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META-ANALYSIS

Inhibitory Control and Mathematical Ability in Elementary School Children: A Preregistered Meta-Analysis

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Abstract
Mathematical ability is a crucial component of human cognitive function, which is defined as the ability to acquire, process, and store mathematical information. While many studies have documented a close relationship between elementary school children's inhibitory control and their mathematical ability, existing empirical evidence remains controversial with some other studies showing a null correlation between these two constructs. This preregistered three-level meta-analysis aims to further elucidate the relationship between inhibitory control and mathematical ability in elementary school children by differentiating various types of inhibitory control, domains of mathematical ability, and exploring various potential moderators. This meta-analysis synthesized 241 effect sizes extracted from 86 samples, involving data from a total of 14,223 primary school children with a mean age of 8.67 years. The results showed a moderate positive correlation between inhibitory control and mathematical ability ($r = 0.19$). Mathematical ability was more strongly correlated with interference inhibition ($r = 0.21$) than response inhibition ($r = 0.14$). The relation between inhibitory control and mathematical ability was not moderated by domains of mathematical ability, inhibitory control task, age, gender, developmental status, socioeconomic status, and sample region. These findings provide novel insights into the cognitive underpinnings of mathematical ability in elementary school children. Practical implications are discussed.

Keywords Inhibitory control · Mathematical ability · Elementary school children · Three-level meta-analysis

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This meta-analysis was preregistered at: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42023437363.

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Introduction

Mathematical ability is defined as the ability to acquire, process, and store mathematical information (Karsenty, 2014), which is considered as a vital component of human cognitive function (Clements & Sarama, 2011), and is closely linked to important life outcomes, such as educational success, career opportunities, and physical and mental health (Silver et al., 2020; Wilkey et al., 2020). Research has demonstrated that children's mathematical ability is influenced by various factors, such as family socioeconomic status (SES), achievement motivation, and learning behaviors (Beisly et al., 2020; Sulik et al., 2020; Waters et al., 2021). Apart from these non-cognitive factors, recent research has highlighted that individual differences in mathematical ability are closely related to information-processing skills described under the broad label of executive functions (EFs; Blair & Razza, 2007; Bull et al., 2008; Spiegel et al., 2021; Swanson et al., 2020; Yang et al., 2019).

EFs are a set of top-down cognitive processes that contribute to goal-directed behaviors (Diamond, 2013), and their close relationship with children's mathematical ability has been confirmed by many cross-sectional and longitudinal studies (e.g., Ahmed et al., 2019; Bull & Scerif, 2001; Georgiou et al., 2020; Kahl et al., 2021; Magalhães et al., 2020; Swanson et al., 2020; Yang et al., 2019). Researchers claim that the cognitive processes underlying mathematical problem solving involve EFs, including filtering out irrelevant stimuli, resisting competing information, flexibly switching between different mathematical operations and problem-solving strategies, and maintaining and manipulating numerical information in mind (Bull & Lee, 2014; Scerif et al., 2023; Zhu & Zhao, 2023).

Numerous studies have documented a close relationship between two core components of EFs (i.e., working memory and cognitive flexibility) and mathematical ability (e.g., Rosen et al., 2019; Schmerold et al., 2016; Yang et al., 2019; Zhu & Zhao, 2023). Both working memory and cognitive flexibility are positively associated with concurrent (Arán Filippetti & Richaud, 2017; De Bruijn et al., 2018) and future (Morgan et al., 2019; Rosen et al., 2019) mathematical ability in children. However, previous studies exploring the extent to which inhibitory control, another core subcomponent of EFs, correlates with mathematical ability have generated conflict results. Some studies observed that inhibitory control positively correlates with mathematical ability (e.g., Blair & Razza, 2007; Bull & Scerif, 2001; Swanson & Fung, 2016; Visier-Alfonso et al., 2020), and documented that inhibitory control accounts for unique variance in children's ability in solving applied mathematical problems (Espy et al., 2004). Neuroimaging research corroborates these findings by showing shared neural activations between inhibitory control and mathematical processing within the frontal and parietal cortices, including regions such as intraparietal sulcus, middle frontal gyrus, and cingulate gyrus (Houdé et al., 2010; Hubbard et al., 2005; McKenna et al., 2017). By contrast, some other studies observed a null or even a negative relation between inhibitory control and mathematical ability (e.g., Bellon et al., 2016; Dekker et al., 2017; Georgiou et al., 2020; Zhu & Zhao, 2023). Cognitive training studies also showed that some interventions can effectively improve inhibitory control but have minimal effects on children's mathematical ability (Blakey et al., 2020; Wang et al., 2019). These divergent findings underscore the need for a systematic exploration of the relationship between inhibitory control and mathematical ability.

Recent meta-analyses have examined the relationship between inhibitory control and mathematical ability (for reviews, see Allan et al., 2014; Cortés Pascual et al., 2019; Emslander & Scherer, 2022; Friso-van den Bos et al., 2013; Spiegel et al., 2021), and explored whether this relationship changes as functions of age, gender, country, inhibitory control task type, sample types, and SES. However, these meta-analytic findings are also inconsistent. It is important to note that both inhibitory control and mathematical ability are multifaceted constructs (Diamond, 2013; Lin, 2011; Nigg, 2000; Xie et al., 2020). As different types of inhibitory control and various domains of mathematical ability follow different developmental trajectories (Spiegel et al., 2021; Tao et al., 2023; Vuillier et al., 2016; Yu & Zuo, 1996), the relationship between different subcomponents of inhibitory control and mathematical ability may vary substantially (Arán Filippetti & Richaud, 2017; Lee, 2023).

By far, no meta-analysis has systematically considered types of inhibitory control and domains of mathematical ability to comprehensively examine the relationship between inhibitory control and mathematical ability. Given that elementary school years are a critical period for the development of both inhibitory control and mathematical ability (Hamm & Perry, 2002; Kang et al., 2022; Lin, 2011; Richardson et al., 2018), clarifying the relationship between these two constructs during this period may provide crucial insight into developing interventions to enhance children's mathematical ability. Therefore, this preregistered meta-analysis aims to systematically consider different types of inhibitory control and domains of mathematical ability, as well as a broad range of potential moderating factors, to elucidate the relationship between inhibitory control and mathematical ability in elementary school children.

Theoretical Framework of the Relationship Between Inhibitory Control and Mathematical Ability

As mentioned in Spiegel et al.'s (2021) review, there are several available theories that account for the relation between inhibitory control and mathematical ability. The *intrinsic cognitive load theory* suggests that the strength of this relationship depends on the complexity of the mathematical problems or tasks (Spiegel et al., 2021; Sweller, 1994). Some mathematical tasks are inherently more complex than others, require individuals to focus more on task goals, and execute a series of problem-solving steps, thus demanding a greater extent of cognitive resources (Spiegel et al., 2021; Wouters et al., 2008). For example, solving single-digit arithmetic problems only requires accessing long-term memory or direct calculation (Cragg et al., 2017), whereas completing word-applied problems requires not only attention to task goals but also inhibitory control to resist interference from the story context and overlearned strategy (Lubin et al., 2013). Therefore, solving complex mathematical problems necessitates executing more steps (Beckmann, 2010; Wouters et al., 2008), which demands substantial inhibitory control resources to coordinate problem-solving steps and maintain goal-relevant information.

The *dual-processing theory* posits that the relationship between inhibitory control and mathematical ability may vary with the difficulty level of the mathematical task (Attridge & Inglis, 2015; Evans & Stanovich, 2013; Spiegel et al., 2021). Simple tasks (e.g., recognizing numerals) become automated earlier, requiring minimal cognitive resources (Stipek & Valentino, 2015). In contrast, complex skills require inhibitory control to integrate problem-relevant information and resist irrelevant interference before they become automated (Spiegel et al., 2021; Tzur, 2011). For instance, comparing whole numbers may require basic understanding, while comparing fractions requires inhibitory control to overcome heuristic biases (e.g., incorrectly assuming that a fraction with a larger denominator is always larger; Attridge & Inglis, 2015; Gómez et al., 2015). Therefore, the relationship between inhibitory control and mathematical ability weakens as mathematical skills become increasingly automated.

The *constrained and unconstrained model* integrates the previous two theories by categorizing mathematical skills into constrained and unconstrained skills, based on if these skills are mastered and automated (Spiegel et al., 2021). Specifically, constrained skills involve a relatively small and finite pool of knowledge (e.g., counting, single-digit arithmetic), which can be fully automated through learning or experience (De Smedt, 2022). In contrast, unconstrained skills involve an infinite pool of knowledge (e.g., word problem-solving), which may be slow or even impossible to automate (McCormick et al., 2020). According to Spiegel et al. (2021), constrained mathematical skills may not require inhibitory control when they become automated, whereas unconstrained skills may consistently demand inhibitory control because these skills may never become automated (De Smedt, 2022; Spiegel et al., 2021).

Taken together, each of the aforementioned theories emphasizes different aspects. The intrinsic cognitive load theory focuses on problem complexity, suggesting stable cognitive demands regardless of learning and experience (Spiegel et al., 2021; Sweller, 1994). The dual-processing theory highlights the impact of learning on cognitive demands and assumes that the relationship between inhibitory control and mathematical ability weakens as mathematical skills become automated (Attridge & Inglis, 2015; Evans & Stanovich, 2013). The constrained and unconstrained model considers both task complexity and developmental factors, proposing that the degree to which mathematical skills are constrained may affect the relationship between inhibitory control and mathematical ability (McCormick et al., 2020). Specifically, the relationship between inhibitory control and mathematical ability should be weaker for constrained skills (those can become automated) and remains stable for unconstrained skills (those cannot become automated) (McCormick et al., 2020; Spiegel et al., 2021).

Inhibitory Control and Its Measurement

Inhibitory control is an ability that allows individuals to regulate their attention, thoughts, and behaviors to resist internal predispositions or external temptations (Diamond, 2013), which is closely related to individuals' academic achievement and important life outcomes (Allan et al., 2014; Friedman & Miyake, 2004). To date, several theorists have proposed different taxonomies of inhibitory control (e.g., Diamond, 2013; Friedman & Miyake, 2004; Nigg, 2000; Rey-Mermet et al., 2018). For instance, Nigg (2000) proposed a theoretical framework based on developmental psychopathology and distinguished eight detailed processes of inhibitory control. Friedman and Miyake (2004), in accordance with Nigg's (2000) taxonomy, used a latent-variable analysis to empirically differentiate two main forms of inhibition: response-distracter inhibition and resistance to proactive interference. Rey-Mermet et al. (2018) further refined this framework using structural equation modeling and identified two key factors: inhibition of prepotent response and resistance to distracter interference. This aligns with the current consensus, recognizing interference inhibition and response inhibition as two primary components of inhibitory control (e.g., Bunge et al., 2002; Diamond, 2013; Gandolf et al., 2014; Howard et al., 2014; Johnstone et al., 2009; Tonizzi et al., 2022; Zhu & Zhao, 2023). Accordingly, the current meta-analysis categorized inhibitory control into two sub-components: interference inhibition and response inhibition.

Interference inhibition refers to the ability to selectively focus on task-relevant stimuli while resisting both internal and external distractions in order to maintain goal-oriented attention (Diamond, 2013; Zhu & Zhao, 2023). Common paradigms for measuring interference inhibition include the Stroop task (e.g., in the color-word Stroop task, children are required to focus on the color in which the word is printed while ignoring the word's semantic meaning; Stroop, 1935), the Flanker task (e.g., in the arrow Flanker task, children are required to determine the direction of the central arrow among five arrows, ignoring the distracting flanking arrows; White et al., 2012), and the Simon task (e.g., in the Simon Says task, children are required to perform an action only if the experimenter says "Simon says," but remain still otherwise; Huyder & Nilsen, 2012). Response inhibition, on the other hand, involves deliberate suppression of prepotent or inappropriate actions (Diamond, 2013). Common paradigms for measuring response inhibition include the Go/No-go task (e.g., children are required to respond to a target stimulus, such as the letter "X", but withhold responses to non-target stimuli, such as the letter "Y"; Redick et al., 2011), and the Stop-signal task (e.g., children are required to withhold their responses when presented with a signal to cease action; Verbruggen & Logan, 2008).

Mathematical Ability and Its Measurement

Mathematical ability is a multifaceted concept, reflecting the complexity and breadth of mathematical cognition (Campbell, 2005; Lin, 2011; Xie et al., 2020). Various theoretical frameworks have been proposed to categorize different aspects of mathematical ability. Campbell (2005) suggested that mathematical ability contains two categories: numerical ability (e.g., basic number representation, counting, number comparison, and simple arithmetic) and mathematical problem-solving ability (e.g., acquiring abstract representations of mathematical relations from contextually rich problems and generating solutions). Lin (2011) expanded this view by including arithmetical ability, logical reasoning, and spatial imaginative ability as key domains. Xie et al. (2020) further synthesized these classifications, and proposed a comprehensive framework that includes numerical ability (e.g., understanding concepts and rules of numerosity, ordinality and counting), arithmetical ability (e.g., accuracy and flexibility in operations for integers, decimals, fractions, percentages, limit, calculus, and algebra), geometric ability (e.g., understanding the movement, transformation and positional relations of plane and solid figures, and geometric interpretation of mathematical and algebraic formulas), and logical reasoning ability (e.g., ability in comparison, generalization, induction and deduction, analyzing and synthesizing of mathematical phenomena, mathematical rules, and quantitative relations). Although spatial imaginative ability and geometric ability may differ in terminology, both pertain to the processing of geometric information (Xie et al., 2020).

Notably, the assessment of mathematical ability often extends these theoretical classifications and includes performance-based measures. Previous research utilized educational assessments, including school examinations and standardized mathematics tests (e.g., WIAT-II), to assess children's synthesized mathematical ability (e.g., Georgiou et al., 2020; Visier-Alfonso et al., 2020). While both methods assess children's synthesized mathematical ability, discrepancies between school examinations and standardized tests may lead to differential relations between their measured outcomes and inhibitory control. For instance, De Bruijn et al. (2018) and Visier-Alfonso et al. (2020) found that the relationship between interference inhibition and standardized test scores ($r = -0.07$) was substantially weaker than that between interference inhibition and school examination scores ($r = 0.44$).

Based on previous classifications and assessments of mathematical ability, the current study focused on six domains of elementary school children's mathematical ability, including numerical ability, arithmetical ability, logical reasoning ability, geometric ability, mathematical ability measured by standardized mathematics tests, and mathematical ability measured by school examinations.

Relationship Between Inhibitory Control and Mathematical Ability

Previous cross-sectional studies have found a positive relationship between inhibitory control and mathematical ability (e.g., Agostino et al., 2010; Arán Filippetti & Richaud, 2017; Park et al., 2022; Visier-Alfonso et al., 2020). For example, research by Espy et al. (2004) and Harvey and Miller (2017) identified a strong relationship between children's inhibitory control and mathematical ability, and this relationship remained significant even after controlling for the confounding effects of many other covariates such as demographic factors and language ability. These findings, while not establishing a causal inference, provide crucial insights for improving children's mathematical development through cognitive intervention (Wang et al., 2019; Whedon et al., 2020).

Several theoretical frameworks have been proposed to account for the underlying mechanisms of the relationship between inhibitory control and mathematical ability. The *cognitive filter model* postulates that focusing on relevant information while excluding distractions is crucial in mathematical contexts because of the brain's limited processing capacity (Miller-Cotto & Byrnes, 2020). Inhibitory control aids in resisting alternative strategies when retrieving arithmetic facts or problem-solving strategies (Cragg et al., 2017) and helps overcome heuristic biases or intuitive misconceptions (Jiang et al., 2019). The *inhibitory control model* contends that cognitive development involves not only acquisition of concepts and knowledge but also suppression of incorrect or overlearned strategies (Jiang et al., 2020). Additionally, it supports maintaining engagement and resisting impulsive responses during mathematical tasks (Allan et al., 2014; Clements et al., 2016; Torgrimson et al., 2021).

Previous meta-analyses consistently showed a medium positive correlation between inhibitory control and mathematical ability (*r*s ranged from 0.27 to 0.34; Allan et al., 2014; Emslander & Scherer, 2022; Friso-van den Bos et al., 2013; Spiegel et al., 2021). However, some empirical studies observed a negative or null relation between inhibitory control and mathematical ability (e.g., Bellon et al., 2016; Bryce et al., 2015; Cantin, 2013; Cassidy et al., 2016; Schmerold et al., 2016; Zhu & Zhao, 2023). Specifically, Cassidy et al. (2016) observed a negative relation between inhibitory control and arithmetical ability and logical reasoning ability in elementary school children. Furthermore, some studies even found no relation between inhibitory control and mathematical ability (e.g., De Bruijn et al., 2018; Hernández et al., 2018; Majumder, 2003; Zhu & Zhao, 2023). For example, Zhu and Zhao (2023) found a weak relationship between response inhibition (measured by Go/No-go task) and various domains of mathematical ability in elementary school children (*r*s ranged from −0.01 to 0.05). Other evidence from cross-sequential studies also showed that inhibitory control does not independently predict children's mathematical ability (Andrés et al., 2022; Yang et al., 2019).

We propose that the conflicting results documented in previous studies may be explained by several factors. First, different types of inhibitory control may affect mathematical processing through distinct mechanisms, leading to variability in observed correlations (Bryce et al., 2015; Medrano & Prather, 2023; Zhu & Zhao, 2023). For example, a stronger correlation may be observed between interference inhibition and mathematical ability, because children need to continuously resist interference from the external environment (e.g., noise), different strategies or algorithms, and previously learned knowledge that is not suitable for solving the current problem (Cragg et al., 2017; Gómez et al., 2015; Lee & Lee, 2019). Second, different domains of mathematical ability may require different levels of inhibitory control. For example, counting may require only basic inhibitory control (Bull et al., 2008), while word problem solving demands greater inhibitory control resources (Spiegel et al., 2021). Third, the relationship between inhibitory control and mathematical ability may vary as a function of development stage (or age), with such relationship weakening in older children due to the automation of mathematical skills

(Stipek & Valentino, 2015; Yang et al., 2019). Additionally, demographic factors, such as developmental status and SES, may also affect the strength of the observed relationship (Duncan et al., 2017; Sartori et al., 2022). Therefore, these potential moderating factors should be carefully considered when evaluating the relationship between inhibitory control and mathematical ability. Thus, the current meta-analysis aims to contribute to a more nuanced understanding of the relationship between inhibitory control and mathematical ability by considering the multidimensional structures of inhibitory control and mathematical ability and exploring potential moderating factors, such as the inhibitory control task, age, gender, developmental status, SES, and sample region.

Potential Moderators

Types of Inhibitory Control

As inhibitory control is a multidimensional construct, the relationship between inhibitory control and mathematical ability should be explored considering different sub-components of inhibitory control. Specifically, interference inhibition involves monitoring goal information, resisting irrelevant distractions, and mitigating heuristic biases during mathematical tasks (Bryce et al., 2015; Jiang et al., 2019; Lee & Lee, 2019). For instance, when comparing the magnitude of fractions, individuals need to employ interference inhibition to resist heuristic bias or intuition that a larger denominator implies a larger fraction (Gómez et al., 2015). Comparatively, response inhibition is crucial for controlling impulsive responses and sustaining engagement during mathematical tasks (Allan et al., 2014; Torgrimson et al., 2021).

While both interference inhibition and response inhibition may contribute to mathematical ability development (e.g., Agostino et al., 2010; 2019; Friso-van den Bos & van de Weijer-Bergsma, 2020; Jiang et al., 2019), their relationship to mathematical ability may differ (e.g., Arán Filippetti & Richaud, 2017; Escobar et al., 2018; Iglesias-Sarmiento et al., 2023). For example, previous cross-sectional studies showed that interference inhibition is closely related with mathematical ability (Bull & Scerif, 2001; Gerst et al., 2015; Lubin et al., 2016), whereas response inhibition does not correlate with mathematical ability (Hernández et al., 2018; Zhu & Zhao, 2023). Therefore, the current meta-analysis considered types of inhibitory control as a possible moderating factor.

Domains of Mathematical Ability

As discussed above, previous studies measured children's mathematical ability in six domains, including numerical ability, arithmetical ability, logical reasoning ability, geometric ability, mathematical ability measured by standardized mathematics tests, and mathematical ability measured by school examinations. According to the constrained and unconstrained model (McCormick et al., 2020; Spiegel et al., 2021), constrained skills, such as numerical ability, require fewer cognitive control resources once automated, while unconstrained skills, such as logical reasoning, demand greater cognitive control resources due to their complexity (De Smedt, 2022). Empirical studies suggest a stronger correlation between inhibitory control and more complex mathematical ability (e.g., logical reasoning) than that between inhibitory control and simple arithmetical ability (Swanson & Fung, 2016; Yu, 2020). Therefore, the current meta-analysis considered domains of mathematical ability as a possible moderating factor.

Inhibitory Control Task

In line with prior meta-analyses (Emslander & Scherer, 2022), we considered inhibitory control measurement tasks as a potential moderator in the relationship between inhibitory control and mathematical ability. Previous studies found that different tasks measuring the same type of inhibition (i.e., interference inhibition or response inhibition) show varying associations with mathematical ability. For example, interference inhibition measured by the Simon task shows different associations with standardized mathematics test scores compared to that measured by the Stroop task (Van der Ven et al., 2012). Additionally, response inhibition measured by the Stop-signal task has a stronger association with arithmetical ability compared to the Go/No-go task (Niu et al., 2018; Zhu & Zhao, 2023). Therefore, it is reasonable to assume that measurement tasks of inhibitory control may also moderate the observed relation between inhibitory control and mathematical ability.

Demographic Characteristics

Age Previous research has suggested that the association between inhibitory control and mathematical ability may decrease as children age (Yang et al., 2019). This is consistent with the 'Fade-out' hypothesis which claims that the relationship between basic cognitive skills and mathematical skills gradually diminishes across childhood (Stipek & Valentino, 2015). However, there are also studies revealing that the association between inhibitory control and mathematical ability increased with age (Navarro et al., 2011; Wilkinson et al., 2019). Given these inconsistent findings, we consider age as a potential moderator.

Gender Previous studies documented gender differences in both inhibitory control and mathematical ability. Girls typically show higher levels of inhibitory control than boys (Memisevic & Biscevic, 2018). Such gender differences may arise from genetic evolutionary requirements for girls to have superior inhibitory control (Bjorklund & Kipp, 1996). Additionally, gender differences also exist in mathematical ability. A meta-analysis conducted by Hyde et al. (1990) found that girls outperformed boys on some mathematical tasks (e.g., arithmetic tasks), while the opposite was true for complex problem-solving. It is possible that gender differences in inhibitory control influence the magnitude of the relation between inhibitory control and mathematical ability (Ellefson et al., 2020). For example, previous evidence has suggested that inhibitory control is more strongly related to boys' than girls' arithmetical ability (Ellefson et al., 2020; Visier-Alfonso et al., 2020). Thus, gender is considered as a potential moderator in the current meta-analysis.

Developmental Status Previous empirical studies have suggested that the relationship between inhibitory control and mathematical skills is stronger in children with developmental disabilities (e.g., learning difficulties, intellectual disabilities, ADHD, hearing impairments, or major physical and mental illnesses) compared to typically developing children (e.g., Andersson & Lyxell, 2007; Meiri et al., 2019; Tan, 2020; Zhu & Zhao, 2023). Brain imaging evidence also shows that children with developmental dyscalculia have smaller gray matter volumes in the intraparietal sulcus and cingulate gyrus, regions closely associated with inhibitory control (McKenna et al., 2017; Rotzer et al., 2008). This highlights the variability in the relationship between inhibitory control and mathematical ability in children with different developmental statuses (typical development versus developmental disability). Thus, the current meta-analysis considered developmental status as a potential moderator of the relationship between inhibitory control and mathematical ability.

Socioeconomic Status SES, which measures a family's socioeconomic resources (wealth, education, and social status; Ng et al., 2021), is closely related to children's mathematical ability development (Blakey et al., 2020; Ellefson et al., 2020). Children from high SES backgrounds tend to have better mathematical ability compared to their counterparts from low SES backgrounds (Blums et al., 2017; Escobar et al., 2018). According to the constrained and unconstrained model, children may require fewer inhibitory control resources to solving mathematical problems when their mathematical skills become more proficient, suggesting a weaker relationship between inhibitory control and mathematical ability in high SES children (Spiegel et al., 2021). Conversely, children from low SES families may rely more on basic cognitive skills (such as inhibitory control) when performing math-related tasks, leading to a higher correlation between inhibitory control and mathematical ability (Duncan et al., 2017; Tucker-Drob, 2009). Indeed, some empirical studies provided evidence supporting this hypothesis (Bellon et al., 2019; Swanson & Fung, 2016). Thus, the current meta-analysis considered SES as a potential moderator of the relationship between inhibitory control and mathematical ability. We acknowledge that we did not pre-preregistered to assess the moderating effect of SES. Instead, SES was included according to the suggestion from an anonymous reviewer.

Sample Region The development of inhibitory control and mathematical ability vary substantially across geographical regions. On one hand, Chinese children typically exhibit better inhibitory control than their counterparts in Canada (Georgiou et al., 2020), the UK (Ellefson et al., 2020) and the US (Lan et al., 2011). This may be a result of Chinese parents valuing self-control and self-regulation and transmitting these values to their children (Roos et al., 2017). On the other hand, Chinese children typically demonstrate developmental advantage in mathematical ability compared to children in other regions (e.g., Ellefson et al., 2020; Georgiou et al., 2020; OECD, 2016), which may be due to Chinese children's earlier exposure to mathematical learning in elementary school (Cui et al., 2017; Georgiou et al., 2020). Cross-cultural studies suggest that the strength of the relationship between inhibitory control and mathematical ability varies across different regions (Ellefson et al., 2020). Therefore, we considered sample region as a potential moderator.

Overview of the Current *Meta*-Analysis

This preregistered meta-analysis presents a comprehensive and systematic investigation of the relationship between inhibitory control and mathematical ability in elementary school children. We extend previous meta-analyses in the following ways. First, we adopted a more systematic and detailed classification of the types of inhibitory control and the domains of mathematical ability. Second, we focused on children in elementary school, a critical development stage of both inhibitory control and mathematical ability (Erbeli et al., 2021; Kang et al., 2022; Lin, 2011; Sadeghi et al., 2022; Vuillier et al., 2016). Third, we included a broader range of databases (e.g., Chinese databases) to include more studies from a broader geographical scope, thereby enhancing the diversity and representation of the included studies. There are substantial variations in mathematics curricula and instructional models across different countries (Wang & Lin, 2009), which can influence the development of children's mathematical ability and may further impact the magnitude of their relationship with inhibitory control. Finally, we considered various potential moderating factors in the relationship between inhibitory control and mathematical ability, including the inhibitory control task, age, gender, developmental status, SES, and sample region. These advances provide a more comprehensive and nuanced understanding of the relationship between inhibitory control and mathematical ability in elementary school children, offering both theoretical knowledge and practical applications in education and cognitive development.

Method

We preregistered the research question, methods, and analyses with PROSPERO in 2023. All data, analysis codes, research materials, and preregistration are publicly available at OSF (https://osf.io/v5a3p/?view_only=b8ef2f607c054686a570597186b5e657).

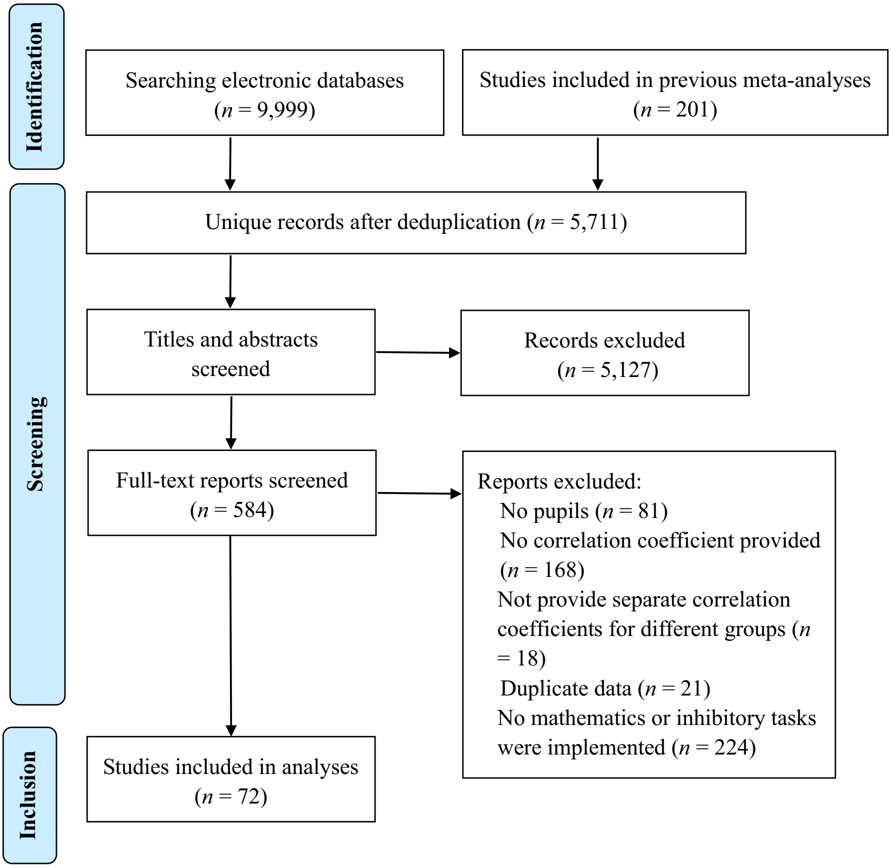

Fig. 1 Flow Diagram Depicting the Study Screening Process

Literature Search

To identify relevant studies, we performed a two-step exhaustive search procedure (see Fig. 1). First, we conducted a literature search in both English and Chinese electronic databases, including Web of Science, PsycINFO, ProQuest (dissertation), Google Scholar, Scopus, Science Direct, PubMed, ERIC, CNKI database, the Database of Chinese Sci-tech Journals (WIP Journals), and Wanfang Database. We used a combination of keywords involving inhibitory control (e.g., "inhibition" OR "executive function"), mathematics (e.g., "math*"), and elementary school children (e.g., "primary" OR "child*"). Details of search terms are available in online Supplementary Materials (SM) Appendix A. Both published and unpublished studies (e.g., dissertations) were included.

Second, we screened the reference lists of the previous five meta-analyses examining the relationship between inhibitory control and academic performance to identify potential eligible studies (Allan et al., 2014; Cortés Pascual et al., 2019; Emslander & Scherer, 2022; Friso-van den Bos et al., 2013; Spiegel et al., 2021).

We ended our database search in February 2023 and retrieved a total of 10,200 articles. After removing duplicates, our search strategy resulted in a total of 5,711 potentially eligible records.

Inclusion and Exclusion Criteria

Studies eligible for inclusion had to meet the following criteria: (1) they used continuous and objective measurement of both inhibitory control and mathematical ability. Studies using subjective rating scales to measure inhibitory control and those using teachers' ratings to measure children's mathematical ability were excluded (e.g., Magalhães et al., 2020; Wilson et al., 2011); (2) they included children in elementary school as participants. Studies that mixed elementary school children with preschool or middle school students were excluded (e.g., Holochwost et al., 2017); (3) in cases where the same data were reported in multiple publications, only one source was selected. Specifically, journal articles were preferred over dissertations (e.g., Niu et al., 2018); (4) they included studies featuring both typically developed children and children with developmental disability, but presented the results separately for each group (e.g., Swanson & Beebe-Frankenberger, 2004); (5) they included data from participants who did not receive any interventions (i.e., only baseline and control group data from intervention studies were used); (6) they reported at least one cross-sectional correlation coefficient between inhibitory control and mathematical ability. While longitudinal studies provide valuable insights into causal relationships, the limited number of longitudinal studies in this field restricts our ability to investigate longitudinal relationships. Most empirical research examines the cross-sectional association between inhibitory control and mathematical ability. Therefore, we chose to focus on cross-sectional data, as it allows for better control of external factors that might influence the relationship between inhibitory control and mathematical ability (Ober et al., 2020). The inclusion of cross-sectional data offers a clearer understanding of the concurrent relationship between inhibitory control and mathematical ability, specifically in elementary school children, as well as how this relationship is influenced by various moderators.

Coding

We coded the following characteristics of each included study: (1) mean age; (2) developmental status (i.e., typical development, developmental disability); (3) SES (i.e., low, middle, high); (4) sample region (i.e., North America, Europe, China, other); (5) gender (i.e., percentage of girl participants); (6) types of inhibitory control (i.e., interference inhibition, response inhibition); (7) domains of mathematical ability (i.e., numerical ability, arithmetical ability, logical reasoning ability, geometric ability, standardized mathematics tests scores, and school examinations scores); (8) inhibitory control task (i.e., Stroop task, Flanker task, Simon task, Go/No-go task, Stop-signal task, Random generation task, other tasks); (9) correlation coefficient between inhibitory control and mathematical ability; (10) sample size.

To determine the inter-rater reliability of the coding process, two coders coded all the included studies. Inter-rater reliability was good, with intraclass correlations (ICC) for continuous variables ranging from 0.96 to 1.00, and Cohen's Kappa for categorical variables ranging from 0.91 to 1.00. In cases of discrepancies in coding between the two coders, resolutions were achieved through discussions among all authors.

Data Analysis

The target effect size is the correlation coefficient (r) between inhibitory control and mathematical ability. Prior to conducting the analyses, we performed a preliminary analysis to exclude potential outliers after converting Pearson's r values to Fisher's z values (Lipsey & Wilson, 2001). After conducting the analyses, we transformed the Fisher's z values back to Pearson's r for interpretability.

Given that many studies included in our analyses reported multiple effect sizes from the same sample, violating the assumption of independent effect sizes in traditional meta-analysis (Cheung, 2014), we performed a three-level random-effects meta-analysis (Assink & Wibbelink, 2016). This method allowed us to include multiple effect sizes from one study while accounting for their dependency by modeling the hierarchical structure of the data (Van den Noortgate & Onghena, 2003). First, we estimated an overall association between inhibitory control and mathematical ability in an intercept-only random-effects model. Second, we performed two separate log-likelihood-ratio tests to determine whether the within-study variance (at level 2 of the model) and the between-study variance (at level 3 of the model) in effect sizes were significant. In case of significant heterogeneity, we extended the random-effects model to mixed-effects models in bivariate moderator analyses to test potential moderators. All analyses were performed via the R *metafor* package (Viechtbauer, 2015).

Assessment of Publication Bias

Publication bias (i.e., statistically significant findings are more likely to be published than non-significant findings) can cause inflated estimates of an effect (Franco et al., 2014). To mitigate the potential influence of publication bias, we included both published articles and unpublished theses. We also employed four statistical methods to detect potential publication bias: 1) Contour-enhanced funnel plots (Peters et al., 2008), 2) Robust Bayesian Meta-Analysis (Bartoš et al., 2022; Maier et al., 2023; Yang et al., 2023), 3) Precision-effect test and precision-effect estimate with standard errors (PET-PEESE) (Bartoš et al., 2022; Silver et al., 2024), and 4) Egger's regression test (Egger et al., 1997).

Results

Included Studies

In total, 72 eligible studies were identified, from which 241 effect sizes were obtained from 86 independent samples. The aggregate sample size was 14,223 participants (see online SM Appendix B for detailed information of the included studies). Sample size ranged from $n = 23$ to 1080 ($M = 165.38$, $SD = 169.42$, $Mdn = 103$). Mean age (reported for 88.37% of the included samples) ranged from 6.17 to 11.43 years ($M = 8.67$, $SD = 1.41$, $Mdn = 8.75$). Proportions of girl participants (reported for 95.35% of the samples) ranged from 0 to 100% ($M = 48.73\%$, $SD = 10.82\%$, $Mdn = 50\%$). The included studies spanned 22 years from 2001 to 2023.

Preliminary Analyses

Two approaches were implemented to identify potential outliers. First, residuals exceeding ± 3 standard deviations in effect sizes were identified using the dplyr package in R 4.2.2 (Hu et al., 2022). Second, Cook's distance test was employed as a supplementary method (Murdoch et al., 2021) to verify the removal of effect sizes exceeding three times of mean distance. Two effect sizes in the study by Tan (2020) were identified as outliers ($r = 0.84$; 0.79). After removing outliers, the adjusted overall effect size was $r = 0.19$, 95% CI [0.14, 0.23], $p < 0.001$, which did not differ statistically from the original overall effect size ($r = 0.20$; see below for details). Using the leave-one-out method to individually exclude effect sizes from the included studies (Dodell-Feder & Tamir, 2018), results showed that removing these two effect sizes slightly reduced the observed correlation between inhibitory control and mathematical ability. Considering these outliers came from a small sample ($n = 64$) of children with developmental disabilities (i.e., Down Syndrome), they were excluded from subsequent analyses to ensure the reliability of the results.

Overall Association and Effect Size Heterogeneity

The analysis yielded a moderate positive correlation between inhibitory control and mathematical ability (Lipsey & Wilson, 2001), $r = 0.19$, 95% CI [0.14, 0.23], $p < 0.001$ (see Table 1), indicating that better inhibitory control is correlated with superior mathematical ability. We found a heterogeneous distribution of effect sizes, both within studies (i.e., variance at level 2), $\chi^2(1) = 174.18$, $p < 0.001$ (representing 21.46% of the total variance), and between studies (i.e., variance at level 3), $\chi^2(1) = 101.71$, $p < 0.001$ (representing 65.89% of the total variance). Thus, the associations between children's inhibitory control and mathematical ability varied both within and between studies, which warrants further exploration of the sources of heterogeneity.

Table 1 Bivariate Moderator Analyses

Moderator variables	s	k	b_0 (95% CI)	b_1 (95% CI)	r	F(df1, df2)	p	Level 2 variance	Level 3 variance
Overall effect	86	239	0.19 [0.14, 0.24]***		0.19			0.011***	0.034***
Types of Inhibitory Control						5.64 (1, 237)	0.018	0.011***	0.033***
Interference inhibition	66	171	0.21 [0.16, 0.26]***		0.21				
Response inhibition	28	68	0.14 [0.08, 0.20]***	−0.07 [−0.13, −0.01]*	0.14				
Domains of Mathematical Ability						0.08 (5, 233)	0.996	0.012***	0.035***
Numerical ability	9	24	0.18 [0.09, 0.26]***		0.17				
Arithmetical ability	54	116	0.19 [0.14, 0.25]***	0.02 [−0.06, 0.10]	0.19				
Logical reasoning ability	26	54	0.18 [0.11, 0.25]***	0.002 [−0.09, 0.09]	0.18				
Geometric ability	2	4	0.18 [0.03, 0.32]*	0.0002 [−0.16, 0.16]	0.17				
Standardized mathematics tests scores	24	30	0.20 [0.11, 0.28]***	0.02 [−0.10, 0.14]	0.19				
School examinations scores	7	11	0.20 [0.06, 0.35]**	0.03 [−0.14, 0.19]	0.20				
Inhibitory Control Task						0.76 (6, 232)	0.601	0.012***	0.033***
Stroop task	52	120	0.18 [0.13, 0.24]***		0.18				
Flanker task	11	23	0.20 [0.10, 0.30]***	0.02 [−0.09. 0.12]	0.20				
Simon task	4	10	0.19 [0.03, 0.34]*	0.001 [−0.15, 0.16]	0.18				
Go/No-go task	14	29	0.17 [0.08, 0.26]***	−0.02 [−0.11, 0.08]	0.17				
Stop signal task	3	7	0.20 [0.05, 0.36]**	0.02 [−0.13, 0.17]	0.20				
Random generation task	3	12	0.41 [0.19, 0.63]***	0.22 [−0.004, 0.45]	0.39				
Other tasks	14	38	0.16 [0.08, 0.24]***	−0.02 [−0.11, 0.06]	0.16				
Demographic Characteristics									
Mean age	76	219	−0.03 [−0.33, 0.26]	0.03 [−0.01, 0.06]		2.37 (1, 217)	0.125	0.012***	0.033***
Girls' percent	82	233	0.21 [0.07, 0.34]**	−0.05 [−0.31, 0.22]		0.12 (1, 231)	0.727	0.011***	0.035***

Table 1 (continued)

Developmental Status						0.87 (1, 237)	0.353	0.011***	0.035***
Typical development	74	206	0.18 [0.13, 0.23]***		0.18				
Developmental disability	12	33	0.25 [0.12, 0.37]***	0.06 [−0.07, 0.20]	0.24				
SES						1.17 (2, 127)	0.315	0.013***	0.032***
Low	22	54	0.20 [0.11, 0.29]***		0.20				
Middle	19	54	0.21 [0.12, 0.31]***	0.02 [−0.11, 0.14]	0.21				
High	9	22	0.09 [−0.05, 0.23]	−0.11 [−0.27, 0.06]	0.09				
Sample Region						0.01 (3, 231)	0.999	0.011***	0.037***
North America	22	57	0.18 [0.09, 0.27]***		0.18				
Europe	28	62	0.19 [0.11, 0.28]***	0.01 [−0.11, 0.13]	0.19				
China	24	60	0.19 [0.10, 0.28]***	0.001 [−0.13, 0.13]	0.18				
Other	10	56	0.20 [0.07, 0.32]**	0.01 [−0.15. 0.17]	0.19				

Note. s = number of independent studies, k = number of effect sizes, b_0 = intercept/mean effect size (Fisher's z); b_1 = estimated regression coefficient; CI = confidence interval; r = intercept/mean effect size (Pearson's r correlation), obtained by transforming Fisher's z (b_0) into r; F ($df1$, $df2$) = omnibus test of all slopes being zero; df = degrees of freedom; Level 2 variance = variance among effect sizes (within studies); Level 3 variance = variance among effect sizes (between studies). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Moderators

Types of Inhibitory Control As shown in Table 1 and online SM Appendix D Table S2, we found a significant moderating effect of types of inhibitory control on the association between inhibitory control and mathematical ability, $F(1, 237) = 5.64$, $p = 0.018$. Specifically, the relationship between interference inhibition and mathematical ability, $r = 0.21$, 95% CI [0.16, 0.25], $p < 0.001$, was significantly stronger than the relationship between response inhibition and mathematical ability, $r = 0.14$, 95% CI [0.08, 0.20], $p < 0.001$, $t = -2.37$, $p = 0.018$. Then, we conducted subgroup analyses for interference inhibition and response inhibition, and tested the moderation effect of domains of mathematical ability. As shown in online SM Appendix E Table S3, interference inhibition was positively correlated with mathematical ability in all domains. The correlations between interference inhibition and different domains of mathematical ability (rs = 0.18—0.27, ps ≤ 0.007) were generally stronger than the correlations between response inhibition and different domains of mathematical ability (rs = −0.01—0.19).

Domains of Mathematical Ability We found no significant moderating effect of domains of mathematical ability, $F(5, 233) = 0.08$, $p = 0.996$ (see Table 1). Six domains of mathematical ability were significantly correlated with inhibitory control, rs = 0.17—0.20, ps ≤ 0.021. Then we conducted subgroup analyses for six domains of mathematical ability and tested the moderation effect of types of inhibitory control. As shown in online SM Appendix E Table S3 and Appendix F Table S4, interference inhibition and response inhibition were similarly related with all domains of mathematical ability, except arithmetical ability, $t = 2.74$, $p = 0.007$. Specifically, the correlation between interference inhibition and arithmetical ability ($r = 0.23$, 95% CI [0.16, 0.29], $p < 0.001$) was significantly stronger than the correlation between response inhibition and arithmetical ability ($r = 0.12$, 95% CI [0.03, 0.21], $p = 0.013$).

Inhibitory Control Task We found no significant moderating effect of inhibitory control task (see Table 1), $F(6, 232) = 0.76$, $p = 0.601$. Inhibitory control measured by different tasks was positively related with all six domains of mathematical ability (rs = 0.16—0.39, ps ≤ 0.018). However, pairwise subgroup comparison (see online SM Appendix D Table S2) suggested that inhibitory control measured by the Random generation task ($r = 0.39$, 95% CI [0.18, 0.56], $p < 0.001$) was more strongly associated with mathematical ability than that measured by the Go/No-go task ($r = 0.17$, 95% CI [0.08, 0.25], $p < 0.001$; $t = 1.97$, $p = 0.050$) and other tasks ($r = 0.16$, 95% CI [0.08, 0.24], $p < 0.001$; $t = 2.06$, $p = 0.041$).

Demographic Characteristics As shown in Table 1, we found no significant moderation effect of age, gender, developmental status, SES and sample region, ps ≥ 0.125 (see online SM Appendix D Table S2 for detailed results).

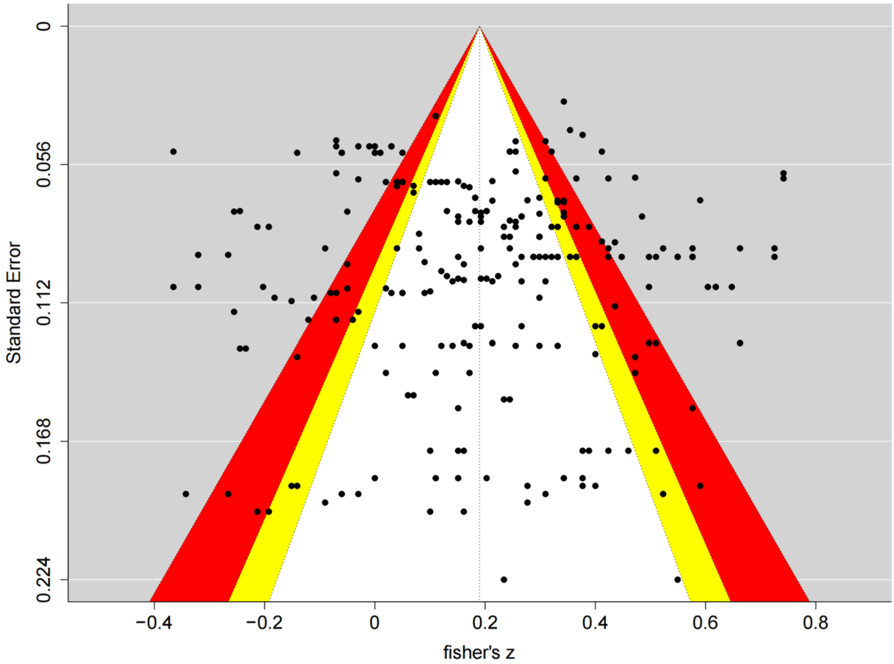

Fig. 2 Funnel plot of effect sizes

Publication Bias Assessment

We used contour-enhanced funnel plots, Robust Bayesian Meta-Analysis, PET-PEESE, and Egger's regression test to assess potential publication bias. The funnel plot indicated a symmetrical distribution of effect sizes around the overall effect, suggesting little risk of publication bias (see Fig. 2). The Robust Bayesian Meta-Analysis results supported the absence of publication bias, $BF_{pb} = 0.226$. The PET-PEESE results indicated that the intercept in PET regression was significant, so the intercepts from PEESE were used as the best estimates of the true effects, $b = 0.17$, 95% CI [0.13, 0.21], $p < 0.001$. This effect size was only slightly smaller than the original estimates reported above, with nearly overlapping confidence intervals, indicating minimal concern for publication bias. Additionally, the Egger's regression test suggested that the funnel graph did not deviate significantly from a symmetrical shape, $t(237) = 0.26$, $p = 0.794$. In summary, these results jointly showed minimal concern of publication bias.

General Discussion

The current meta-analysis is the first to systematically examine the relationship between inhibitory control and mathematical ability in elementary school children, and explore various potential moderating factors on this relationship, including types of inhibitory control, domains of mathematical ability, inhibitory control task, age, gender, developmental status, SES, and sample region. Results indicated a positive correlation between inhibitory control and mathematical ability. Importantly, interference inhibition was more strongly correlated with mathematical ability than response inhibition. The relationship between inhibitory control and mathematical ability did not vary across different domains of mathematical ability, inhibitory control task, and demographic characteristics (i.e., age, gender, developmental status, SES, and sample region).

Overall Association Between Inhibitory Control and Mathematical Ability

We found a positive correlation between inhibitory control and mathematical ability in elementary school children, consistent with some prior empirical studies and meta-analyses (e.g., Allan et al., 2014; Friso-van den Bos et al., 2013; Lee et al., 2012; Spiegel et al., 2021; Sulik et al., 2018). Such a finding also supports the intrinsic cognitive load theory, dual-processing theory, and the constrained and unconstrained model, indicating that inhibitory control may be a crucial cognitive foundation for mathematical processing (Attridge & Inglis, 2015; Beckmann, 2010; De Smedt, 2022).

Notably, the overall association between inhibitory control and mathematical ability identified in the current meta-analysis is slightly weaker than that reported in previous meta-analyses (e.g., Allan et al., 2014; Emslander & Scherer, 2022; Friso-van den Bos et al., 2013; Spiegel et al., 2021). One plausible explanation for this discrepancy may be the unique age range of the sample included in the current meta-analysis. Previous research suggested that inhibitory control is not an independent construct in preschool children (Shing et al., 2010). That is to say, the relationship between inhibitory control and mathematical ability in this age group may be influenced by other executive function subcomponents (such as working memory; Lee & Lee, 2019). Meanwhile, mathematical ability in preschool children was primarily measured by numerical ability tasks, such as counting, numerical comparison, and simple arithmetic operations such as single-digit addition and subtraction (Tobia et al., 2016). According to the constrained and unconstrained model (Spiegel et al., 2021), these constrained skills, while simpler, still require the allocation of cognitive control resources before these skills become automated (De Smedt, 2022; McCormick et al., 2020). During elementary school, these skills are mostly automated, reducing the need for inhibitory control (Spiegel et al., 2021). Indeed, studies have shown that simple mathematics tasks, such as counting, usually require only inhibitory control in preschoolers (Lan et al., 2011). Taken together, inhibitory control plays a vital role in mathematical ability development during preschool years, which are distinct from the elementary school years covered in the current meta-analysis.

Another possible reason for the discrepancy may be differences in the included domains of mathematical ability in the current meta-analysis. Previous research has shown that inhibitory control is differently related to various domains of mathematical ability (Arán Filippetti & Richaud, 2017; Spiegel et al., 2021). For example, inhibitory control is more closely associated with numeric and arithmetic ability (Swanson, 2006; Wongupparaj & Kadosh, 2022). This is because simple mathematical facts, typically stored in the associative networks of long-term memory (Campbell et al., 2011), require inhibitory control to suppress automated responses and inhibit alternative strategies, ensuring retrieval of correct answers (Cragg et al., 2017). However, inhibitory control plays a less important role in more complex mathematic abilities such as geometry and logical reasoning, which rely heavily on working memory for analysis, representation, and maintenance of spatial geometrical information, as well as continuous updating to process and construct mental representations of reasoning-related problems (Clements et al., 2016; Holmes et al., 2009; Miller-Cotto & Byrnes, 2020; Zhu & Zhao, 2023). Given these considerations, future research should account for both educational stage and specific domains of mathematical ability when examining the relationship between inhibitory control and mathematical ability.

Moderators

Types of Inhibitory Control

We found that interference inhibition was more strongly correlated with mathematical ability than response inhibition. We interpreted this finding in the context of the inhibitory control development. Research indicates that response inhibition develops earlier than interference inhibition (Tao et al., 2023; Vuillier et al., 2016) and facilitates the development of the latter (Cragg, 2016). As one of the earliest developing executive functions (Tao et al., 2023), response inhibition aids young children in resisting task-irrelevant impulsive behaviors during mathematical learning and processing (Morgan et al., 2019), and supports fundamental mathematical ability, such as counting (Purpura et al., 2017). Indeed, previous research observed that, among preschoolers, response inhibition has a stronger relationship with basic mathematical ability than interference inhibition (Duncan et al., 2017), suggesting its crucial role in early mathematical processing. However, as children acquire autonomous behavioral control, the role of response inhibition in mathematical ability may decrease, transitioning to an implicit supporting role in the development of higher cognitive skills and more complex mathematical abilities.

During elementary school years, interference inhibition becomes increasingly important, supporting a variety of mathematical processes (Arán Filippetti & Richaud, 2017; Van Dooren & Inglis, 2015; Waters et al., 2021). Specifically, it helps children focus on classroom activities and ignore distractions (Lee & Lee, 2019), facilitates retrieval of arithmetic facts by resisting erroneous answers or inappropriate strategies (Cragg et al., 2017; Wang et al., 2018), and evolves into a generalized executive function, laying the groundwork for higher functions like updating and cognitive flexibility. These functions are essential for solving complex mathematical problems, making interference inhibition a core component influencing mathematical ability (Wen et al., 2007). As children progress through elementary school, they encounter more complex mathematical problems (Sulik et al., 2020) and need to manage a growing body of mathematical knowledge. This requires not only dedicating more attentional resources to mathematical processing (Spiegel et al., 2021) but also inhibiting prior learning experience that is not pertinent to the current mathematical problem (Lee & Lee, 2019). This highlights the necessity of interference inhibition in mathematical processing for elementary school children.

This finding also provides a new perspective on the relationship between inhibitory control and mathematical ability in elementary school children, emphasizing the importance of considering different types of inhibitory control. Specifically, when the underlying mechanisms are more similar between inhibitory control and mathematical tasks, there will be a stronger relationship between the two (Lee & Lee, 2019). It also holds practical implications: future interventions aimed at enhancing mathematical ability in primary school should prioritize cultivating interference inhibition.

Domains of Mathematical Ability

We did not find a moderation effect of domains of mathematical ability in the association between inhibitory control and mathematical ability. Inhibitory control showed a positive correlation with all domains of mathematical ability, indicating its pervasive role in mathematical processing. Thus, the results of this meta-analysis did not support the views of the dual-processing theory (Evans & Stanovich, 2013) and the constrained and unconstrained model (De Smedt, 2022), which suggest that numerical ability may become automated during elementary school (Spiegel et al., 2021), reducing the need for inhibitory control resources and thereby weakening its association with inhibitory control. In contrast, the findings of the current review support the perspective of the intrinsic cognitive load theory, which suggests that due to the inherent complexity of mathematical skills, the relationship between inhibitory control and mathematical ability should persist stably (Spiegel et al., 2021; Sweller, 1994). However, it should be noted that the disparity in the number of effect sizes across different mathematical domains in the current meta-analysis may have concealed the true nature of the relationship between inhibitory control and various domains of mathematical ability. Therefore, further research is warranted to explore these relationships longitudinally or from a neuroscientific perspective.

Inhibitory Control Task

While we did not find a moderation effect of measurement tasks of inhibitory control in the association between inhibitory control and mathematical ability, we did find that inhibitory control measured by the Random generation task exhibited the strongest correlation with mathematical ability compared to other tasks. We interpreted these findings through the lens of task difficulty. Prior research showed partial overlap in brain regions involved in completing tasks related to different subcomponents of executive functions (McKenna et al., 2017). Consequently, inhibitory control tasks with varying levels of complexity inherently impose different demands on working memory and cognitive flexibility. Common tasks, such as the Stroop, Flanker, and Go/No-go tasks (e.g., Bellon et al., 2019; Zhu & Zhao, 2023), primarily require flexible responses to target stimuli based on task rules, demanding relatively small amounts of cognitive resources. In contrast, the Random Generation Task, which requires participants to inhibit habitual responses, update their strategies, and switch continuously between responses, imposes substantially higher cognitive demands. Additionally, this task requires participants to override well-established sequences, such as numerical or alphabetical orders (Swanson, 2006), which aligns more closely with the cognitive complexity inherent in mathematical tasks. Empirical studies support this interpretation by showing that more complex inhibitory control tasks exhibit a stronger correlation with standardized mathematical test scores compared to simpler tasks (Jiao et al., 2017). Therefore, it is imperative for future research to consider the complexity of inhibitory control measurement tasks when exploring the relationship between inhibitory control and mathematical ability.

Demographic Characteristics

Age Consistent with previous meta-analyses (Friso-Van den Bos et al., 2013; Spiegel et al., 2021), the current meta-analysis found no evidence that the relationship between inhibitory control and mathematical ability vary as a function of age. While some studies (Wilkinson et al., 2019) have observed a stronger relationship in older children, the current meta-analysis included complex mathematical abilities, such as logical reasoning measured by standardized tests, which require consistent cognitive control resources throughout elementary school (Spiegel et al., 2021; Wen et al., 2007). Previous literature indicated that while simple mathematical ability (e.g., numerical ability) becomes automated in early education stages, there is a subsequent shift towards teaching more complex mathematical skills (e.g., logical reasoning), which generally require more cognitive control resources (Spiegel et al., 2021). Furthermore, Wen et al. (2007) also emphasized that inhibitory control plays a consistent role across all phases of mathematical processing in primary school-aged children, suggesting that inhibitory control's contribution to mathematical ability may be consistent across elementary education. Taken together, the relationship between inhibitory control and mathematical ability may remain similar throughout elementary years.

Gender The relationship between inhibitory control and mathematical ability was consistent across samples with varying proportions of girl participants. This finding aligns with previous empirical findings (Aadland et al., 2017) and corroborates results from previous meta-analyses (Emslander & Scherer, 2022). However, the limited variation of gender ratio across studies could contribute to the null moderation effect of gender. Further investigation into this question is warranted.

Developmental Status We found a positive relationship between inhibitory control and mathematical ability in both typically developing children and those with developmental disability, with no significant difference between the two groups. This contradicts our hypothesis but may reflect different mechanisms of how inhibitory control supports mathematical processing between these two groups. Children with developmental disability, particularly those experiencing difficulties in mathematical processing, often struggle with insufficient inhibition control capacity, which may lead to mathematical difficulties (Bull & Scerif, 2001; Geary et al., 2004). Therefore, inhibitory control may serve as an important cognitive foundation for basic mathematical processing in children with developmental disability. In contrast, for typically developed children, inhibitory control not only is directly involved in basic mathematical processing but also acts as a prerequisite for operation of other higher-order cognitive skills (such as updating and cognitive flexibility) that support development of complex mathematical skills (Wen et al., 2007). Therefore, inhibitory control plays a crucial role in mathematical processing in both groups.

SES As an additionally included exploratory potential moderator, we found no evidence that the relationship between inhibitory control and mathematical ability vary across samples from different SES backgrounds. We interpreted this result in the context of children's developmental stage. It is possible that SES may have a more substantial influence during the preschool stage, as children from high-SES backgrounds receive more mathematical guidance from their parents and develop better mathematical abilities (Blakey et al., 2020). Consequently, these children would require less inhibitory control to perform mathematical tasks. In contrast, at the elementary school stage, all children receive formal and equal mathematics education, which further reduces SES-related disparities in mathematical abilities (Daucourt et al., 2021). As a result, children's more homogeneous mathematical ability levels may lead to similar demands for inhibitory control resources during mathematical processing. Future research should examine SES across a broader age range to better understand its role in the relationship between inhibitory control and mathematical ability.

Sample Region We found no evidence that the relationship between inhibitory control and mathematical ability vary across different regions, contradicting our expectation of regional differences. A possible explanation is that for children in regions typically characterized with inferior mathematical ability, inhibitory control serves as a cognitive foundation for basic mathematical ability development (Finch et al., 2022). For children in regions typically characterized with superior mathematical ability, inhibitory control is involved in development of more advanced mathematical skills (Spiegel et al., 2021). Therefore, the relationship between inhibitory control and mathematical ability may be similar across regions.

Strengths, Limitations, and Future Research Directions

The current meta-analysis provided a comprehensive exploration of the relationship between inhibitory control and mathematical ability in elementary school children. Strengths of the current meta-analysis include (1) adherence to open science practices and resultant reproducibility of all results; (2) the novel set of moderation analyses; (3) focusing on the critical developmental period of children; (4) inclusion of studies from diverse countries/regions, and (5) extensive robustness analyses. However, the current meta-analysis also bears several limitations. First, the reliance on cross-sectional correlational designs means that findings do not address the directionality of effects. Children's inhibitory control and mathematical ability may influence each other bidirectionally over time (Son et al., 2019). Future research should incorporate longitudinal data to explore the bidirectional relationship between inhibitory control and mathematical ability. Second, while the current meta-analysis considered a broad range of potential moderators, other factors (e.g., fluid intelligence, and processing speed) could also explain the variability in effect sizes (Bull & Lee, 2014; Peng et al., 2018). Future research is needed to explore these factors further. Third, while the current meta-analysis categorized both inhibitory control and mathematical ability based on relevant theories and empirical evidence, it did not account for the variability in task difficulty. For instance, differences in the complexity of the Stroop task employed by Zhu and Zhao (2023) and Zhao (2022) could influence the strength of correlation between inhibitory control and mathematical ability. Therefore, future research should further investigate the potential moderating role of task difficulty in the observed relationship between inhibitory control and mathematical ability.

Implications

From a theoretical standpoint, the observed findings support the intrinsic cognitive load theory (Spiegel et al., 2021; Sweller, 1994), which suggests a stable relationship between inhibitory control and mathematical ability regardless of learning and experience due to the inherent complexity of mathematical tasks (Sweller, 1994; Wouters et al., 2008). The observed findings also support the perspective that the strength of relationship between inhibitory control and mathematical ability depends on the similarity of underlying mechanisms for resisting interference in processing the two types of tasks (Lee & Lee, 2019). When inhibitory processes involved in mathematical tasks are more similar to those required for inhibitory control tasks, there will be a stronger correlation between the two (Lee & Lee, 2019). Since interference inhibition is more broadly involved in mathematical processing, it generally exhibits a stronger relationship with mathematical ability.

Our findings also have crucial practical implications. While previous studies have identified inhibitory control as a potential focal point for interventions aimed at improving children's mathematical abilities (Wilkinson et al., 2019), these investigations have generally not reported strong transfer effects to mathematical abilities. Based on our findings, the relationship between interference inhibition and mathematical ability is stronger than that between response inhibition and mathematical ability. Therefore, future research aimed at designing interventions to enhance mathematical ability through inhibitory control training should primarily focus on interference inhibition training. Additionally, the current meta-analysis found a stronger association between inhibitory control and mathematical ability as measured by the Random generation task compared to other tasks. Following the findings of Jiao et al. (2017), future researchers should consider implementing more complex training programs when designing inhibitory control interventions, in order to achieve greater improvements of mathematical abilities.

Concluding Remarks

Inhibitory control is positively related to mathematical ability in elementary school children, with interference inhibition showing a stronger correlation with mathematical ability than response inhibition. This suggests that future researchers should focus on interference inhibition when examining the relationship between inhibitory control and mathematical ability. The relationship between inhibitory control and mathematical ability does not vary across different domains of mathematical ability, inhibitory control task, and is stable across a variety of demographic characteristics, such as age, gender, developmental status, SES, and sample region. The intrinsic cognitive load theory provides a suitable framework to account for the relationship between inhibitory control and mathematical ability in elementary school children. Future research aimed at developing interventions to improve children's mathematical abilities through inhibitory control training should focus on interference inhibition and employ tasks with higher cognitive load.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10648-024-09976-w.

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Data and Code Availability The study data and code can be accessed at: https://osf.io/v5a3p/

Declarations

Conflict of Interest The authors declare no competing interests.

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