The Mediating Role of Executive Function between Socioeconomic Status and Academic Achievement: Meta-Analytic Structural Equation Modeling

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Abstract

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Full Text

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Abstract

Using 34 empirical studies (38 independent samples), this study employed meta-analytic structural equation modeling to examine the mediating role of executive function between family socioeconomic status and academic achievement. Results revealed: (1) Family socioeconomic status directly influences academic

achievement and also indirectly influences academic achievement through executive function, supporting a partial mediation model; (2) Participant age and gender significantly moderate these relationships.

Keywords: family socioeconomic status; executive function; academic achievement; structural equation model; meta-analysis

Academic achievement in children and adolescents is crucial for individual development, as higher academic achievement is associated with greater college enrollment rates and better quality of life in adulthood. Extensive research has demonstrated that family socioeconomic status (SES) is one of the important predictors of academic achievement (Sirin, 2005). Children from lower SES backgrounds typically exhibit poorer academic performance and have higher probabilities of absenteeism, dropout, and behavioral problems (Bradly & Corwyn, 2002; Kim, Cho, & Kim, 2019; Liu, Peng, & Luo, 2019; Sirin, 2005). This further exacerbates the disadvantaged situation of already vulnerable children. Despite substantial efforts by educational practitioners to reduce the SES-related academic achievement gap, this gap has persisted for over half a century (Eric A. Hanushek, 2019). Therefore, revealing the mechanisms through which SES influences academic achievement is essential for establishing effective intervention strategies.

Numerous studies have found that family socioeconomic status may affect academic achievement by influencing the development of children's executive function (Albert et al., 2020; Dilworth-Bart, 2012; Lawson & Farah, 2017; Poon, Ho, & Chou, 2022). However, previous research has three unresolved issues: First, although empirical studies have found that executive function can explain the academic achievement gap resulting from socioeconomic status, these studies remain inconsistent. It remains unclear whether executive function mediates the relationship between SES and academic achievement, and if so, whether it is a partial or complete mediation. Second, while previous meta-analyses have examined the relationships among the three variables, they have all used bivariate models, which cannot test the relationships among all three variables when simultaneously included in a model. Finally, the inconsistency in empirical research results may be caused by moderating variables, but previous studies have not examined moderating effects and thus cannot determine under what conditions these relationships hold.

In summary, on the one hand, whether SES influences academic achievement through EF remains unclear, preventing a definitive answer to the question of the mechanism through which SES affects academic achievement. On the other hand, these ambiguous findings prevent policymakers and practitioners from developing the most effective interventions to interrupt the SES-achievement gap. Therefore, this meta-analysis integrates previous relevant studies and utilizes meta-analytic structural equation modeling to examine whether family socioeconomic status indirectly influences academic achievement through executive function and to identify potential moderating variables within a multivariate model.

Family Socioeconomic Status and Executive Function

Executive functions (EF) refer to a series of top-down, goal-directed higher-order cognitive structures (A. Diamond, 2013). Researchers generally agree that EF comprises three interrelated yet independent components: working memory, inhibitory control, and cognitive flexibility (Baggetta & Alexander, 2016; Miyake et al., 2000).

During childhood and adolescence, EF and its associated brain region (the prefrontal cortex) are not yet mature and remain in a continuous developmental period (John R. Best & Miller, 2010). Consequently, EF is susceptible to environmental factors, including family socioeconomic status (Kimberly G. Noble, McCandliss, & Farah, 2007). Numerous empirical studies have examined the relationship between SES and EF, yielding relatively consistent conclusions. The relationship pattern between SES and EF is consistent across countries at different developmental levels (Haft & Hoeft, 2017a). Evidence of SES influencing EF has been found across different age groups from infancy to early adulthood (Last, Lawson, Breiner, Steinberg, & Farah, 2018; Kimberly G. Noble et al., 2015).

Compared to other cognitive abilities, the impact of SES on executive function is more pronounced (Farah et al., 2006; Kimberly G. Noble et al., 2007; K. G. Noble, Norman, & Farah, 2005), characterized by early onset (Daneri et al., 2019; Hanson et al., 2013; Murphy, Zhang, & Gatzke-Kopp, 2022; Xing, Liu, & Wang, 2019) and long duration (Moorman, Carr, & Greenfield, 2018). For example, Xing (2019) and Daneri (2019) both found that as early as age 4, children from different SES backgrounds showed significant differences in performance on inhibitory control, working memory, and cognitive flexibility tasks (Daneri et al., 2019; Xing et al., 2019). Additionally, some studies found that 4-year-old children from lower SES backgrounds had significantly smaller gray matter volume, particularly in frontal regions closely associated with executive function (Hanson et al., 2013). Childhood SES can even predict executive function performance in old age (Moorman et al., 2018).

Lower SES may hinder children's EF development for various reasons. Families with lower SES often have poorer parenting quality, limited availability of cognitive stimulation materials, and more monotonous environments (Daniel A. Hackman, Farah, & Meaney, 2010; D. A. Hackman, Gallop, Evans, & Farah, 2015; Haft & Hoeft, 2017b). Children from lower SES families are also more likely to be exposed to a series of stressors including economic pressure, neighborhood violence, crowding and noise, and family chaos and unpredictability (Merz, Wiltshire, & Noble, 2019). These factors are all detrimental to EF development, further leading to significant EF gaps between children from different SES families.

Executive Function and Academic Achievement

Research indicates that from childhood to adolescence, executive function is consistently significantly correlated with academic achievement (J. R. Best, Miller, & Naglieri, 2011). Longitudinal studies further demonstrate that EF's predictive power for academic achievement persists over time (Ahmed, Tang, Waters, & Davis-Kean, 2018; Samuels, Tournaki, Blackman, & Zilinski, 2016). Better executive function is associated with better academic performance across various subject areas including mathematics, reading, science, language, and social studies (J. R. Best et al., 2011; Latzman, Elkovitch, Young, & Clark, 2010; Samuels et al., 2016).

Moreover, this relationship pattern remains consistent across different cultural contexts. For example, Thorell (2013) and colleagues studied 6-15-year-old children in Sweden, Spain, Iran, and China, finding that although EF development levels differed across countries, all showed significant correlations between EF and academic achievement (Thorell, Veleiro, Siu, & Mohammadi, 2013). A cross-cultural study of Chinese and American preschoolers also found similar relationships between EF and academic achievement in both countries: better EF predicted better academic task performance (Lan, Legare, Ponitz, Li, & Morrison, 2011).

Some researchers have conducted intervention experiments on executive function to further validate its relationship with academic achievement. For instance, Dias (2016) and colleagues implemented EF training for first-grade children in real classroom settings, finding that the intervention group showed significantly improved EF and better arithmetic and reading performance compared to the control group. These improvements in EF levels and prosocial behavior were still evident in a follow-up survey one year later (Dias & Seabra, 2016).

Good EF in childhood can predict later academic success, likely through two pathways. On one hand, EF includes abilities to store and manipulate information, inhibit irrelevant information, and shift strategies, which are essential for completing learning tasks (Cragg, Keeble, Richardson, Roome, & Gilmore, 2017; Magalhaes, Carneiro, Limpo, & Filipe, 2020). On the other hand, EF helps inhibit interference and distraction, maintain focus on tasks, and develop good learning habits, thereby achieving better learning outcomes (Blair & Peters Razza, 2007; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017; Nesbitt, Farran, & Fuhs, 2015).

The Mechanism of Family Socioeconomic Status Influence on Academic Achievement: The Mediating Role of Executive Function

As described above, higher family socioeconomic status can facilitate children's executive function development, and better executive function can further promote academic task performance, leading to higher academic achievement. However, few empirical studies have examined the relationships among all three variables, and the limited available research has yielded inconsistent conclusions.

Some researchers have used cross-sectional designs to examine the relationships among EF, SES, and academic achievement. Dilworth (2012) and colleagues studied 49 children aged 54-66 months and found that EF partially mediated the relationship between SES and math performance (Dilworth-Bart, 2012). Similarly, Fitzpatrick (2014) studied children aged 36-71 months and found the same result: after controlling for vocabulary ability, EF partially mediated the relationship between SES and math performance (Fitzpatrick, McKinnon, Blair, & Willoughby, 2014). Researchers studying Portuguese, Chilean, and Latino American children also validated the partial mediating role of EF (Cadima, Gamelas, McClelland, & Peixoto, 2015; Escobar et al., 2018; Greenfader, 2019).

However, other researchers have found inconsistent results. Bachman (2022) studied 4-year-old children and found that EF completely mediated the relationships between SES and math performance, spatial ability, and approximate number system acuity (Bachman et al., 2022). Another study of 8-year-old children examining Chinese, English, and math performance also found that EF completely mediated the relationships between SES and achievement in all three subjects (Poon et al., 2022). Additionally, Ellefson (2020) conducted a cross-cultural study of 9-16-year-old children in Hong Kong and the UK, finding that EF partially mediated the relationship between SES and numeracy skills only in the UK boys' sample, but not in UK girls or Chinese children (Ellefson, Zachariou, Ng, Wang, & Hughes, 2020).

Longitudinal studies have also provided evidence for mediation. The research of Merz (2014), Waters (2021), and Barnes (2022) collectively demonstrates that preschool EF partially mediates the relationship between SES and academic achievement in preschool and first grade (Barnes, Boedeker, Cartwright, & Zhang, 2022; Merz et al., 2014; Waters, Ahmed, Tang, Morrison, & Davis-Kean, 2021). Some studies with larger age spans have similarly found that the partial mediating role of EF for SES and math and reading achievement remains valid during elementary school (Albert et al., 2020; Crook & Evans, 2014). Lawson (2017) studied 6-15-year-old children and found that EF also partially mediated the relationship between SES and changes in math performance two years later.

However, Nesbitt (2013) simultaneously included SES, ethnicity, expressive vocabulary ability, EF, and academic achievement in a model and found that SES only indirectly influenced academic achievement through EF, without directly affecting academic achievement (Nesbitt, Baker-Ward, & Willoughby, 2013). Similarly, a longitudinal study of 0-18-year-old children found that when control variables such as gender, verbal intelligence, and extracurricular activities were included in the model, SES could only indirectly influence academic achievement through EF (Deer, Hastings, & Hostinar, 2020).

In summary, most current empirical research suggests that EF mediates the relationship between SES and academic achievement, but the conclusions are not entirely consistent. Most researchers have found that EF plays a partial mediating role, yet some studies have found complete mediation or even no

mediation (Bachman et al., 2022; Deer et al., 2020; Ellefson et al., 2020; Poon et al., 2022). Therefore, it is necessary to use meta-analysis to integrate these mixed findings and reach a consistent conclusion. This study not only includes current empirical research but also incorporates many studies that did not test mediation models, enabling more accurate conclusions based on a large sample size.

Review of Previous Meta-Analyses

To date, some researchers have used meta-analysis to explore the pairwise relationships among SES, EF, and academic achievement. However, no meta-analysis has simultaneously examined the relationships among all three variables, and thus could not test the mediating role of EF between SES and academic achievement.

Three meta-analyses have established that the significant correlation between SES and academic achievement is universal across countries. Sirin (2005) conducted a meta-analysis based on 74 independent samples with 101,157 students and found a moderate-to-strong correlation between SES and academic achievement (Sirin, 2005). Meta-analyses by Kim (2019) and Liu (2019) based on developing countries and Chinese samples, respectively, also found significant correlations between SES and academic achievement, though the magnitude of the correlations was somewhat reduced (Kim et al., 2019; Liu et al., 2019).

Regarding the predictive effect of EF on academic achievement, Pascual (2019) and Spiegel (2021) both conducted meta-analyses on EF and academic achievement in elementary school children, consistently finding moderate correlations (r=0.365; r=0.33) (Cortes Pascual, Moyano, & Quilez Robres, 2019; Spiegel, Goodrich, Morris, Osborne, & Lonigan, 2021). Allan (2014) used meta-analysis to examine the relationship between inhibitory control and literacy and math achievement in preschool and kindergarten children (Allan, Hume, Allan, Farrington, & Lonigan, 2014). Santana (2021) examined the relationship between cognitive flexibility and math achievement in 5-8-year-old children (Santana, Roazzi, & Nobre, 2022). Both found that the relationships were significant.

For the relationship between SES and EF, Lawson's (2017) meta-analysis involving 8,760 children aged 2-18 found small-to-moderate correlations between SES and EF (r=0.16-0.28) (Lawson, Hook, & Farah, 2018).

Potential Moderating Variables

The inconsistent patterns of relationships among family socioeconomic status, executive function, and academic achievement in previous empirical studies suggest that additional factors may moderate these relationships.

Age On the one hand, executive function continues to develop throughout childhood and adolescence. On the other hand, as children grow older, they have more contact with school and society, and their connection with family

may gradually weaken. These factors suggest that the relationship patterns among SES, EF, and academic achievement may be influenced by age. Some meta-analyses have found moderating effects of age or grade. For example, Spiegel (2021) found that the correlations between working memory, inhibitory control, and academic achievement were stronger in later elementary school than in earlier elementary school (Spiegel et al., 2021). However, Santana's (2022) meta-analysis found that the relationship between cognitive flexibility and math achievement decreased with age during elementary school (Santana et al., 2022). Additionally, meta-analyses on SES and academic achievement have found different moderating effects of age or grade. For instance, Harwell (2017) found that the relationship between SES and academic achievement was stronger in early elementary school than in later elementary school (Harwell, Maeda, Bishop, & Xie, 2016), but Kim (2018) found the opposite result (Kim et al., 2019). Therefore, previous studies have not reached consistent conclusions regarding the influence of age on the relationships among SES, EF, and academic achievement, making it necessary to explore this in the current study.

Gender Gender has received less attention in previous relevant research, and existing findings are inconsistent. For example, regarding the relationship between SES and EF, one bivariate meta-analysis found that gender did not moderate the relationship between SES and EF (Lawson et al., 2018). However, Ellefson's (2020) study found that the significant correlation between SES and EF only held for UK boys, not for girls (Ellefson et al., 2020), suggesting that gender is a significant moderating variable in the relationship between SES and EF. Therefore, considering the inconsistency in previous research, this study also includes gender as a moderating variable.

Study Design Previous examinations of the relationships among SES, EF, and academic achievement have employed either cross-sectional or longitudinal designs. A considerable portion of the original literature included in this meta-analysis used longitudinal research designs. Therefore, this study conducted a separate meta-analysis based on longitudinal studies to test whether the effects of SES and EF on academic achievement persist over time.

In summary, current meta-analyses have used traditional bivariate meta-analytic methods. First, this approach can only address the relationship between any two of the three variables (SES, EF, and academic achievement) and cannot simultaneously include the third variable in the model. Therefore, previous meta-analyses could not answer whether EF mediates the relationship between SES and academic achievement or resolve the disagreements in current empirical research. Second, although previous meta-analyses have examined heterogeneity in original literature and used moderator analysis to explain variability in bivariate relationships, these methods cannot determine whether mediation models are affected by moderating variables.

Therefore, this study adopts the latest meta-analytic structural equation model-

ing method to integrate previous empirical research. This method can use structural equation modeling to fit meta-analytic data, making it possible to examine complex multivariate models, which traditional bivariate meta-analysis cannot achieve. Consequently, meta-analytic structural equation modeling can effectively answer whether SES indirectly influences academic achievement through EF and the magnitude of EF's mediating effect. Additionally, this study conducts moderation analysis to examine variations in EF's mediating role under different conditions.

This study proposes the following hypotheses: (1) SES positively predicts EF, and EF positively predicts academic achievement; (2) EF partially mediates the relationship between SES and academic achievement; (3) The partial mediating role of EF is moderated by age and gender.

Definition Criteria

Socioeconomic Status: There is relatively little controversy regarding the measurement of socioeconomic status, with income, education level, and occupation generally considered appropriate indicators (Bradly & Corwyn, 2002; Ensminger & Fothergill, 2003). This study adopts this measurement approach, considering family income, educational level of either or both parents, occupation of either or both parents, and combinations of these indicators as qualified measures of socioeconomic status. For studies that use other indicators to represent SES, they were included in the meta-analysis if most indicators (>50%) were qualified.

Executive Function: This study considers inhibitory control, working memory, cognitive flexibility, and combinations of these indicators as qualified measures of executive function. It should be noted that due to controversies regarding EF measurement tasks, this study determined the measurement target based on descriptions of the tasks themselves in the literature, referring to measurement methods proposed by Diamond (2013) and Spiegel (2021) (A. Diamond, 2013; Spiegel et al., 2021), rather than relying entirely on the original literature's descriptions. For example, this study excluded delay of gratification tasks and forward digit span tasks, and defined the Head-Toes-Knees-Shoulders task as a measure of inhibitory control.

Since previous research has found that behavior-based measures only correlate moderately with parent or teacher reports (r=0.30), and the former has higher concurrent and predictive validity for academic achievement (Soto et al., 2020), and considering that other-report-based measures may be confounded by subjective expectations and to ensure comparability among included studies, this study only included executive function measures based on behavioral performance.

Academic Achievement: There is currently no unified definition, standard, or measurement method for academic achievement. Researchers have used standardized psychological scales, teacher evaluations, school academic proficiency

tests, large-scale national standardized exams, and college enrollment rates to assess student achievement. Since academic development goals differ across ages, different academic achievement measurement indicators exist for different age stages. Therefore, this study does not provide a strict definition of academic achievement but accepts the definitions and measurement indicators proposed in the original literature as representing academic achievement.

Inclusion and Exclusion Criteria

Studies included in the meta-analysis needed to meet the following conditions: (1) Empirical studies published or unpublished before August 2022; (2) Participants under 18 years of age; (3) Typically developing samples, meaning participants had no physical or mental disorders (e.g., ADHD) or special circumstances (e.g., single-parent families); (4) Inclusion of all three variables in the same study—that is, at least one measure of SES: income, education, occupation, or composite measure; at least one behavior-based EF measure: inhibitory control, working memory, or cognitive flexibility; and at least one measure of academic achievement, such as reading or mathematics; (5) Reporting of at least two effect sizes (Pearson correlation coefficients) or provision of data sufficient for calculating effect sizes; (6) Exclusion of studies based on duplicate databases.

Literature Search and Screening

This study systematically searched Chinese and English literature across six databases: Web of Science, psycINFO, ERIC, psycARTICLES, Psychology and Behavioral Sciences Collection, and CNKI, with the search period set before August 2022. For English databases, the search terms were: ("socioeconomic status" OR SES OR "socio-economic status" OR "social status" OR income OR poverty OR disadvantaged OR "social class" OR education* OR occupation* OR economic OR "social inequality" OR "social gradient") AND ("executive function*" OR "executive control" OR "cognitive control" OR inhibition OR "inhibitory control" OR "working memory" OR "cognitive flexibility" OR "set shifting" OR "mental flexibility" OR "mental set shifting" OR "self regulation") AND (academic OR achievement OR success OR performance). For Chinese databases, the search terms were: (执行功能 + 抑制 + 工作记忆 + 认知灵活性) and (学业 + 能力 + 发展 + 表现 + 成绩) and (社会经济地位 + 社会阶层 + 收入 + 教育 + 职业 + 贫困). Keywords for executive function and academic achievement were searched in titles. Considering that family socioeconomic status is often included as a control variable in research, SES keywords were searched in abstracts, with full-text reading conducted when abstract descriptions were ambiguous to determine inclusion.

Unpublished dissertations were also included to reduce publication bias. Based on these search criteria, Web of Science yielded 389 articles, psycINFO yielded 387, ERIC yielded 159, Psychology and Behavioral Sciences Collection yielded 65, psycARTICLES yielded 22, and CNKI yielded 175. Additionally, we re-

viewed the reference lists of all ultimately included articles and obtained 10 more articles using the same screening criteria.

After initial retrieval, screening by title and abstract was conducted to exclude literature that did not meet inclusion criteria (e.g., non-empirical studies, inappropriate age ranges, non-typically developing samples, not including all three variables, duplicate studies), resulting in 114 eligible articles. These articles were then read in full to determine whether they provided at least two effect sizes or sufficient statistical data for calculating effect sizes. For articles that did not provide data, we emailed corresponding authors requesting data but received no responses. Finally, 34 articles meeting all screening criteria were included in the meta-analysis. Two of these articles included three independent samples each, resulting in 38 independent samples included in the meta-analysis (Figure 1 [Figure 1: see original paper]).

Literature Feature Coding

All collected studies were coded for characteristics including bibliographic information (title, author, publication year, journal name), sample characteristics (gender ratio, age range, country), study design (cross-sectional or longitudinal), variable measurement methods (including SES, EF, and academic achievement), and effect sizes. Coding rules were as follows: (1) Coding was conducted at the independent sample level, with each independent sample producing one effect size; (2) If a study reported multiple independent samples, each was coded separately; (3) In longitudinal studies with multiple measurement time points for the same sample, the most recent and nearest time points for academic achievement and executive function were selected to calculate effect sizes, in order to better reflect the long-term impact of socioeconomic status.

Additionally, during coding, if a study did not report participants' ages, age was estimated based on the average age for the reported grade level. When coding effect sizes, if original articles only reported correlation coefficients for sub-dimensions of socioeconomic status, executive function, or academic achievement, correlations between variables were synthesized using the following formula (Hunter & Schmidt, 2004):

When data were missing and the above formula could not be applied, conceptually equivalent correlation coefficients were averaged to obtain the correlation between variables (Geyskens, Krishnan, Steenkamp, & Cunha, 2008). Additionally, when variables were reverse-scored in original articles, correlation coefficients were reverse-coded to ensure that positive correlations across all studies represented the same meaning.

Before coding, coding rules, content, and 注意事项 were established. Each study was independently coded by two coders. Discrepancies were resolved through discussion. The first author reviewed all coding results for accuracy and resolved disagreements by consulting full texts.

Data Analysis

Publication bias refers to the tendency for significant results to be published more easily; therefore, including only published literature in meta-analysis may overestimate effect sizes. This study included not only published journal articles but also unpublished dissertations to reduce potential publication bias. To ensure the reliability of meta-analytic results, funnel plots and Egger's test were used to examine publication bias.

Then, this study tested heterogeneity for each of the three correlation coefficients. A significant Q statistic or I^2 greater than 50% indicates heterogeneity, necessitating moderator analysis.

After confirming data reliability, this study used webMASEM developed by Cheung (2021) to conduct a one-stage meta-analytic structural equation model (Cheung, 2021). Meta-analytic structural equation modeling can use structural equation modeling to fit meta-analytic data, enabling examination of complex multivariate models. One-stage meta-analytic structural equation modeling is currently the most flexible method, particularly for moderation analysis. Its significant advantages include the ability to assess model heterogeneity and directly analyze continuous moderating variables. One-stage MASEM uses full information maximum likelihood to handle missing data, employs random-effects models to synthesize correlation matrices, and fits hypothesized structural equation models to the synthesized correlation matrices. Following Cheung's (2021) recommendations, continuous moderating variables (e.g., age, gender ratio) were standardized during moderation analysis, while categorical moderating variables (e.g., region, measurement method, research design) were not standardized (Cheung, 2021).

Path (a) Socioeconomic status → Executive functions
Path (b) Executive functions → Academic achievement
Path (c) Socioeconomic status → Academic achievement

Figure 2 [Figure 2: see original paper] Univariate meta-analyses and forest plots

The meta-analysis included 34 studies published between 2003 and July 2022, with 38 independent samples and a total sample size of 45,916. Sample sizes ranged from 44 to 14,860 (median = 201). The mean ages at measurement were 5.5 years for socioeconomic status, 6.3 years for executive function, and 7.3 years for academic achievement.

Publication bias tests for the three sets of effect sizes revealed that funnel plots showed effect values concentrated at the top of the graph and relatively evenly distributed on both sides of the overall effect (see supplementary materials), suggesting minimal possibility of publication bias. Further Egger's test results showed no significant publication bias for any of the three effect sizes (EF-SES p=0.99; academic achievement-EF p=0.41; academic achievement-SES p=0.42), indicating that the studies included in this meta-analysis reasonably represent the research in this field without overestimation of effect sizes.

Heterogeneity tests for the three sets of effect sizes revealed significant heterogeneity, suggesting potential moderation effects and necessitating moderator analysis. Heterogeneity test results were: EF-SES (Q statistic=1019.278 (df=35), p<.001, I^2=96.566%>50%), academic achievement-EF (Q statistic=4671.114 (df=37), p<.001, I^2=99.208%>50%), academic achievement-SES (Q statistic=525.974 (df=37), p<.001, I^2=92.979%>50%).

Mediation analysis results showed that the partial mediation model was supported (Figure 3 [Figure 3: see original paper]). All three paths were significant: SES→EF (β=0.215, p<0.001), EF→academic achievement (β=0.439, p<0.001), and SES→academic achievement (β=0.227, p<0.001). Further testing of indirect effects revealed that the SES→EF→academic achievement indirect effect was significant at 0.094 [95%CI 0.074,0.117], indicating that EF's mediating role explained 29.2% of the relationship between SES and academic achievement. Testing in the longitudinal study subsample also found that the partial mediation model held, with SES→EF (β=0.22, p<0.001), EF→academic achievement (β=0.34, p<0.001), and SES→academic achievement (β=0.27, p<0.001) all significant. The indirect effect was significant at 0.074 [95%CI 0.053,0.100], with EF explaining 21.5% of the SES-academic achievement relationship.

Separate moderation analyses for each moderator revealed that the moderating effects of age at SES measurement ($Chi^2(3) = 2.572$, p = 0.462) and age at EF measurement ($Chi^2(3) = 4.52$, p = 0.211) were not significant. The moderating effect of age at academic achievement measurement was significant ($Chi^2(3) = 12.701$, p = 0.005). The EF→academic achievement path was moderated by age at academic achievement measurement: at the mean age (M=7.35), the effect size was 0.443, and it decreased by 0.059 for each one standard deviation increase in age (SD=3.36).

The moderating effect of gender ratio was significant ($Chi^2(3)$=10.623, p=0.014). The EF→SES path was moderated by gender ratio: as the proportion of males in the sample increased by one standard deviation (SD=0.04), the effect size decreased by 0.093 (Table 1).

Table 1 Results for the categorical and continuous moderators through OSMASEM. The numbers in parentheses represent standard error. * p < .05. ** p < 0.01. *** p < 0.001.

	SES-EF	Academic achievement-EF	SES-Academic achievement	Omnibus Test
	Estimate	Estimate	Estimate	^{2}(df)
Intercept	0.209(0.021)***	0.447(0.030)***	0.222(0.256)***	
Male percentage	-0.059(0.024)	-0.023(0.032)	-0.022(0.027)	10.623(3)

	SES-EF	Academic achievement-EF	SES-Academic achievement	Omnibus Test
Child age at SES assessment	-0.016(0.020)	-0.018(0.030)	-0.018(0.025)	2.572(3)
Child age at EF assessment	-0.023(0.019)	-0.051(0.029)	0.017(0.025)	4.52(3)
Child age at academic achievement assessment	-0.022(0.019)	-0.093(0.026)**	0.031(0.024)	12.701(3)

This study used meta-analytic structural equation modeling to synthesize data from 35 studies with 39 independent samples, examining for the first time the relationships among SES, EF, and academic achievement in a multivariate model. The results revealed that EF partially mediates the relationship between SES and academic achievement. Age and gender moderate the strength of the relationships among SES, EF, and academic achievement. These findings further clarify the mechanism through which SES influences academic achievement.

The results support Hypothesis 1. This study found that in a multivariate model simultaneously including SES, EF, and academic achievement, SES significantly correlates with EF. This is consistent with previous bivariate meta-analyses (Lawson et al., 2018) and numerous empirical studies (D. A. Hackman et al., 2015; Last et al., 2018; Sarsour et al., 2011), indicating that children from higher SES families tend to have better EF performance compared to children from lower SES families. Simultaneously, EF significantly correlates with academic achievement, even when examining the effect of SES on academic achievement. This further validates previous meta-analyses (Allan et al., 2014; Cortes Pascual et al., 2019; Santana et al., 2022; Spiegel et al., 2021) and empirical research findings (J. R. Best et al., 2011; Clark, Pritchard, & Woodward, 2010; St Clair-Thompson & Gathercole, 2006), showing that higher EF levels are often accompanied by better academic performance. This study employed meta-analytic structural equation modeling to further confirm the relationship pattern among SES, EF, and academic achievement beyond previous bivariate models.

The results support Hypothesis 2. EF partially mediates the relationship between SES and academic achievement, rather than completely mediating it. Moreover, this partial mediation remains valid in the longitudinal study subsample, indicating that EF's partial mediating role persists over time. This is consistent with most previous cross-sectional and longitudinal studies (Albert et al., 2020; Dilworth-Bart, 2012). As mentioned earlier, SES can influence EF

development through parenting quality, resource availability, and stress, while EF not only directly participates in academic task completion but also indirectly affects learning outcomes by influencing study habits. Therefore, SES can indirectly influence children's academic achievement through EF. Longitudinal subsample data further indicate that this indirect effect can persist for some time. This study found partial rather than complete mediation, suggesting that SES's impact on academic achievement remains significant even after controlling for EF. This further emphasizes the importance of SES for children's academic achievement. Additionally, although EF's mediating role is significant, it only explains 29.5% of the SES-academic achievement relationship. This may mean that the relationship between SES and academic achievement can be explained not only by EF but also by other factors not included in this study. For example, Tazouti (2016) and colleagues found that SES indirectly influences children's academic achievement through parental self-efficacy and parental involvement (Tazouti & Jarlégan, 2016). Coley (2020) showed that SES can influence children's reading, math, and science achievement through family investments (such as home-based reading activities, TV/video time, outdoor enrichment activities, and camp/childcare time) (Coley, Kruzik, & Votruba-Drzal, 2020). Therefore, the mechanism underlying the relationship between SES and academic achievement requires further exploration of other potential mediating factors and their interactions.

Moderation analysis results support Hypothesis 3, with age and gender as significant moderating variables. Regarding age, as age increases, the strength of the relationship between EF and academic achievement decreases, further validating previous bivariate meta-analysis results (Santana et al., 2022). This may be explained by dual-process theory: as age increases and knowledge of specific subjects becomes more proficient, academic achievement relies more on the accumulation and retrieval of learned knowledge and rules, and relatively less on top-down executive function control (A. Diamond, 2013). Particularly for language-related academic domains such as reading and literacy, cognitive processes become increasingly automated over time (Blair & Peters Razza, 2007). Given that most literature included in this study measured academic achievement including reading, this may partially explain why age significantly moderated the relationship between EF and academic achievement. It should be noted that although this study included a wide age range (4-18 years), which can reveal the full developmental picture of the relationships among socioeconomic status, executive function, and academic achievement, it may also obscure critical developmental periods. For example, Best (2011) found that the relationship between EF and academic achievement in 5-17-year-olds was not linear but fluctuating and changing, with correlation strength peaking at ages 6 and 8-9, then decreasing and stabilizing after age 9 (J. R. Best et al., 2011). Spiegel's (2021) meta-analysis also found that the relationship between EF and academic achievement gradually strengthened during elementary school (Spiegel et al., 2021). Therefore, the relationship pattern between EF and academic achievement is complex, and future research should explore their developmental

relationship within narrower age bands.

Regarding gender, this study found that as the proportion of males in the sample increased, the strength of the relationship between SES and EF decreased. This result supports Ellefson et al. (2020) but is inconsistent with previous bivariate meta-analysis results (Lawson et al., 2018). This may be because during childhood and adolescence, the development of brain regions related to EF (prefrontal cortex) and associated neurotransmitters show gender differences (Grissom & Reyes, 2019), making males' EF development potentially more vulnerable to early life adversity than females' (Grissom & Reyes, 2019). However, it should be noted that, as Ellefson (2020) pointed out, the inconsistent studies on gender's moderating role in the relationship between SES and EF have included samples from different countries, suggesting that region may also be a factor to consider in the relationship between SES and EF (Ellefson et al., 2020). Given the relatively limited research on gender differences in EF, more studies are needed in the future to reach definitive conclusions.

Finally, considering the plasticity of executive function (A. Diamond, 2013), the results of this study are undoubtedly good news, indicating that EF intervention programs may help reduce the socioeconomic status-related academic achievement gap (SES-achievement gap). This possibility is particularly encouraging given findings that children from poverty backgrounds benefit more from EF training (Blair & Raver, 2014; Weiland & Yoshikawa, 2013). The moderating effect of age also suggests that EF training may be more effective when started early in childhood, as the relationship between EF and academic achievement is stronger during this period. There are already training programs aimed at improving academic ability by enhancing EF (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Adele Diamond, Barnett, Thomas, & Munro, 2007; Raver et al., 2011), such as Tools of the Mind, the Head Start REDI program, and the Chicago School Readiness Project, which primarily target preschool and kindergarten children. Some intervention studies have shown positive effects. For example, Bierman (2008) and colleagues conducted EF training with preschool children and found that the training group showed significant improvements in EF and literacy, with improvements in EF tasks mediating gains in literacy (Bierman et al., 2008). Blair (2014) and colleagues' EF intervention with kindergarten children also achieved positive results, with improvements in reading, vocabulary, and math persisting into first grade (Blair & Raver, 2014). However, it should be noted that current intervention results are mixed, with many studies not finding significant EF improvements or far transfer to academic achievement (Blair, 2016), requiring future researchers to further explore the most appropriate intervention methods, frequency, timing, training dosage, and target populations.

This study has four main limitations. First, due to methodological constraints, the conclusions are primarily correlational and do not allow for strict causal inferences. Most current research is also correlational, and future studies should use more longitudinal research, cross-lagged designs, and randomized controlled

trials to establish causality. Second, executive function is only one mediating factor between socioeconomic status and academic achievement; SES also indirectly influences children's academic achievement through parenting, family environment, stress, and other factors, which can also interact with each other. The mechanism linking socioeconomic status and academic achievement is very complex, requiring continued use of advanced research methods to identify key mediating and moderating factors and their interconnections. Third, due to limitations in the included literature data, this study could only use gender ratio as a continuous moderating variable to assess gender's moderation of model parameters, rather than evaluating model parameters separately for boys and girls. Future research should further explore whether the relationship patterns found in this study hold in separate boys' and girls' samples. Therefore, this study could not accurately explore whether the structural relationships among SES, EF, and academic achievement remain invariant across boys and girls. Finally, although the current meta-analysis included several East Asian samples, most studies were conducted in Western and urban contexts. Therefore, the results cannot be generalized to all cultural backgrounds. Future research should examine the relationships among SES, EF, and academic achievement in more diverse cultural and regional contexts.

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Note: Figure translations are in progress. See original paper for figures.