fraction and algebra (e.g., Common Core State Standards Initiative, 2010; Peng, Namkung, Barnes, & Sun, 2016). It is suggested that foundational skills such as numerical knowledge and calculation involve *Gf,* especially in the early stage when children are learning to master the numerical symbols, their relations/applications in the number system, and the rules in calculation (Fuchs et al., 2006; Östergren & Träff, 2013). *Gf* may become less important for these foundational skills as children become more fluent in mathematics facts retrieval from the long-term memory (Locuniak & Jordan, 2008). Compared with those foundational mathematics skills, more complex mathematics skills in later grades seem to involve more *Gf*. For example, word problems become increasingly important and complex in mathematics curricula such that there is a strong focus on performance assessments that pose real-world problem solving dilemmas and require students to develop solutions involving the application of multiple skills (Fuchs & Fuchs, 2002; Resnick & Resnick, 1992; Rothman, 1995). Solving word problems heavily taps the reasoning skills to construct (a) a coherent structure to capture the text's essential ideas, (b) a situation model that requires supplementing the text with inferences based on the child's world knowledge, including knowledge about relations among quantities, and (c) problem models or schema to formalize the conceptual relations among quantities and guide application of solution strategies (e.g., Fuchs, Fuchs, Compton, Hamlett, & Wang, 2015; Kaufmann & Schmalstieg, 2003; Reuhkala, 2001). Besides word problems, other complex mathematics skills in later mathematics curricula such as fraction and algebra are built on foundational numerical and calculation skills, and are often embedded in a word-problem format, which is supposed to require much *Gf* (Fuchs et al., 2012; Jordan et al., 2013).

In the present study, besides the general relations between *Gf* and reading/mathematics, we also examine whether these relations are moderated by different reading/mathematics skills and whether this moderation is affected by age that reflects the curriculum effect. We focus on code skills (word reading and related metalinguistic skills) and comprehension skills (vocabulary, reading comprehension, and listening comprehension) in the reading domain as suggested by the Simple View of Reading (Hoover & Gough, 1990). For mathematics, we focus on numerical knowledge, calculation, word problems, fraction, and algebra according to the Common Core State Mathematics Standards (Common Core State Standards Initiative, 2010). We did not include geometry in mathematics because it is a much less researched mathematics domain (with few effect sizes available in the literature) and also because geometry often confounds with nonverbal reasoning tasks as they both tap nonverbal processing skills (Linn & Petersen, 1985; Uttal et al., 2013).

Age Effects: Investment Theory Versus Mutualism Theory

Age is an important factor in understanding the developmental nature of the relations between *Gf* and reading/mathematics, which can be contextualized within two developmental theories: Investment theory and Mutualism theory. According to the Investment theory, the development of *Gf* itself is mostly influenced by biological/genetic factors and factors related to nutritional quality and health status (infections, handicaps, toxins, quality of health systems; Cattell, 1987; Deary, Penke, & Johnson, 2010; Nisbett et al., 2012). *Gf* should not depend on nonbiological environmental factors such as education and cognitive stimulation. In contrast, academic performance is the result of the interaction between *Gf* and environmental stimulation such as education. *Gf* gives the basis for the development of academic performance (Ackerman, 2000; Cattell, 1987; Kvist & Gustafsson, 2008).

The Investment theory received support from empirical studies. For example, there is evidence showing that *Gf* is influenced by nutritional quality (e.g., Eysenck & Schoenthaler, 1997; Lynn, 2009), by nutritional and health programs in developing countries (Glewwe & King, 2001; Whaley et al., 2003), by brain size (Rushton & Ankney, 2009), and by mental speed associated with white matter in brain (Jensen, 2006), while nonbiological environmental and personality factors seem to exert stronger influence on academic performance than *Gf* (Rindermann & Neubauer, 2000, 2001). Moreover, studies using longitudinal growth modeling showed that *Gf* predicts academic achievement and the rate of change in learning and achievement (Primi et al., 2010). The prediction of *Gf* on academic performance tends to decrease as age/experience/grade increases, reflecting the investment nature of *Gf* (Ackerman & Lohman, 2003; Willingham, 1974). It is argued that *Gf* is important for an academic task when it is novel, but when the student has familiarized with the academic task/content, *Gf* becomes a less important determinant of performance on that academic task (Ackerman, 1994).

In contrast, the Mutualism theory claims that different types of intelligence (including *Gf* and academic performance) are related to each other reciprocally (Van Der Maas et al., 2006). That is, the correlations between different types of intelligence are theorized to emerge during human development, as a consequence of mutually beneficial interactions between originally uncorrelated cognitive processes. Thus, as the originally orthogonal cognitive processes interact beneficially over time, positive associations emerge between their respective capacities (Van Der Maas et al., 2006). Unlike the Investment theory, the Mutualism theory emphasizes that *Gf* and academic performance should influence each other through development and their relations become stronger as a function of time.

There is evidence supporting the Mutualism theory, showing reciprocal relations between *Gf* and academic performance, particularly the effects of academic performance on *Gf* (Ferrer et al., 2007; Ferrer & McArdle, 2004; Kievit et al., 2017). Specifically, there are large differences in *Gf* tests between different countries, similar to differences in knowledge-based tests such as PISA/TIMSS (Lynn, Meisenberg, Mikk, & Williams, 2007; Rindermann, 2007, 2008), which may be influenced by differences in educational policies among countries (Rindermann & Ceci, 2009).

Education in school tends to have effects on *Gf*. For example, some research shows that there are strong relations between *Gf* and the number of total years of school completed ($r = .60 \sim .80$) even when SES is partialed out (Ceci, 1991; Ceci & Williams, 1997). Children who attended school early and continuously tend to have higher *Gf* scores than those who attended school late and intermittently, and *Gf* tends to decline, on average, during the period in which school is not in session (e.g., summer vacation; Ackerman & Lohman, 2003; Blair, 2010; Protzko, 2015). There is also direct evidence from studies with the cross-lagged panel design, showing that *Gf* and academic performance measured at one time significantly predicted each other at a later time (Ferrer et al., 2007; Ferrer & McArdle, 2004; Kievit et al., 2017; Rindermann et al., 2010; Schroeders, Schipolowski, Zettler, Golle, & Wilhelm, 2016).

Although both Investment and Mutualism theory have received support from empirical studies, most of these studies only used a relatively short age span (e.g., spanning several years), treated age as a categorical variable (likely because of the lack of sample for different age groups), or majorly focused on very broad and general education outcomes (e.g., GPA; e.g., Ferrer et al., 2007; Ferrer & McArdle, 2004; Schroeders et al., 2016). With meta-analysis, we are able to synthesize studies across a much wider age range and different reading/mathematics skills to consider age as a continuous variable to more accurately reflect its effects on the relations between *Gf* and different reading/mathematics skills.

Furthermore, it is suggested that the developmental trajectories of *Gf* and *Gc* are nonlinear such that *Gf* typically peaks in early adulthood ($20 \sim 30$) and then steadily declines (Horn, & Cattell, 1967; Horn & McArdle, 1980; McArdle, Ferrer-Caja, Hamagami, & Woodcock, 2002), while *Gc* increases gradually, stays relatively stable across most of adulthood, and then declines starting around 60s (Cavanaugh & Blanchard-Fields, 2006). These findings suggest that age and schooling may be confounded early on, and thus age should be considered as a continuous as well as a categorical moderator (early adulthood usually with formal schooling vs. adulthood usually without formal schooling) in the relations between *Gf* and reading/mathematics. Given the developmental trajectories of *Gf* and *Gc*, the prediction of the relations between *Gf* and reading/mathematics based on the Investment theory and the Mutualism theory may be a little different. That is, based on the Investment theory, in early adulthood, the relations between *Gf* and reading/mathematics can be influenced by both maturation and schooling such that the relations may be stable or increase with age, but the relations should decrease with age significantly in the adulthood (Schweizer & Koch, 2002; Kvist & Gustafsson, 2008). In contrast, based on the Mutualism theory, the relations between *Gf* and reading/mathematics should increase with age all the time, but this positive age effect may be even stronger in adulthood when *Gf* is biologically decreasing significantly, more sensitive to the reciprocal effects from reading/mathematics. In this study, besides using age as a continuous variable, we also used the age of 20 and the age of 30 as the cut-off points to define early adulthood (before 20) versus adulthood (after 30) to reflect the growing and declining phase of *Gf* (Hartshorne & Germine, 2015), respectively, and further examine the effects of developmental trajectories of *Gf* on the relations between *Gf* and reading/mathematics.

Social Economic Status

Another important factor influencing both *Gf* and reading/mathematics is SES (Deary et al., 2010; Sirin, 2005; White, 1982), and there are usually two variables of SES in the education research: country SES (developing country vs. developed country; Lynn & Vanhanen, 2012) and family SES (middle class or above vs. below middle class; Haveman & Wolfe, 1995). Specifically, the famous Flynn effect suggests a substantial and long-sustained increase in both *Gf* and academic performance test scores measured in many parts of the world from roughly 1930 to recent years (Flynn, 2007). One explanation for the Flynn effect is the positive impact of overall societal improvement in nutrition and life quality on intelligence, implying the effects of country SES on *Gf* and academic performance (Flynn, 2007). In the meanwhile, it is also widely acknowledged the family SES, indexed by family income, parental education, and occupation, affects *Gf* and academic performance (Fischbein, 1980; Haveman & Wolfe, 1995; Sirin, 2005). In the present meta-analysis, we control for both SES variables in investigating the relations between *Gf* and reading/mathematics.

More importantly, SES can be viewed as a moderator in the relations between *Gf* and reading/mathematics based on behavioral genetics research. Specifically, converging evidence suggests a gene–SES interaction on *Gf* and academic performance among children and adolescents. That is, the heritability of *Gf* is higher in higher SES background because such environment is likely to provide more opportunities to realize differences in children's genetic potentials, whereas in lower SES background, genetic differences might be restrained (e.g., Bronfenbrenner & Ceci, 1994; Turkheimer et al., 2003). Based on the gene–SES interaction hypothesis, it is likely that the relations between *Gf* and reading/mathematics, in general, may be stronger among children with higher SES than those with lower SES.

However, a closer look into all these prior studies reveals that the gene–SES interaction hypothesis was mostly studied among young individuals (i.e., children or adolescents) within a relatively narrow developmental span (e.g., for certain young age groups or spanning several years in early development; see Tucker-Drob & Bates, 2016; Tucker-Drob, Briley, & Harden, 2013 for review). In contrast, a few studies on the gene–SES interaction comparing younger individuals with older individuals (e.g., adults) suggest that SES exerts less impact on *Gf* among older individuals (Grant et al., 2010; van der Sluis, Willemsen, de Geus, Boomsma, & Posthuma, 2008). These findings, taken together, suggest a need to investigate the gene–SES interaction effect from a broader development perspective (e.g., life span) and the gene–SES interaction may be time sensitive.

Two hypotheses may explain the developmental nature of gene–SES interaction (if any) on the relations *Gf* and academic performance: schooling effects and genetics effects. With respect to the schooling effects, education policy research suggests that schools could offset the effects of low SES (Ladd, 2012), partially reflecting the historical observation that schooling has often served as the route to prosperity and social mobility (Goldin & Katz, 2008). This view, together with the Mutualism theory, suggests that SES may mostly affect the relations between *Gf* and reading/mathematics in early development. As children progress in school, the *Gf* development and the relations between *Gf* and reading/mathematics are being mostly influenced by schooling or experiences with reading/mathematics, not so much by SES.

With respect to the genetic effects, studies showed that the influence of genetics and environment (e.g., SES) on academic performance was a function of age. Specifically, individual differences in academic achievement are substantially heritable (Gill, Jardine, & Martin, 1985; Plomin, DeFries, Knopik, & Neiderhiser, 2016). The heritability increases with age while the environmental influence decreases with age (Haworth et al., 2007, 2009; Kovas et al., 2007, 2013; Shakeshaft et al., 2013). The high heritability of academic performance is attributable to influence of many heritable factors including (but not limited to) *Gf*, self-efficacy, personality, and behavior problems, among which *Gf* is the most important one (Krapohl et al., 2014). This finding suggests that the relations between *Gf* on reading/mathematics may be less subjective to environmental influences such as SES in later ages.

Research Questions

To sum, this meta-analysis seeks to address four major questions. First, are there significant relations between *Gf* and reading/mathematics, and if so, what is the size or strength of these relations? Second, are the relations between *Gf* and reading/mathematics affected by types of *Gf* tasks, types of reading/mathematics skills, age, or SES? Third, is there an interaction between age and SES on the relations between *Gf* and reading/mathematics? Fourth, does *Gf* predict reading/mathematics after patialling out initial reading/mathematics, and does reading/mathematics predict *Gf* after partialing out initial *Gf*?

Based on our literature review, we have the following hypotheses for those research questions: (a) *Gf* is significantly related to reading/mathematics. *Gf* is more strongly related to mathematics than to reading. The relations between *Gf* and reading/mathematics may differ by different *Gf* tasks and different reading/mathematics skills. (b) Based on the Investment theory, we predict that *Gf* is significantly related to reading/mathematics, and the strength of these relations would decrease with age; *Gf* predicts reading/mathematics longitudinally, but reading/mathematics does not predict *Gf* longitudinally. (c) Based on the Mutualism theory, we predict that *Gf* is not or weakly related to reading/mathematics early on, but the strength of these relations increases with age; reading/mathematics and *Gf* predict each other in the development. (d) Based on reading/mathematics curriculum hypothesis, as individuals become more fluent in foundational reading (code skills) and mathematics (numerical knowledge and calculation) skills through school, the relations between *Gf* and these foundational skills may decrease with age, in line with the Investment theory and intrinsic cognitive load theory. In contrast, the relations between *Gf* and more complex reading (comprehension skills) and mathematics (word problems and fraction and algebra) skills may increase with age, in line with the Mutualism theory and intrinsic cognitive load theory. (e) Based on the gene–SES interaction hypothesis, schooling effect hypothesis, and genetic effect hypothesis, we predict an interaction between SES and age on the relations between *Gf* and reading/mathematics: the relations between *Gf* and reading/mathematics may be stronger among young children with higher SES than young children with lower SES; SES may not exert significant effects on the relations between *Gf* and reading/mathematics in later development because of increasing schooling effects or genetic effects.

Method

Literature Search

Articles for this meta-analysis were identified in three ways. First, a computer search of the Academic Search Premier, Education Resources Information Center, Google Scholar, and PsycINFO for literature was conducted. We used the earliest possible start date till October 2017. Titles, abstracts, and keywords were searched for the following terms: ("non-verbal intelligence" OR "non-verbal abilit*" OR "fluid intelligence" OR "reasoning" OR "Fluid abilit*" OR "general intelligence" "Raven's" OR "Raven" OR "culture fair" OR "culture-fair" OR "Kaufman" OR "Wechsler" OR "Woodcock–Johnson" OR "Woodcock Johnson" OR "Stanford–Binet" OR "Differential Ability Scale*") AND ("reading" OR "decoding" OR "word identification" or "word recognition" OR "comprehension" OR "vocabulary" OR "language" OR math* OR "arithmetic" OR "calcul*" OR "computation" OR num* OR fraction* OR algebr* OR "word problem*" OR "problem solving" OR "problem-solving"). * can help include different forms of search terms (e.g., calcul* can include calculation and calculating). Second, we searched unpublished literature through Dissertation and Masters Abstract indexes in ProQuest and Cochrane Database of Systematic Reviews. Third, we searched in previous relevant reviews and also contacted researchers to request correlation tables not provided in their reported studies. The initial search yielded 43,584 studies. Three authors of this study then reviewed all studies by titles and abstracts. After excluding the duplicate 29 articles and 35,190 irrelevant articles, the remaining 8,365 articles were closely reviewed using the specific criteria described below (see Figure 1 for the flow diagram for the search and inclusion criteria for studies in the present review).

First, studies have to include at least one quantitative task measuring *Gf* and at least one quantitative task measuring reading or mathematics. *Gf* measures refer to the tasks that majorly tap nonverbal reasoning skills including matrix reasoning, nonmatrix reasoning (e.g., series completion, classification, analogies), visuospatial reasoning, and composite nonverbal reasoning such as performance intelligence and perceptual organization (see Table 1 for definitions of different *Gf* tasks and task examples). Reading measures refer to the tasks that tap one of the following skills: phonological awareness, orthographic awareness, word/nonword reading, vocabulary, reading comprehension, and comprehensive reading that tap at least two of the above-mentioned reading skills (see Table 1 for definitions of different reading skills and task examples). Mathematics measures refer to the tasks that tap one of the following skills: numerical knowledge (e.g., counting, subsitizing, number comparison), calculation, word problems, fraction, and algebra (see Table 1 for definitions of different mathematics skills and task examples). Second, studies have to report at least one correlation (r) between any measure of *Gf* and any measure of reading/mathematics, or the percentage of variance (R^2) in reading/mathematics (*Gf*) accounted for by *Gf* (reading/mathematics) only.

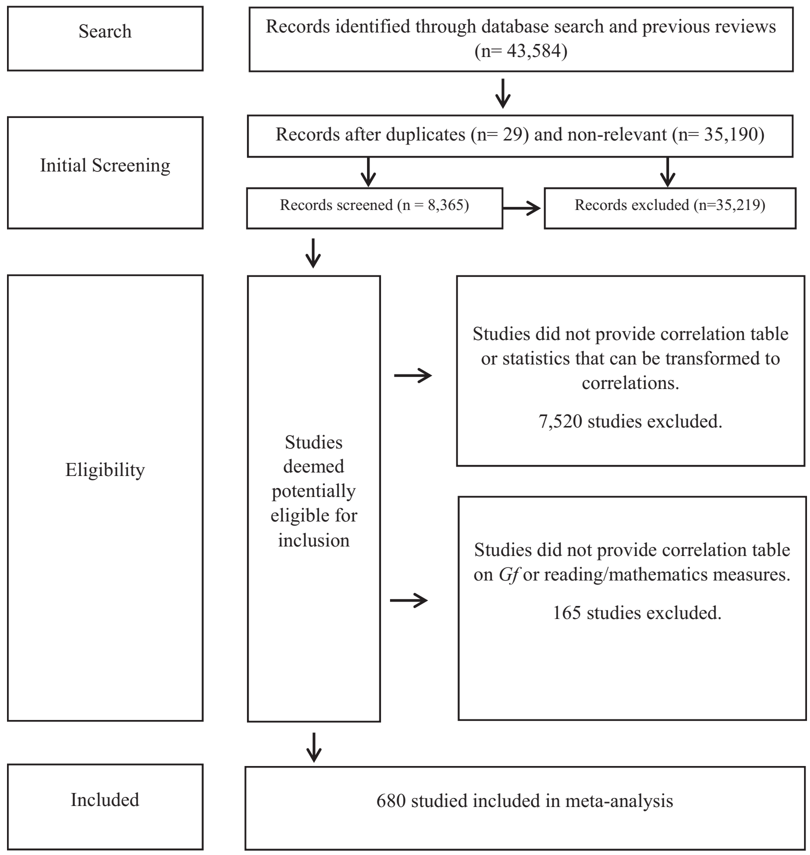

Figure 1. Flow diagram for the search and inclusion criteria for studies in the present review.

Coding Procedure

Studies were coded according to the characteristics of participants and tasks used to measure *Gf* and reading/mathematics. In addition to these variables, we also coded the country SES and family SES. Country SES is coded as either developing country or developed country based on Country classification report from United Nations (United Nations, 2014). Family SES is coded as middle class or above and below middle class based on two resources from the original studies. One is the direct report of family SES (e.g., middle class) from the study. If the study did not explicitly define family SES but provided relevant SES information (e.g., parental education level; years of education, income level, and free-reduced lunch rate), we coded the family SES based on this information in reference to the overall population from the region/country where the study was conducted. We also coded number of participants (*N*) for each correlation, which was needed to weight each effect size, so that correlations obtained from larger samples were given more weight in the analysis than those obtained from smaller samples. The important features of individual studies are provided in the online supplemental materials.

Variables were discussed until a consensus was reached between the first and the second authors. Then, using this coding system, the first author and one trained research assistant (with a masters' degree in psychology) each independently coded half of the included studies, while the second author and another trained research assistant (with a masters' degree in psychology) each independently coded the other half of the included studies. The interrater reliability among four coders was .85 ~ 1.00 for all variables of interests in this study. Any disagreements were resolved by consulting the original article or by discussion.

Missing Data

Not all studies provided sufficient information on the variables of interest for the present study. In case of insufficient information, authors were contacted to obtain the missing information. However, if missing data could not be retrieved, especially for data missing for moderator variables, the studies were excluded from the moderator analyses for which data were missing but were included in all moderator analyses for which data were provided.

Analytic Strategies

The effect size index used for all outcome measures is Pearson's *r*, the correlation between *Gf* and reading/mathematics. We considered all eligible effect sizes in each study. That is, studies could contribute multiple effect sizes as long as the sample for each effect size was independent. For studies that reported multiple effect sizes from the same sample, we accounted for the statistical dependencies using the random effects robust standard error estimation technique developed by Hedges, Tipton, and Johnson

Table 1
Description of Codes and Examples of Response Categories for Types of Gf, Reading, and Mathematics Tasks

Types of task	Definition	Examples of response categories
Gf tasks		
Matrix reasoning	Tasks that require individuals to identify a rule underlying an incomplete matrix of geometric figures and subsequently use this rule to generate an answer to a question about which one of several geometric figures would satisfy the rule.	Raven's Matrices, Wechsler Abbreviated Scale of Intelligence Matrices; Stanford-Binet Matrices; BAS Matrices; MAT-Matrices; KBIT-Matrices; Latin Square Task; KABC-Matrices
Nonmatrix reasoning	Tasks that tap the ability to identify a rule underlying a set of pictures by inductive reasoning or deductive reasoning or both. The tasks could be in the form of analogies, series, or classifications etc.	Analysis-Synthesis; Concept Formation; Topology; Test of Nonverbal Intelligence; Stanford–Binet Pattern Analysis; Picture Analogies and Sequences; Series Completion; Pattern Recognition; Geometric Sequences; Figural Analogical Reasoning; Classifications; Abstract Reasoning
Visuospatial reasoning	Tasks that not only require non-verbal reasoning, but also rely heavily on the ability to generate, store, retrieve, and transform visual images and sensations.	Block Design, Picture Completion; Object Assembly; Spatial Reasoning; Picture Concepts; Pattern Construction; Cube Design
Composite nonverbal reasoning	Synthesized scores derived from a hybrid of tasks that tap at least two or more of the above mentioned non-verbal reasoning tasks.	Performance IQ; Perceptual Reasoning; Perceptual Organization; Wechsler Nonverbal Scale of Ability
Reading tasks		
Code-focused reading	Phonological Processing: Tasks that tap the ability to identify and manipulate units of oral language parts (words, syllables, onsets and rimes, and phonemes) and phonological codes retrieval efficiency;	Identify the rhyme of words; Identify initial sounds or final sounds in words; Identify medial sounds in words; Segment words into their component syllable/sound; delete/add sounds from/to words; Sound blending; Name letters/digits/colors/objects rapidly
	Orthographic Awareness: the probable sequence and positions of letters/radicals within words/characters.	Judgement of whether a letter string is looks like a word. Spelling of non-words;
	Decoding: Tasks that tap the ability to translate written language into speech with accuracy and fluency	Real word recognition, Non-word reading; reading word list, Accuracy/fluency of passage/sentence reading
Comprehension-focused reading	Vocabulary: Tasks that require individuals to point to a picture corresponding to a word or explain what a word means	Peabody Picture Vocabulary Test, Wechsler Abbreviated Scale of Intelligence-Vocabulary, Nelson Reading Skills Test-Vocabulary, Word production fluency (e.g., say words that start with letter B); Extended Range Vocabulary Test
	Comprehension: Tasks that require individuals to comprehend a passage in either oral format (listening comprehension) or written format (reading comprehension).	Nelson Denny Reading Comprehension; Woodcock Reading Mastery Tests-Reading Comprehension; Gray Oral Reading Comprehension Tests; The Peabody Individual Achievement Test- Reading Comprehension
Mathematics tasks		
Numerical knowledge	Questions that tap numerosity (i.e., cardinality) as well as the relation between numbers (i.e., ordinality), counting words, and Arabic digits (i.e., symbolic knowledge)	Counting; Seriation; Classification of Numbers; Number Comparison; Compare Pairs of Piles of Objects; Quantity Estimation; Number Line; Number Identification/Naming; Early Numeracy Test; Place Value; Transcoding from Arabic to Verbal Numerals
Calculation	Single-digit or multi-digit addition, subtraction, multiplication, and division	Addition (e.g., $2 + 1 =$; $20 + 60 =$;), Subtraction (e.g., $6 - 4 =$; $20 - 15 =$), Division (e.g., $6/2 =$; $20/10 =$), Multiplication (e.g., $2 \times 4 =$; $20 \times 12 =$;); WJ-Math Fluency; CBM-Calculation; WRAT-4-Math; WIAT-Arithmetic
Word problems	Questions that involves the ability to understand the problem narrative, focus on relevant and ignore irrelevant information, construct a number sentence, and solve for the missing number to find the answer	WISC-Word Problem; Arithmetic Word Problems (e.g., John had nine pennies. He spent three pennies at the store. How many pennies did he have left?); Key-Math Problem Solving
Fraction	Questions that tap the understanding of the part-whole relation, measurement interpretation of fractions, and math problems that involve fractional quantities	Fractions Calculations (e.g., ¼ + ½); Fractions Comparisons (e.g., ¼ ___ ½); NAEP-Fraction; Symbol-Picture Correspondence; Calculations and Word Problem-Solving Involving Fractions; Fractional Estimate

(*table continues*)

Table 1 (*continued*)

Types of task	Definition	Examples of response categories
Algebra	Problems that can be solved by prelearned symbol manipulation algorithms that are taught in many algebra curricula	Algebra Problem Solving (e.g., if $x + 2 = 3$, then $x - 5 =$); Algebra Judgement (e.g., $3y + 2 = 20$; $y = 2$)

(2010). This analysis allowed for the clustered data (i.e., effect sizes nested within samples) by correcting the study standard errors to take into account the correlations between effect sizes from the same sample. The robust standard error technique requires that an estimate of the mean correlation (ρ) between all the pairs of effect sizes within a cluster be estimated for calculating the between-study sampling variance estimate, τ^2. In all analyses, we estimated τ^2 with $\rho = .80$; sensitivity analyses showed that the findings were robust across different reasonable estimates of ρ.

Analyses were based on Borenstein, Hedges, Higgins, and Rothstein's (2005) recommendations. Specifically, we converted the correlation coefficients to Fisher's *Z* scale, and all analyses were performed using the transformed values. The results, such as the summary effect and its confidence interval, were then converted back to correlation coefficients for presentation. Also, because we hypothesized that this body of research reports a distribution of correlation coefficients with significant between-studies variance, as opposed to a group of studies that attempts to estimate one true correlation, a random-effects model was appropriate for the current study (Lipsey & Wilson, 2001). Weighted, random-effects metaregression models using Hedges et al.'s (2010) corrections were run with ROBUMETA in Stata (Hedberg, 2014) to summarize correlation coefficients and to examine potential moderators.

Specifically, we first estimated only the overall weighted mean correlations between *Gf* and reading/mathematics, respectively. Then, subgroup analyses were used to examine the relations between *Gf* and reading/mathematics for each subgroup of each moderator. Metaregression analyses were used to examine whether types of *Gf* tasks, types of reading/mathematics skills, age, and SES moderated the relations between *Gf* and reading/mathematics. For the moderation analysis, all moderators were entered into the model simultaneously, with publication type (peer reviewed vs. other types of publications), publication years, and sample status (typically developing vs. atypically developing) as the covariates in the model as well. For categorical moderators, we created dummy coded variables to examine the comparisons among categories (Cohen, Cohen, West, & Aiken, 2013).

To examine the relations between *Gf* and reading/mathematics longitudinally, we calculated (a) the correlations between reading/mathematics measured at Time 1 and *Gf* measured at Time 2 (a later time point), partialing out the relations between reading/mathematics measured at Time 1 and Time 2, and (b) the correlations between *Gf* measured at Time 1 and reading/mathematics measured at Time 2 (a later time point), partialing out the relations between *Gf* measured at Time 1 and Time 2. The partial correlations was done based on the correlation matrices retrieved from the original studies. We then synthesized these partial correlations to indicate whether reading/mathematics measured earlier predict *Gf* later or vice versa. We accounted for the statistical dependencies of multiple partial correlations from one study using the random effects robust standard error estimation technique developed by Hedges et al. (2010) as mentioned earlier.

Publication bias (the problem of selective publication, in which the decision to publish a study is influenced by its results) was examined using the method of Egger, Davey Smith, Schneider, and Minder (1997) and funnel plot. We did not find significant publication bias based on Egger et al.'s (1997) publication bias statistics (i.e., the standard errors of correlations did not significantly predict correlations among studies with ROBUMETA in Stata, $ps > .07$)

Results

Based on our inclusion criteria, 680 studies (including nine non–peer-reviewed articles) involving 793 independent samples, 374,577 participants, and 5,117 correlations between *Gf* and reading/mathematics were included for the final analyses. The size of the relation between *Gf* and reading (including all reading skills) was $r = .38$, 95% CI [.36, .39], and $r = .41$, 95% CI [.39, 44] for *Gf* and mathematics (including all mathematics skills). Next, we examined the relations between *Gf* and reading/mathematics for the subcategory of each moderator, and whether types of *Gf* tasks, types of reading/mathematics skills, age and SES affected the relations between *Gf* and reading/mathematics.

Moderation Effects of *Gf* Tasks

With respect to the relations between *Gf* and reading, there are 1,426 correlations involving matrix reasoning, 406 correlations involving nonmatrix reasoning, 667 correlations involving visuospatial reasoning, and 831 correlations involving composite nonverbal reasoning. As Table 2 shows, the average correlation between reading (including all reading skills) and *Gf* for each of the four *Gf* tasks was significant: matrix reasoning, $r = .35$, 95% CI [.33, .36]; nonmatrix reasoning, $r = .35$, 95% CI [.31, .39]; visuospatial reasoning, $r = .33$, 95% CI [.30, .35]; composite nonverbal reasoning, $r = .45$, 95% CI [.42, .47]. As Table 3 shows, after controlling for covariates and other moderators, composite nonverbal reasoning was more strongly related to reading than were matrix reasoning and visuospatial reasoning, $\beta = .06/.08$, $t = 2.15/3.03$, $ps < .05$, $\tau^2 = .03$. No significant differences were found in other comparisons.

We next examined the moderation of *Gf* tasks for each type of reading. For code skills, as Table 4 shows, after controlling for covariates and other moderators, matrix reasoning, nonmatrix reasoning, and composite nonverbal reasoning were more strongly related to code skills than were visuospatial reasoning, $\beta = .09/.12/.11.$, $t = 2.49/2.32/2.75$, $ps < .05$, $\tau^2 = .02$. For comprehension skills, as Table 4 shows, after controlling for covariates and other moderators, types of *Gf* tasks did not affect the relation between *Gf* and comprehension skills.

Table 2
Correlations Between Gf and Reading and Mathematics

Measure	*Gf*–Reading				*Gf*–Mathematics			
	k	*r*	95% CI of *r*	τ^2	*k*	*r*	95% CI of *r*	τ^2
Main average correlation	3340	.38	[.36, .39]	.07	1129	.41	[.39, .44]	.11
Publication type								
1. Peer-reviewed	3256	.38	[.36, .39]	.08	1107	.41	[.39, .43]	.11
2. Non–peer-reviewed	84	.49	[.34, .62]	.06	22	.49	[.03, .76]	.09
Sample								
1. Typical developing	2259	.37	[.35, .39]	.07	252	.42	[.39, .47]	.04
2. Atypical developing	1081	.39	[.36, .42]	.09	877	.41	[.39, .43]	.10
Country SES								
1. Developed country	3120	.38	[.36, .40]	.08	1042	.42	[.40, .45]	.10
2. Developing country	220	.36	[.28, .43]	.06	87	.32	[.20, .42]	.07
Family SES								
1. Middle class or above	2598	.37	[.36, .39]	.08	241	.45	[.40, .49]	.07
2. Below middle class	742	.39	[.36, .41]	.04	398	.40	[.36, .43]	.03
Types of *Gf* tasks								
1. Matrix reasoning	1426	.35	[.33, .36]	.04	552	.39	[.35, .42]	.05
2. Nonmatrix reasoning	406	.35	[.31, .39]	.02	205	.43	[.37, .48]	.06
3. Visuospatial reasoning	677	.33	[.30, .35]	.03	190	.38	[.35, .41]	.02
4. Composite nonverbal reasoning	831	.45	[.42, .47]	.07	182	.45	[.42, .49]	.08
Types of reading skills								
1. Code reading	1125	.29	[.27, .31]	.03				
2. Meaning reading	1744	.37	[.35, .39]	.04				
3. Comprehensive reading	400	.49	[.45, .52]	.05				
Types of mathematics skills								
1. Numerical processing					236	.35	[.31, .40]	.05
2. Calculation					340	.35	[.31, .37]	.03
3. Word problems					207	.43	[.40, .45]	.01
4. Fraction and algebra					13	.37	[.23, .50]	.04
5. Comprehensive mathematics					267	.46	[.43, .49]	.10

Note. *k* = number of effect sizes; CI = confidence interval, τ^2 = Between-study sampling variance.

With respect to the relations between *Gf* and mathematics, there are 552 correlations involving matrix reasoning, 205 correlations involving nonmatrix reasoning, 190 correlations involving visuospatial reasoning, and 182 correlations involving composite nonverbal reasoning. As Table 2 shows, the average correlation between mathematics and *Gf* for each of the four Gf tasks was significant: matrix reasoning, $r = .39$, 95% CI [.35, .42]; nonmatrix reasoning, $r = .43$, 95% CI [.37, .48]; visuospatial reasoning, $r = .38$, 95% CI [.35, .41]; composite nonverbal reasoning, $r = .45$, 95% CI [.42, .49]. As Table 3 shows, after controlling for covariates and other moderators, composite nonverbal reasoning was more strongly related to mathematics than was visuospatial reasoning, $\beta = .09$, $t = 2.34$, $p < .05$, $\tau^2 = .03$. No significant differences were found in other comparisons.

We next examined the moderation of *Gf* tasks for each type of mathematics. For numerical knowledge, as Table 5 shows, after controlling for covariates and other moderators, matrix reasoning and nonmatrix reasoning were more related to numerical knowledge than were visuospatial reasoning, $\beta = .13/.34$, $t = 2.42/3.34$, $p = .02/.003$, $\tau^2 = .03$; composite nonverbal reasoning was more related to numerical knowledge than were matrix reasoning and visuospatial reasoning, $\beta = .27/.41$, $t = 2.88/4.25$, *p*s $< .01$, $\tau^2 = .03$. For calculation skills, as Table 5 shows, after controlling for covariates and other moderators, types of *Gf* tasks did not affect the relation between *Gf* and calculation skills. For word problems, as Table 5 shows, after controlling for covariates and other moderators, types of *Gf* tasks did not affect the relation between *Gf* and calculation skills. Because of insufficient effect sizes for fraction and algebra, we didn't run the moderation analysis for types of *Gf* tasks.

Taken together, these findings showed that the relations between *Gf* and reading/mathematics were affected by types of *Gf* tasks. Among *Gf* tasks, composite nonverbal reasoning showed the strongest relations with overall reading and subtypes of reading as well as with overall mathematics and subtypes of mathematics, whereas matrix reasoning and visuospatial reasoning showed relatively weaker relations to reading and mathematics.

Moderation Effects of Reading/Mathematics Skills

We first ran a model to examine whether *Gf* related to reading and mathematics differently. After controlling for covariates and other moderators, *Gf* showed stronger relations to mathematics than to reading, $\beta = .05$, $t = 3.31$, $p = .001$, $\tau^2 = .04$. Next, we examined whether *Gf* relate to different reading skills and mathematics skills to varying degrees.

With respect to reading, we were mostly interested in code skills (1125 correlations) and comprehension skills (1,744 correlations). As Table 2 shows, the average correlation between *Gf* and each of the two reading types was significant: code skills, $r = .29$, 95% CI [.27, .31]; comprehension skills, $r = .37$, 95% CI [.35, .39]. As Table 3 shows, after controlling for covariates and other moderators, comprehension skills were more strongly related to *Gf* than were code skills, $\beta = .08$, $t = 4.04$, $p < .001$, $\tau^2 = .03$.

Table 3
Moderations on the Correlations Between Gf and Reading and Mathematics

Correlation	β	*SE*	*t*	95% CI	*p* value
Gf–Reading					
Publication year	.001	.001	.99	[−.001, .003]	.32
Publication type					
Peer-reviewed vs. non–peer-reviewed	**−.24**	**.09**	**−2.83**	**[−.41, −.07]**	**.01**
Sample type					
Typical developing vs. atypical developing	**−.06**	**.03**	**−2.52**	**[−.11, −.01]**	**.01**
Country SES					
Developed country vs. developing country	−.05	.08	−.72	[−.20, .10]	.47
Family SES					
Middle class or above vs. below middle class	−.03	.02	−1.75	[−.07, .004]	.08
Age	**.003**	**.001**	**5.06**	**[.002, .004]**	**<.001**
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.008	.03	.22	[−.06, .08]	.82
Visuospatial reasoning vs. matrix reasoning	−.02	.02	−1.04	[−.06, .02]	.30
Composite nonverbal reasoning vs. matrix reasoning	**.06**	**.03**	**2.15**	**[.005, .11]**	**.03**
Visuospatial reasoning vs. nonmatrix reasoning	−.03	.04	−.81	[−.10, .04]	.42
Composite nonverbal reasoning vs. nonmatrix reasoning	.05	.04	1.23	[−.03, .12]	.22
Composite nonverbal reasoning vs. visuospatial reasoning	**.08**	**.03**	**3.03**	**[.03, .13]**	**<.01**
Types of reading skills					
Comprehension vs. code	**.08**	**.02**	**4.04**	**[.04, .12]**	**<.001**
Comprehensive vs. code	**.13**	**.03**	**4.49**	**[.08, .19]**	**<.001**
Comprehensive reading vs. comprehension	.05	.03	1.85	[−.003, .11]	.07
Gf–Mathematics					
Publication year	.001	.001	.61	[−.002, .004]	.54
Publication type					
Peer-reviewed vs. non–peer-reviewed	−.18	.17	−1.10	[−.58, .17]	.27
Sample Type					
Typical developing vs. atypical developing	−.06	.04	−1.53	[−.13, .02]	.13
Country SES					
Developed country vs. developing country	.01	.08	.18	[−.14, .17]	.86
Family SES					
Middle class or above vs. below middle class	.02	.03	.61	[−.04, .08]	.54
Age	**.003**	**.001**	**3.60**	**[.001, .005]**	**<.001**
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.08	.06	1.30	[−.04, .20]	.20
Visuospatial reasoning vs. matrix reasoning	−.01	.03	−.44	[−.08, .05]	.66
Composite nonverbal reasoning vs. matrix reasoning	.08	.04	1.95	[−.001, .16]	.05
Visuospatial reasoning vs. nonmatrix reasoning	−.09	.07	−1.40	[−.23, .04]	.16
Composite nonverbal reasoning vs. nonmatrix reasoning	−.002	.07	−.02	[−.14, .14]	.98
Composite nonverbal reasoning vs. visuospatial reasoning	**.09**	**.04**	**2.34**	**[.01, .17]**	**.02**
Types of mathematics skills					
Calculation vs. numerical knowledge	−.05	.04	−1.20	[.14, .03]	.23
Word problems vs. numerical knowledge	.04	.04	.96	[−.04, .12]	.34
Fraction and algebra vs. numerical knowledge	.10	.11	.90	[−.12, .31]	.37
Comprehensive mathematics vs. numerical knowledge	.05	.05	1.12	[−.04, .15]	.26
Word problems vs. calculation	**.09**	**.04**	**2.41**	**[.02, .17]**	**.02**
Fraction and algebra vs. calculation	.15	.11	1.41	[−.06, .36]	.16
Comprehensive mathematics vs. calculation	**.10**	**.04**	**2.76**	**[.03, .18]**	**<.01**
Fraction and algebra vs. word problems	.06	.10	.58	[−.14, .26]	.56
Comprehensive mathematics vs. word problems	.01	.04	.30	[−.07, .10]	.76
Comprehensive mathematics vs. fraction and algebra	−.04	.11	−.42	[−.25, .17]	.68

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within categorical moderators are all listed in the model. CI = confidence interval. The second group in each group comparison variable is the reference group (e.g., in Developed Country vs. Developing Country, Developing Country is the reference group in the dummy coding of Country SES). For the *Gf*–Reading model, there are 1,566 correlations and 354 independent samples. For the *Gf*–Mathematics model, there are 619 correlations and 147 independent samples. Between-study sampling variance (τ^2) is .03 for both models. The bold variables are significant moderators.

With respect to mathematics, we focused on four skills: numerical knowledge (236 correlations), calculation (340 correlations), word problems (207 correlations), fraction, and algebra (13 correlations). As Table 2 shows, the average correlation between *Gf* and each of the four mathematics skills was significant: numerical knowledge, r = .35, 95% CI [.31, .40]; calculation, r = .35, 95% CI [.31, .37]; word problems, r = .43, 95% CI [.40, .45], fraction and algebra, r = .37, 95% CI [.23, .50]. As Table 3 shows, after controlling for covariates and other moderators, word problems were more strongly related to *Gf* than was calculation, β = .09, t =

Table 4
Moderations on the Correlations Between Gf and Different Types of Reading

Correlation	β	*SE*	*t*	95% CI	*p* value
Gf–Code					
Publication year	−.001	.001	−.69	[−.004, .002]	.49
Publication type					
Peer-reviewed vs. non–peer-reviewed	**−.17**	**.06**	**−2.95**	**[−.28, −.06]**	**<.01**
Sample type					
Typical developing vs. atypical developing	.001	.04	.02	[−.07, .07]	.99
Country SES					
Developed country vs. developing country	.14	.07	1.95	[−.002, .28]	.05
Family SES					
Middle class or above vs. below middle class	−.02	.03	−.58	[−.08, .04]	.56
Age	**.003**	**.001**	**2.58**	**[.001, .005]**	**.01**
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.03	.05	.59	[−.06, .12]	.56
Visuospatial reasoning vs. matrix reasoning	**−.09**	**.04**	**−2.49**	**[−.16, −.02]**	**.01**
Composite nonverbal reasoning vs. matrix reasoning	.02	.04	.59	[−.06, .10]	.43
Visuospatial reasoning vs. nonmatrix reasoning	**−.12**	**.05**	**−2.32**	**[−.22, −.02]**	**.02**
Composite nonverbal reasoning vs. nonmatrix reasoning	−.004	.05	−.08	[−.10, .10]	.94
Composite nonverbal reasoning vs. visuospatial reasoning	**.11**	**.04**	**2.75**	**[.03, .20]**	**.01**
Gf–Comprehension					
Publication year	.002	.001	1.91	[−.0001, .004]	.06
Publication type					
Peer-reviewed vs. non–peer-reviewed	**−.33**	**.10**	**−3.30**	**[−.52, −.13]**	**<.01**
Sample type					
Typical developing vs. atypical developing	**−.07**	**.03**	**−2.50**	**[−.13, −.02]**	**.01**
Country SES					
Developed country vs. developing country	−.06	.10	−.67	[.25, .12]	.50
Family SES					
Middle class or above vs. below middle class	−.01	.02	−.49	[−.05, .03]	.62
Age	**.003**	**.001**	**4.76**	**[.002, .004]**	**<.001**
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.02	.04	.62	[−.05, .10]	.54
Visuospatial reasoning vs. matrix reasoning	.01	.02	.24	[−.04, .05]	.81
Composite nonverbal reasoning vs. matrix reasoning	.06	.03	1.83	[−.004, .12]	.07
Visuospatial reasoning vs. nonmatrix reasoning	−.02	.04	−.46	[−.10, .06]	.65
Composite nonverbal reasoning vs. nonmatrix reasoning	.03	.05	.71	[−.06, .13]	.48
Composite nonverbal reasoning vs. visuospatial reasoning	.05	.03	1.77	[−.01, .11]	.08

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within categorical moderators are all listed in the model. CI = confidence interval. The second group in each group comparison variable is the reference group (e.g., in Developed Country vs. Developing Country, Developing Country is the reference group in the dummy coding of Country SES). For the *Gf*–Code model, there are 483 correlations from 145 independent samples. For the *Gf*–Comprehension model, there are 880 correlations from 272 independent samples. For the *Gf*–Comprehensive Reading model, there are 203 correlations from 107 independent samples. Between-study sampling variance (τ^2) is .02 ~ .05 across models. The bold variables are significant moderators.

2.45, $p < .05$, $\tau^2 = .03$. No significant differences were found in other comparisons.

Moderation Effects of SES

We examined two SES variables: family SES and country SES. With respect to the relations between *Gf* and reading, we coded 742 correlations from studies based on participants with below-middle-class background, and 847 correlations from studies based on participants with middle class or above background. We also coded 220 correlations from studies conducted in developing countries, and 3,120 correlations from studies conducted in developed countries. As Table 2 shows, the average correlation between reading and *Gf* for each of the two family SES level was significant: below middle class, $r = .39$, 95% CI [.36, .41]; middle class and above, $r = .37$, 95% CI [.36, .39]. The average correlation between reading and *Gf* for each of two country SES level was significant: developing countries, $r = .36$, 95% CI [.28, .43]; developed countries, $r = .38$, 95% CI [.36, .40]. As Table 3 and 4 show, after controlling for covariates and other moderators, neither country SES nor family SES affected the relations between *Gf* and reading or different types of reading.

With respect to the relations between *Gf* and mathematics, we coded 398 correlations from studies based on participants with below-middle-class families, and 241 correlations from studies based on participants with middle class or above background. We also coded 87 correlations from studies conducted in developing countries, and 1042 correlations from studies conducted in developed countries. As Table 2 shows, the average correlation between *Gf* and mathematics for each of the two family SES level was significant: below middle class, $r = .40$, 95% CI [.36, .43]; middle class and above, $r = .45$, 95% CI [.40, .49]. The average correlation between mathematics and *Gf* for each of two country SES level was significant: developing countries, $r = .32$, 95% CI [.20,

Table 5
Moderations on the Correlations Between Gf and Different Types of Mathematics

Correlation	β	*SE*	*t*	95% CI	*p* value
Gf–Numerical knowledge					
Publication year	−.002	.004	−.52	[−.01, .01]	.61
Publication type					
Peer-reviewed vs. non–peer-reviewed	—	—	—	—	—
Sample type					
Typical developing vs. atypical developing	−.06	.09	−.70	[−.24, .12]	.49
Country SES					
Developed country vs. developing country	−.04	.06	−.55	[−.17, .10]	.59
Family SES					
Middle Class or above vs. below middle class	−.004	.07	−.06	[−.16, .15]	.95
Age	.002	.001	1.82	[−.0002, .004]	.08
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.20	.10	2.03	[−.003, .41]	.05
Visuospatial reasoning vs. matrix reasoning	**−.13**	**.05**	**−2.42**	**[−.24, −.02]**	**.02**
Composite nonverbal reasoning vs. matrix reasoning	**.27**	**.10**	**2.88**	**[.08, .47]**	**.01**
Visuospatial reasoning vs. nonmatrix reasoning	**−.34**	**.10**	**−3.34**	**[−.54, −.13]**	**<.01**
Composite nonverbal reasoning vs. nonmatrix reasoning	.07	.13	.55	[−.19, .33]	.59
Composite nonverbal reasoning vs. visuospatial reasoning	**.41**	**.10**	**4.25**	**[.21, .60]**	**<.001**
Gf–Word problems					
Publication year	−.004	.004	−1.02	[−.01, .004]	.31
Publication type					
Peer-reviewed vs. non–peer-reviewed	—	—	—	—	—
Sample type					
Typical developing vs. atypical developing	−.05	.06	−.86	[−.18, .07]	.40
Country SES					
Developed country vs. developing country	−.07	.06	−1.22	[−.18, .05]	.23
Family SES					
Middle class or above vs. below middle class	.09	.06	1.43	[−.04, .22]	.16
Age	−.001	.001	−.54	[−.003, .002]	.59
Types of *Gf* tasks					
Nonmatrix reasoning vs. matrix reasoning	.10	.05	1.99	[−.002, .20]	.06
Visuospatial reasoning vs. matrix reasoning	.07	.06	1.22	[−.05, .20]	.23
Composite nonverbal reasoning vs. matrix reasoning	.11	.08	1.32	[−.06, .28]	.20
Visuospatial reasoning vs. nonmatrix reasoning	−.03	.08	−.35	[−.18, .13]	.73
Composite nonverbal reasoning vs. nonmatrix reasoning	.01	.09	.11	[−.18, .20]	.91
Composite nonverbal reasoning vs. visuospatial reasoning	.04	.08	.45	[−.13, .20]	.65
Gf–calculation					
Publication year	−.001	.003	−.24	[−.006, .005]	.81
Publication type					
Peer-reviewed vs. non–peer-reviewed	**−.16**	**.07**	**−2.42**	**[−.29, −.03]**	**.02**
Sample type					
Typical developing vs. atypical developing	−.08	.05	−1.65	[−.17, .02]	.11
Country SES					
Developed country vs. developing country	−.11	.07	−1.68	[−.24, .02]	.10
Family SES					
Middle class or above vs. below middle class	.05	.06	.85	[−.06, .16]	.40
Age	**.004**	**.002**	**2.15**	**[.0003, .008]**	**.04**
Types of *Gf* tasks					
Non-matrix reasoning vs. matrix reasoning	.06	.08	.71	[−.11, .23]	.48
Visuospatial reasoning vs. matrix reasoning	−.03	.04	−.80	[−.12, .05]	.43
Composite nonverbal reasoning vs. matrix reasoning	.04	.07	.54	[−.11, .18]	.59
Visuospatial reasoning vs. nonmatrix reasoning	−.09	.09	−1.01	[−.28, .09]	.32
Composite nonverbal reasoning vs. nonmatrix reasoning	−.02	.11	−.18	[−.25, .21]	.86
Composite nonverbal reasoning vs. visuospatial reasoning	−.07	.07	1.07	[−.06, .21]	.29

Note. All moderators were entered in one model. Several models were run for thorough subgroup comparisons among moderators with more than two categories. For the convenience of presentation, subgroup comparisons within categorical moderators are all listed in the model. CI = confidence interval. The second group in each group comparison variable is the reference group (e.g., in Developed Country vs. Developing Country, Developing Country is the reference group in the dummy coding of Country SES). For the *Gf*–Numerical knowledge model, there are 139 correlations from 34 independent samples. For the *Gf*–Calculation model, there are 204 correlations from 68 independent samples. For the *Gf*–Word Problems model, there are 155 correlations from 40 independent samples. For the *Gf*–Comprehensive Mathematics model, there are 112 correlations from 59 independent samples. Between-study sampling variance (τ^2) is .02 ~ .06 across models. We did not run moderation analyses for Fraction and Algebra because of insufficient effect sizes ($n = 13$). The bold variables are significant moderators.

.42]; developed countries $r = .42$, 95% CI [.40, .45]. As Table 3 and 5 show, after controlling for covariates and other moderators, neither country SES nor family SES affected the relations between *Gf* and mathematics or different mathematics skills.

Moderation Effects of Age

Next, we investigated whether age affected the relations between *Gf* and reading/mathematics. With respect to the relation between *Gf* and reading, after controlling for covariates and other moderators, age significantly affected the relation between *Gf* and reading, $\beta = .003$, $t = 5.06$; $p < .001$, $\tau^2 = .03$, such that the relation increased with age. After controlling for covariates and other moderators, age also positively affected the relations between *Gf* and different types of reading (code, comprehension, and comprehensive reading), respectively, $\beta = .003/.003/.005$, $t = 2.58/4.76/2.16$, $ps < .05$, $\tau^2 = .02/.03/.06$. A further examination within different age groups showed that, before age 20, the relation between *Gf* and reading did not vary with age, $\beta = -.002$, $t = -.81$; $p = .42$, $\tau^2 = .03$; after age 30, the relation between *Gf* and reading did not vary with age, $\beta = -.001$, $t = -.81$; $p = .42$, $\tau^2 = .03$. In addition, after controlling for covariates and other moderators, the relation between *Gf* and reading was significantly larger after age 30 than that before age 20, $\beta = .17$, $t = 6.12$; $p < .001$, $\tau^2 = .03$.

With respect to the relation between *Gf* and mathematics, after controlling for covariates and other moderators, age significantly affected the relation between *Gf* and mathematics, $\beta = .003$, $t = 3.54$; $p < .01$, $\tau^2 = .03$, such that the relation increased with age. After controlling for covariates and other moderators, age did not influence the relations between *Gf* and numerical knowledge/word problems, but positively influenced the relation between *Gf* and calculation, $\beta = .004$, $t = 2.15$; $p < .05$, $\tau^2 = .02$. A further examination within different age groups showed that, before age 20, the relation between *Gf* and mathematics did not vary with age, $\beta = -.004$, $t = -1.00$; $p = .32$, $\tau^2 = .03$; after age 30, the relation between *Gf* and mathematics did not vary with age, $\beta = .003$, $t = 1.48$; $p = .16$, $\tau^2 = .04$. In addition, after controlling for covariates and other moderators, the relation between *Gf* and mathematics was significantly larger after age 30 than that before age 20, $\beta = .19$, $t = 4.24$; $p < .001$, $\tau^2 = .03$.

Taken together, the age effects were not detected within the before-age-20 group or the afterage-30 group. However, based on the whole age span, age positively affected the relations between *Gf* and overall reading and different types of reading as well as overall mathematics and calculation. Moreover, the relations between *Gf* and reading/mathematics were significantly larger after age 30 than those before age 20. Taken together, our findings suggest that the relations between *Gf* and reading/mathematics increased with age.

Interaction Effects Between SES and Age

Next, we examined the interaction between SES and age. We created two interaction terms. One is the interaction between country SES and age, the other is the interaction between family SES and age. With respect to the relation between *Gf* and reading, results showed that after controlling for covariates and other moderators, the interaction between country SES and age was not significant, but the interaction between family SES and age was significant, $\beta = -.003$, $t = -3.02$; $p = .003$, $\tau^2 = .03$, such that the relation between *Gf* and reading was higher for individuals from middle class or above than for individuals from below-middle-class background at a younger age, whereas family SES effects were less obvious for older individuals.

We also examined whether there was an interaction between SES and age on the relations between *Gf* and subtypes of reading. With respect to the relation between *Gf* and code skills, after controlling for covariates and other moderators, the interaction between country SES and age was not significant, but the interaction between family SES and age was significant, $\beta = -.005$, $t = -2.11$; $p = .04$, $\tau^2 = .02$, such that the relation between *Gf* and code skills was higher for individuals from middle class or above than for individuals from below-middle-class background at a younger age, whereas family SES effects were less obvious for older individuals.

With respect to the relation between *Gf* and comprehension skills, after controlling for covariates and other moderators, the interaction between country SES and age was not significant, but the interaction between family SES and age was significant, $\beta = -.004$, $t = -3.96$; $p < .001$, $\tau^2 = .02$, such that the relation between *Gf* and comprehension was higher for individuals from middle class or above than for individuals from below-middle-class background at a younger age, whereas family SES effects were less obvious for older individuals.

With respect to the relation between *Gf* and mathematics, results showed that after controlling for covariates and other moderators, the interaction between country SES and age was not significant, but the interaction between family SES and age was significant, $\beta = -.004$, $t = -2.50$; $p = .01$, $\tau^2 = .03$, such that the relation between *Gf* and mathematics was higher for individuals from middle class or above than for individuals from below-middle-class background at a younger age, whereas family SES effects were less obvious for older individuals.

We next examined whether there was an interaction between SES and age on the relations between *Gf* and different mathematics skills. With respect to the relation between *Gf* and numerical knowledge, after controlling for covariates and other moderators, the interaction between country SES and age or between family SES and age was not significant. With respect to the relation between *Gf* and calculation, after controlling for covariates and other moderators, the interaction between family SES and age was not significant, but the interaction between country SES and age was significant, $\beta = -.04$, $t = -9.97$; $p < .001$, $\tau^2 = .02$, such that the relation between *Gf* and calculation was higher for individuals from developed countries than for individuals from developing countries at a younger age, whereas country SES effects were less obvious for older individuals. With respect to the relation between *Gf* and word problems, after controlling for covariates and other moderators, the interaction between family SES and age was not significant and we did not have sufficient effect sizes ($n = 2$) for the interaction between country SES and age.

To sum, we found significant interactions between SES (mostly family SES) and age on the relations between *Gf* and reading/mathematics. That is, *Gf* was more important for reading and mathematics among young individuals from a relatively high SES background than for young individuals from a relatively low SES background.

Longitudinal Correlations Between *Gf* and Reading/Mathematics

Next, we examined whether *Gf* and reading/mathematics were correlated from a longitudinal perspective. With respect to longitudinal correlations between *Gf* and reading, we first investigated whether *Gf* predicted later reading performance partialing out the initial reading performance. Toward this end, there are 42 studies involving 920 correlations, with the majority of studies focusing on children before age 13 (around 5~8 years old) and the prediction time interval spanning from .25 to 7 years. Results showed that *Gf* significantly predicted later reading performing partialing out initial reading performance, $r = .17$, 95% CI [.15, .20]; Time interval did not affect this relation. We then investigated whether reading predicted later *Gf* partialing out initial *Gf*. Toward this end, there are 9 studies involving 110 correlations, with all studies focusing on children before age 11 (around 7~10 years old) and the prediction time interval spanning from 1 to 3 years. Results showed that reading significantly predicted later *Gf* partialing out initial *Gf*, $r = .21$, 95% CI [.15, .27]. Time interval significantly affected this relation, $\beta = -.10$, $t = -10.89$; $p < .001$, $\tau^2 = .01$, such that the prediction became weaker when the time interval was larger.

With respect to longitudinal correlations between *Gf* and mathematics, we first investigated whether *Gf* predicted mathematics partialing out the initial mathematics performance. Toward this end, there are 30 studies involving 275 correlations, with all studies focusing on children before age 14 (around 6~10 years old) and the prediction time interval spanning from .5 to 4 years. Results showed that *Gf* significantly predicted mathematics partialing out initial mathematics performance, $r = .21$, 95% CI [.17, .26]. Time interval did not affect this relation. We then investigated whether mathematics predicted *Gf* partialing out initial *Gf*. We found 7 studies involving 52 correlations, with the majority of studies focusing on children before age 11 (most around 6~11 years old) and the prediction time interval spanning from 1 to 3 years. Results showed that mathematics significantly predicted *Gf* partialing out initial *Gf*, $r = .24$, 95% CI [.17, .32]. Time interval did not affect this relation.

Because of insufficient effect sizes and studies, we didn't run other moderation analyses based on the longitudinal data. That said, the findings, taken together, suggest that *Gf* significantly predicted later reading/mathematics performance when initial reading/mathematics performance was controlled for. Likewise, reading/mathematics also significantly predicted later *Gf* when initial *Gf* was controlled for. These findings are primarily based on data among children from a relatively short time intervals that generally did not affect these longitudinal relations.

Discussion

The current meta-analysis investigated the relations between *Gf* and reading/mathematics, and whether types of *Gf* tasks, types of reading/mathematics skills, age, and SES influenced these relations. Results indicated that *Gf* had stronger relations to mathematics than to reading. The relation between *Gf* and reading was moderate ($r = .38$) and was influenced by types of *Gf* tasks, different reading skills, and age. Specifically, composite nonverbal reasoning showed a stronger relation with reading than were matrix reasoning and visuospatial reasoning. *Gf* showed a stronger relation with comprehension skills than with code skills. The relations between *Gf* and reading increased with age. In addition, there was a significant interaction between SES and age such that for younger individuals, the relations between *Gf* and reading were higher for those with a relatively high SES background than for those with a relatively low SES background. We also found several moderation effects for each reading skill. Code skills showed stronger relations with matrix reasoning, nonmatrix reasoning, and composite nonverbal reasoning than to visuospatial reasoning. The relation between code skills and *Gf* increased with age. The relation between comprehension skills and *Gf* also increased with age.

We found a moderate correlation between *Gf* and mathematics ($r = .41$), which was influenced by types of *Gf* tasks, different mathematics skills, and age. Specifically, composite nonverbal reasoning showed a stronger relation with mathematics than visuospatial reasoning. *Gf* showed a stronger relation to word problems than to calculation. The relation between *Gf* and mathematics increased with age. We also found a significant interaction between SES and age such that for younger individuals, the relation between *Gf* and mathematics was higher for individuals with relatively high SES than individuals with relatively low SES. There were several moderation effects for each mathematic skill. For numerical knowledge, matrix reasoning and composite nonverbal reasoning were more important than visuospatial reasoning. For calculation, the relation between *Gf* and calculation increased with age.

Moreover, findings from longitudinal studies suggest that *Gf* significantly predicted later reading/mathematics when initial reading/mathematics was controlled for. Likewise, reading/mathematics also significantly predicted later *Gf* when initial *Gf* was controlled for. In the following, we discuss these findings in detail.

Age Effects

Most prior research on the relations between *Gf* and academic performance did not consider the developmental effect (e.g., Strenze, 2007) or only considered these relations within a relatively short developmental window or treated age as a categorical variable, which could not accurately reflect the age effects (Schroeders, Schipolowski, & Wilhelm, 2015; Schweizer & Koch, 2002). With the meta-analysis, we were able to investigate the relations between *Gf* and reading/mathematics from a wide age span (3~80 years old) in a more fine-tuned way by treating age as a continuous variable. We had two competing hypotheses: (a) based on the Investment theory (Cattell, 1987), the relations between *Gf* and reading/mathematics decrease with age; *Gf* predicts reading/mathematics longitudinally, not vice versa; (b) based on the Mutualism theory (Van Der Maas et al., 2006), the relations between *Gf* and reading/mathematics would increase with age; *Gf* and reading/mathematics predict each other in the development. Our findings suggest that over the entire age span, the relations between *Gf* and reading/mathematics increased with age. In addition, *Gf* and reading/mathematics significantly predicted each other in the development. These findings, taken together, partially support the Investment theory but are more in line with the Mutualism theory. That is, the relations between *Gf* and reading/mathematics may be reciprocal from a developmental perspective.

The findings from the longitudinal correlations synthesis are in line with recent longitudinal research on the Mutualism theory. For example, Rindermann et al. (2010) based on a Brazilian sample and a Germany sample of children (ages 7∼19) and used the cross-lag model on two time points to investigate the relation between *Gf* (measured by matrix reasoning and nonverbal figural reasoning) and *Gc* (composite of verbal and quantitative knowledge). Their findings showed that after controlling for initial *Gf* and *Gc*, initial *Gf* still predicted later *Gc* and vice versa even when SES was controlled for. With a relatively older sample (ages 14∼25) and latent change score models, Kievit et al. (2017) found a similar pattern such that individuals with higher scores in vocabulary showed greater gains in matrix reasoning and vice versa.

One possible explanation for this investment and mutualism nature underlying the relations between *Gf* and reading/mathematics is learning (Schweizer & Koch, 2002; Kvist & Gustafsson, 2008; Thorsen, Gustafsson, & Cliffordson, 2014). Specifically, children invest *Gf* into the learning of reading and mathematics, especially in the early development stage when they do not have sufficient domain-specific knowledge to perform reading/mathematics tasks. The learning of reading and mathematics becomes increasingly complex with age/grade so children need both domain-specific knowledge (long-term memory knowledge) and *Gf* to perform reading/mathematics tasks. The constant use of *Gf* in learning increasingly complex reading and mathematics tasks also serves as a training of *Gf* to some extent (Martinez, 2000). Even after the formal schooling period, the rich experiences using reading and mathematics skills in daily life (Ross, McKechnie, & Rothbauer, 2006) may help maintain the reciprocity between *Gf* and reading/mathematics.

We found the positive age effect very robust with/without controlling for other covariates or moderators in the analyses, but the relations between *Gf* and reading/mathematics only increase by .02∼.03 every decade. Moreover, we only detected the age effects when including the whole age span. We did not find the age effects on the correlations between *Gf* and reading/mathematics before age 20 when both *Gf* and reading/mathematics are increasing or after age 30 when *Gf* is decreasing. These findings are in line with findings from standardized commercial testing batteries that used representative samples from United States. Specifically, Evans, Floyd, McGrew, and Leforgee (2002) and Floyd, Evans, and McGrew (2003) used data from Woodcock Johnson III on a U.S. representative sample including students from 6 to 19 years of age. They both found that the relations between *Gf* and reading (comprehension and foundational reading skills) and mathematics (calculation and mathematics reasoning) increased before 20 years of age, but the increase was rather small ($<.05$ on regression coefficients). These findings, together with ours, further imply the characteristics of the reciprocity between *Gf* and reading/mathematics. That is, *Gf* is an inherent trait that is relatively stable, but *Gf* may be malleable (Protzko, 2015; Sauce & Matzel, 2018), and it may take very intensive cognitive trainings (Jaeggi et al., 2008) or a long-time learning/experiences on reading/mathematics to modify *Gf*.

Types of *Gf* and Reading/Mathematics Skills

Previous research on the relation between *Gf* and academic performance usually used one or two tasks or a composite score from multiple tasks, which are insufficient on their own to test the effects of complexity within different *Gf* and academic tasks. In the current meta-analysis, we synthesized studies across different *Gf* tasks and different reading/mathematics skills to investigate the more fine-grained relations between *Gf* and reading/mathematics. Overall, findings suggest that among all *Gf* tasks, composite nonverbal reasoning showed the strongest relations with reading/mathematics, whereas visuospatial reasoning showed the weakest relations with reading/mathematics. This finding is expected and in line with the intrinsic cognitive theory. That is, composite nonverbal reasoning taps various reasoning skills, and matrix reasoning and nonverbal matrix reasoning are heavily reasoning-loaded, all being more complex than visuospatial reasoning.

Compared with reading, mathematics showed stronger relations to *Gf*, in line with previous research suggesting that mathematics requires more reasoning to understand and apply rules and principles than does reading (Ackerman & Lohman, 2003; Blair et al., 2005; Geary, 2011). Within reading, *Gf* showed a stronger relation to comprehension than to code skills. Within mathematics, word problems were more closely related to *Gf* than was calculation. These findings indicate that different types of reading/mathematics skills influence the relations between *Gf* and reading/mathematics, which are also in line with the intrinsic cognitive load theory (Chandler & Sweller, 1991; Sweller, 1994), indicating that the complexity of academic tasks may determine the involvement of cognitive skills such that relatively complex academic skills (e.g., comprehension and word problems) involve more *Gf* than relatively foundational academic skills (e.g., code skills and calculation). That said, we found *Gf* showed comparable relations to numerical knowledge and word problems. One explanation may be that we categorized numerical reasoning tasks as part of numerical knowledge, which may strengthen the relations between *Gf* and numerical knowledge. Also, we did not find other complex mathematics skills such as fraction and algebra showed stronger relations to *Gf* compared to calculation, which may be attributable to the underpowered analyses with a relative small number of effect sizes on fraction and algebra from the reviewed studies.

Because the curricula of reading and mathematics emphasize the learning progression of different reading and mathematics skills, we expected that the relations between *Gf* and different reading/mathematics skills may vary with age in different patterns. Specifically, based on the curriculum sequence, it is reasonable to expect that *Gf* is needed in learning foundational reading/mathematics skills (e.g., code skills and calculation) in the early instructional stage (e.g., Fuchs et al., 2006; Ho et al., 1999; Levy, 2011; Östergren & Träff, 2013; Tiu et al., 2003), but the involvement of *Gf* in these foundational skills may decrease as children become more fluent in these skills through schooling. As the curricula gradually shift to complex reading/mathematics skills (e.g., comprehension and word problems), the relations between *Gf* and these more complex reading/mathematics skills may increase with age.

However, we found that for most reading and mathematics skills including foundational and complex skills, their relations to *Gf* increased with age. Thus, the positive age effects did not support the curriculum effects. One explanation may be the mutualistic effects within/across academic domains. Research showed that within an academic domain, foundational skills (e.g., numerical knowledge and code skills) and complex skills (e.g., word problems and reading comprehension) can facilitate each other's growth. For example, while word reading promotes reading comprehension, reading comprehension also facilitates new words acquisition and word reading fluency (Stanovich & West, 1989). While numerical knowledge and calculation can promote word problems, solving word problems can also increase fluency of numerical and calculation skills (Fuchs, Gilbert, Fuchs, Seethaler, & Martin, 2018). Even across academic domains, reading and mathematics mutually predict each other's development (e.g., word reading and comprehension skills promote mathematics learning such as calculation and word problems, whereas mathematics such as word problems also facilitate reading development; e.g., Purpura, Logan, Hassinger-Das, & Napoli, 2017; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). The mutualistic influence within/across academic domains may boost the relations between *Gf* and foundational academic skills with age. That is, the reciprocity within/across reading/mathematics domains may partially explain the relations between *Gf* and foundational academic skills in the development. That said, more longitudinal studies are needed to further investigate the mutualism underlying *Gf* and foundational academic skills.

SES Effects

SES is an important factor in consideration of the relations between *Gf* and reading/mathematics. To systematically examine the moderating effects of SES, we included two SES variables that are usually not considered simultaneously in empirical studies: country SES (developing country vs. developed country) and family SES (middle class or above vs. below middle class). Our findings suggest the effects of SES on the relations between *Gf* and reading/mathematics were influenced by age. That is, for younger individuals, the relations between *Gf* and reading/mathematics were generally higher in those with relatively high SES than those from relatively low SES background. Interestingly, these interactions mostly involved family SES (country SES only interacted with age on the relations between *Gf* and calculation), suggesting that family SES is very important for the relations between *Gf* and academic achievement (Haveman & Wolfe, 1995).

We think there may be several reasons for the null effects of country SES. First, only about 7% of effect sizes in the present meta-analysis came from studies conducted in developing countries. The unbalanced number of effect sizes between studies conducted in developed countries versus those conducted in developing countries may underpower the moderation analysis of country SES. Second, although country SES may influence overall *Gf* (Lynn & Vanhanen, 2012), it may not be an important factor influencing academic performance or the relation between *Gf* and academic performance. For example, comparative education research on countries with high PISA scores in reading and mathematics (Organization for Economic Cooperation and Development, 2006) indicates that compared with the country economic status, educational policy (Waldow, Takayama, & Sung, 2014) and cultural beliefs (value placed upon academic performance, Francis & Archer, 2005) exert more impact on academic performance. Third, compared with family SES, country SES may less accurately reflect SES effects on the relations between *Gf* and academic performance. For example, because of unbalanced economic development among regions in a country (especially for the developing countries), country SES for studies conducted in the same country may mean something different based on where the samples come from (e.g., in China, the country SES may not accurately represent the SES level of samples from Beijing in comparison to samples from a much less developed areas; Kunrong, & Jun, 2002). Unfortunately, most original studies did not provide detailed sampling information for the further investigation on this possibility.

In contrast to most null effects of country SES, the interaction between age and family SES is in line with and also supplements the gene–SES interaction hypothesis proposed by the behavioral genetics research. Specifically, most prior studies on gene–SES interaction hypothesis were conducted in the early development stage with samples from a relatively narrow development span. Thus, from a lifespan development perspective, findings of the current meta-analysis add to the gene–SES interaction hypothesis by suggesting that there may be a sensitive period of time for this interaction (e.g., Grant et al., 2010; van der Sluis et al., 2008). That is, the SES effects on the relations between *Gf* and reading/mathematics are most obvious in early development.

There are two possible explanations. One is that younger individuals are more likely to benefit from the high SES background using their *Gf* to learn and perform reading and mathematics, whereas the SES effects on *Gf* may wash out gradually as individuals receive schooling and gain experiences with reading and mathematics (Ceci, & Williams, 1997; Ladd, 2012). In other words, as individuals progress in school and gain more learning experiences, it is the schooling and experiences with reading/mathematics, not their family SES, that majorly affect the relations between *Gf* and reading/mathematics.

The other explanation is the age effect on the heritability of academic achievement (Gill et al., 1985; Plomin, DeFries, Knopik, & Neiderhiser, 2016). Specifically, with respect to the academic performance, the genetic effects increase with age while the environmental effects decrease with age (Haworth et al., 2007, 2009; Kovas et al., 2007, 2013; Shakeshaft et al., 2013). The increasingly high heritability of academic performance as a function of age is mostly likely attributable to *Gf*, a very important and heritable trait (Krapohl et al., 2014). That said, given the robust positive age effects on the relations between *Gf* and reading/mathematics and Mutualism theory, we think that environmental influences such as schooling or daily experiences with reading/mathematics tasks may be constantly important for the development of *Gf* and reading/mathematics and their reciprocity. Longitudinal studies on the effects of SES from a long developmental perspective are needed to further test these hypotheses.

Because of limited information from the original studies, we were unable to disentangle the family SES and school SES (e.g., school resources, teacher quality, and the like), which are usually linked with each other (Strenze, 2007). It may be possible that family SES indirectly influenced the relations between *Gf* and reading/mathematics through school SES (Frempong, Ma, & Mensah, 2012; Hart, Soden, Johnson, Schatschneider, & Taylor, 2013). For example, Hart et al. (2013) found that the gene–SES interaction model also applied to school SES when it comes to reading achievement among elementary children. Their study suggested that higher school SES allowed genetic variance to contribute as sources of individual differences in reading comprehension outcomes, whereas lower school SES suppressed these influences. Frempong et al. (2012) further supported this mediation role of school SES among adolescents. They found that family SES significantly affected postsecondary education outcomes but a substantial portion of this family SES effect operated through the impact of high school SES. These findings, taken together, highlight the possible indirect effects of family SES on the relations between *Gf* and academic achievement through other environmental factors such as school SES. Thus, further studies may be needed to investigate whether school SES mediates the effects of family SES on the relations between *Gf* and reading/mathematics and whether the mediation (if any) is also time sensitive.

Limitations

We noted several limitations when interpreting our findings. First, we did not include other factors that may influence the relations between *Gf* and reading/mathematics. For example, Ackerman (1996) proposed an intelligence-as-Process, Personality, Interests, and intelligence-as-Knowledge (PPIK) model, in which social-emotional traits may moderate the relations between *Gf* and academic achievement. That is, individuals devote greater or lesser amounts of *Gf* to the acquisition of domain-specific knowledge depending on their personality and interests. For example, children who are interested in mathematics tend to invest more *Gf* into mathematics learning, which will in return further strengthen their mathematics skills and the relations between *Gf* and mathematics based on the Mutualism theory. Future meta-analysis should include those trait variables and investigate how they influence the relations between *Gf* and academic performance among different populations (experts vs. novices).

Second, to increase the generalizability of our findings, we included heterogeneous samples (i.e., typical and nontypical developing individuals). Although we controlled for the sample type in our analyses, we could not conduct further analyses within the nontypical sample. This is because the atypically developing group is quite heterogeneous, including different developmental or acquired disorders such as Autism, learning disability, cerebral palsy, brain injuries, and the like, and the sample size for those subgroups is often very small. Future studies should further examine whether different disorders influence the relations between *Gf* and academic performance differently.

Third, because of the small sample size, we were unable to run analyses for some categories of moderators and some moderation analyses may be underpowered. For example, we only have a small number of effect sizes for the moderation analyses on each mathematics skills (e.g., fraction and algebra), and thus the results of those moderation analyses may be more exploratory in nature and warrant further investigations. A similar issue is that because of the limited number of studies, the findings on longitudinal relations between *Gf* and reading/mathematics were primarily based on children and adolescents. Future studies should further investigate whether *Gf* and academic performance predict each other among a relatively older population.

Last, we did not differentiate deductive from inductive reasoning tasks in the current meta-analysis. This is because most deductive reasoning tasks are based on verbal or numerical materials (Evans, 2013; Polk & Newell, 1995), and most nonverbal reasoning tasks tap the inductive and deductive reasoning simultaneously (e.g., matrix reasoning). Recent studies suggest both inductive and deductive reasoning may share the same cognitive mechanism (Stephens, Dunn, & Hayes, 2018; Osman, 2004), which may suggest unnecessity to differentiate these two types of reasoning. That said, it is still of interest to investigate whether deductive and inductive reasoning relate to different reading/mathematics tasks differently, especially from a curriculum perspective. That is, whether the relation between inductive/deductive reasoning and a reading/mathematics skill changes during the learning process (e.g., inductive reasoning may be more important at the knowledge-learning stage, while deductive reasoning may be more important during the knowledge-application stage; Markman & Gentner, 2001).

Implications for Theory

With all those limitations in mind, this is the first meta-analysis that systematically investigated the relations between *Gf* and reading/mathematics and important moderators for these relations. Findings have implications for our understanding of learning and intelligence theories. First, our findings contribute to our understanding of the CHC theory. On one hand, the moderate relations between *Gf* and reading/mathematics suggest that *Gf*, reading, and mathematics are related but relatively independent constructs, in line with CHC theory. On the other hand, the fine-grained differences on the relations between *Gf* and different reading/mathematics skills add to the CHC theory, suggesting that reading or mathematics may not only be considered as a unitary construct itself but also a multicomponent construct in relations to *Gf*.

Second, our findings support and integrate the Investment theory and the Mutualism theory. Children may rely on *Gf* to learn and perform reading and mathematics early on, but the gaining experiences on reading and mathematics may also promote the development of *Gf*, strengthening the relations between *Gf* and reading/mathematics. The mutualism underlying *Gf* and reading/mathematics is robust even in the face of curriculum effects.

Third, our findings support and supplement the gene–SES interaction hypothesis. That is, the SES effects on individual development may depend on developmental stages. In the early development stage, low family SES may restrict the effects of *Gf* on reading/mathematics due to the inhibition of the heredity of *Gf*, whereas in the later development stage, schooling and experiences with reading/mathematics may compensate for low SES effects on the relations between *Gf* and reading/mathematics.

Fourth, our findings may help understand the relations among domain-specific skills, domain-general skills, and academic achievement. Specifically, there is an ongoing debate on the relative importance of domain-specific and domain-general factors for academic achievement (e.g., Fuchs et al., 2010; Cromley, Snyder-Hogan, & Luciw-Dubas, 2010; Geary, 2011; Passolunghi & Lanfranchi, 2012). Our findings suggest that *Gf* and domain-specific skills may be mutually influencing each other during development. In addition, Peng et al. (2018) and Schmitt et al. (2017) suggested a bidirectional relation between the executive functioning system and domain-specific reading and mathematics skills during development. These findings, taken together, suggest the contributions of advanced domain-general skills (e.g., *Gf* and executive functions) and domain-specific skills to academic achievement may be related from a developmental perspective. Both domain-general and domain-specific should be considered important for academic development.

Fifth, our findings may contribute to our understanding on the debate regarding the age-related differentiation (relations among cognitive abilities decrease across the life span) versus dedifferentiation (relations among cognitive abilities increase across the life span) hypotheses of cognitive abilities. According to the dedifferentiation hypothesis, the factor structure of cognitive abilities might be less differentiated in later development than it is in early development (Baltes, Staudinger, & Lindenberger, 1999; Hülür, Ram, Willis, Schaie, & Gerstorf, 2015; Kievit et al., 2017), whereas the differentiation hypothesis holds the opposite view (Gignac, 2014; Hülür, Wilhelm, & Robitzsch, 2011; Tucker-Drob, 2009; Tucker-Drob & Salthouse, 2008). The mutualism nature between *Gf* and reading/mathematics as a function of age may help explain the dedifferentiation hypothesis. That is, *Gf* is invested in the acquisition of knowledge, and meanwhile more learning experiences will boost the development of *Gf*. This reciprocal relation between *Gf* and knowledge accumulation observed across the life span may partially contribute to the dedifferentiation of cognitive abilities.

Considering all these findings, we tentatively propose an *Educational and Developmental Hypothesis of Gf*. Based on this hypothesis, children in the early developmental stage would rely on their *Gf* to learn reading and mathematics skills. In this stage, family SES exerts a significant impact on this learning process. That is, compared with children from the relatively low SES family background, children from the relatively high SES family background are more likely to realize their genetic potentials on *Gf* in learning reading and mathematics skills. As children gradually receive more formal schooling and gain more experiences with reading and mathematics, their reading and mathematics improvement may also promote their *Gf* development. During this development, the negative effects of low family SES on the relations between *Gf* and reading/mathematics may be offset by education or learning experiences on reading/mathematics.

Implications for Practice

Our findings also have important implications for education practice. First, from a broad perspective, our findings indicate the importance of schooling for individual development, which is consistent with accumulating evidence suggesting the substantial impact of schooling on general abilities (Brinch & Galloway, 2012; Ceci, 1991; Ceci & Williams, 1997). On one hand, schooling may not only help children accumulate domain-specific knowledge (becoming "book-smart") but also help children improve general cognitive abilities (becoming "smart"). For example, mathematics curricula move from relatively simpler forms of counting and arithmetic operations to more complex tasks such as word problems, fraction, and algebra (Blair et al., 2005). These learning experiences in mathematics classes may facilitate the ability to develop and use abstract rules or strategies to solve complex problems (Artman & Cahan, 1993). As for reading, during reading instruction, children frequently learn new words by inferring their meanings from the contexts in which the words are embedded and often use inferencing and analogy skills to comprehend expository texts (e.g., Jenkins, Stein, & Wysocki, 1984; Spiro, Bruce, & Brewer, 2017). Such kinds of exercises may also facilitate the acquisition of abstract thinking and reasoning (Ritchie, Bates, & Plomin, 2015). On the other hand, schooling may help offset the negative effects of low family SES on children's cognitive and academic development. This view also receives support from recent intervention studies showing early high-quality and sustained academic interventions and schooling (e.g., preschool education) help alleviate delayed cognitive development and prevent academic failure for young children from the low family SES background (e.g., Fuchs & Fuchs, 2006; Jenkins et al., 2018; Tucker-Drob, 2012; Wang, Ren, Schweizer, & Xu, 2016).

Moreover, recent research on cognitive training has shed some light on whether training cognitive skills can improve *Gf* and academic performance. The findings are mixed, with most studies failing to detect training effects on *Gf* or academic performance (e.g., Jacob & Parkinson, 2015; Melby-Lervåg & Hulme, 2013; Shipstead et al., 2012). A closer look at all those cognitive training studies suggests that researchers usually adopt a relatively short but intensive training approach (e.g., one hour per day for several weeks). Diamond and Lee (2011) suggested that training high-level cognitive skills must not be limited to designated training blocks, but instead occur throughout the day, integrated into a variety of activities beyond the scope of one specific training regimen. This view has implications for thinking about improving *Gf* and reading/mathematics. Specifically, reading and mathematics are the primary instructional components at school (Common Core State Standards Initiative, 2010) and are the important academic outcomes (National Reading Panel, National Institute of Child Health & Human Development, 2000; National Council of Teachers of Mathematics, 2000). Teachers are more likely to spend time on reading and mathematics instruction than on abstract cognitive training, and instructions/experiences on reading and mathematics take place throughout childhood and adulthood. All these facts, together with the small but robust age effects on the relations between *Gf* and reading/mathematics, suggest that the learning or experiences of exercising reading and mathematics skills (especially complex ones) at school, compared with short-term intensive cognitive training (Protzko, 2015), may be a better (the ideal) approach to improving reading/mathematics and Gf for most children (Ceci & Williams, 1997). For children with learning difficulties who often have cognitive deficits (e.g., Peng, Wang, & Namkung, 2018; Willcutt et al., 2001), reading and mathematics instruction should be explicit (Stockard, Wood, Coughlin, & Rasplica Khoury, 2018) and designed to compensate for their cognitive weakness (Kearns & Fuchs, 2013) so that accumulating learning experiences can help improve those children's academic performance and cognitive functions (e.g., *Gf*) in the long run. With all said, the findings from the current meta-analysis are correlational in nature, and causal effects between *Gf* and reading/mathematics should be further validated by experimental studies.

Conclusion

In summary, the current meta-analysis investigated the relations between *Gf* and reading/mathematics and the main findings provided some new and updated information for the field as follows: (a) *Gf* showed moderate relations with reading and mathematics; The relation between *Gf* and mathematics was stronger than the relation between *Gf* and reading; The more complex reading and mathematics skills (e.g., comprehension and word problems) showed stronger relations with *Gf* than those of foundational reading and mathematics skills (e.g., code skills and calculation); (b) among *Gf* tasks, composite nonverbal reasoning tended to show stronger relations with reading/mathematics than those of matrix reasoning and nonmatrix reasoning, whereas visuospatial reasoning tended to show the weakest relations with reading/mathematics; (c) the relations between *Gf* and reading/mathematics increased with age. *Gf* and reading/mathematics predicted each other in the development; (d) Compared with country SES, family SES was more important to the relations between *Gf* and reading/mathematics but this family SES effect was more obvious in the early development.

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Received June 22, 2018
Revision received October 3, 2018
Accepted October 28, 2018 ■