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RESEARCH

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Early numeracy and literacy skills and their influences on fourth-grade mathematics achievement: a moderated mediation model

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Abstract

This study explored the influence of early literacy and numeracy skills on fourth-grade math achievement using the Trends in International Mathematics and Science Study (TIMSS). The study utilized valuable information collected by TIMSS about context related questionnaires such as home resources for learning, early literacy and numeracy development, readiness for school, and students' home and school lives in a cross cultural and linguistic framework. The main purpose of this study was aligned with those of TIMSS to improve math learning and performance and strengthen future employees' skills in the global workplace. Participants were comprised of mostly Asian and European students. Results show that (1) early literacy skills have a stronger effect on G4 math scores than early numeracy skills; (2) Home resources for learning impact more on children's early literacy skills than early numeracy skills; (3) both early literacy and numeracy activities have progressed to early literacy skills but demonstrated limited advancement to early numeracy skills, a missing link; (4) students' confidence in math emerged as the strongest predictor of G4 math scores; (5) students with stronger early literacy skills and early numeracy skills are more confident in math; and (6) The moderated mediation analysis revealed that (a) early literacy skills have stronger direct effects on G4 math achievement than early numeracy skills; (b) the effects of early numeracy skills on G4 math scores become more pronounced for children with weaker early literacy skills (i.e., conditional effects); and (c) the effect of early numeracy skills on G4 math achievement is transmitted through students' confidence (i.e., mediator) and the effect is more prominent for those who had more proficient early literacy skills (i.e., conditional indirect effects). Findings from the conditional direct and indirect effects of early numeracy skills on G4 math achievement suggest that children who had more proficient early literacy skills utilize strategies beyond just early numeracy skills to solve G4 math problems and that children's strategies to solve math problems may be enhanced by the proficiency of their literacy skills.

Keywords: Literacy, Numeracy, Resources, Confidence, Moderated mediation

Introduction

A prolific body of literature has identified the family as the key dynamic influencing the early development of children's academic skills including literacy and numeracy (e.g., Liu et al., 2019; Manolitsis et al., 2013; McCormick et al., 2020; Munro et al., 2021; Van

Voorhis et al., 2013). To further understanding of the influence of early literacy skills (ELS) and early numeracy skills (ENS) stemming from the home learning environment on children's academic achievement, many researchers have focused on identifying the specific skills which may predominantly impact later math performance. Considerable research has confirmed ENS are the strongest predictor for later math achievement (e.g.,Duncan et al., 2007; Kiss et al., 2019; Nelson & McMaster, 2019; Nguyen et al., 2016; Scalise & Ramani, 2021). In contrast, other studies have found that ELS were the foremost predictor in later math achievement (e.g., Aragón et al., 2016; Birgisdottir et al., 2020; Purpura et al., 2011; Yang et al., 2021). In addition, topics related to children's family resources and confidence in math have also received research attention seeking to identify factors that might affect the gaps in math achievement observed among various ethnic groups in the United States and among countries in the international comparisons.

Additionally, multiple studies have utilized mediation models to illustrate the indirect effects of ENS on later math achievement. For example, the effect of ENS on later math achievement has been found to transmit through a third variable which is math language skills (King & Purpura, 2021). However, the extant studies have rarely, if ever, examined whether the effect of ENS on later math achievement becomes more (or less) pronounced for children with different levels of ELS (i.e., moderation effect). Likewise, few if any studies have been initiated utilizing a moderated mediation model to explore whether the effects of ENS on later math achievement transmitted through a mediator differs depending upon the levels of a moderator (e.g., ELS). The present study will address these gaps by constructing a moderated mediation model utilizing the Trends in International Mathematics and Science Study (TIMSS, 2019) data to explore the conditional direct and indirect effects of ENS on G4 math achievement.

Early literacy and numeracy activities

There is substantial literature demonstrating that home learning environments with parent–child early literacy activities (ELA) and early numeracy activities (ENA) encouraged children's learning and enhanced their school achievement. Respective studies found differences in children's outcomes resulted from distinct approaches in which parents interact with their children and have consistently confirmed home numeracy environment predicted ENS (e.g., Clerkin & Gilligan, 2018; Fazio et al., 2014; Segers et al., 2015; Siegler, 2016; Susperreguy et al., 2020). Parent–child activities in basic addition and subtraction lead to improved academic ability (Munro et al., 2021) and the home numeracy environment was predictive of numeracy (Napoli & Purpura, 2018). Children engaged in ELA and ENA became more confident and curious about math at age 10 (Clerkin & Gilligan, 2018) and later school academic achievement benefitted (Lehrl et al., 2020; Niklas & Schneider, 2017). Mothers who shared picture books with their children enhanced their math and literacy skills (Ribner et al., 2020) whereas fathers in Hong Kong reported higher frequencies of engagement in more real-life number game activities than mothers (Liu et al., 2019). Parents posed more complex questions about numbers to their sons than daughters (Uscianowski et al., 2020) while maternal use of relevant math facts during games were associated with their daughters' later addition accuracy (Casey et al., 2020). Parent–child letter–sound interactions predicted growth in counting skills

(Soto-Calvo et al., 2020) and formal home ENA (e.g., comparing numerals) predicted children's symbolic number system knowledge (Skwarchuk et al., 2014). Moreover, symbolic knowledge was found to relate to broader mathematical competence (Chen & Li, 2014; Scalise & Ramani, 2021; Schneider et al., 2017, 2018). Parents reported engaging in more literacy than numeracy practices as they considered literacy development more important than numeracy development (Napoli et al., 2021). Other parents reported prioritizing early numeracy and providing more math activities at home (Zippert & Rittle-Johnson, 2020).

McCormick et al. (2020) affirmed that unconstrained language and math activities predicted gains in children's language and math skills. Examples of unconstrained skills are vocabulary and problem solving, while constrained skills would include competencies like letter knowledge and counting. Constrained skills are directly teachable and have a ceiling, while unconstrained skills are limitless and are acquired gradually through experience (Snow & Matthews, 2016). Everyday contexts such as shopping in grocery stores can promote math related conversations and potentially provide learning opportunities for children (Hanner et al., 2019). It appears that negligible research has been conducted exploring attainable ways for ELA to evolve to ELS or for ENA to advance to ENS much less how to develop curricula and remedial programs that help parents and teachers facilitate ELA and ENA to extend to ELS and ENS.

Early literacy and later math achievement

Studies on the influence of early literacy to later math achievement have largely focused on phonological awareness. Researchers have demonstrated the associations between phonological awareness and math achievement (De Smedt et al., 2010; Fuchs et al., 2006; Krajewski & Schneider, 2009) and fifth-grade computation skills (Hecht et al., 2001). Studies show that ENS and phonological processing influenced growth in math from kindergarten through third grade (Vukovic, 2012) and elementary school children with mild intellectual disabilities were found to profoundly rely on phonological awareness when solving math problems (Foster et al., 2015). However, other studies found early written language skills, but not phonological awareness, are unique predictors of Icelandic fourth graders' (Birgisdottir et al., 2020) and Finnish third and fourth graders' math achievement (). Verbal skills and visuomotor skills uniquely predicted fourth-grade math achievement (Kurdek & Sinclair, 2001) and reading skills significantly predicted Canadian children's third-grade reading and math performance (Romano et al., 2010). Manfra et al. (2017) reported that writing and counting skills were consistently strong predictors of third-grade reading and math achievement among low-income, ethnically diverse children while Fuchs et al. (2016) found that second-grade language comprehension is more critical for fourth-grade word-problem solving than pre-algebraic knowledge. Furthermore, Kiss et al. (2019) affirmed that reading skills explained significant variations in third graders' performance on number operations, algebra, data analysis, and geometry measurement. Third grade reading comprehension was related to a conceptual understanding and the application of math knowledge at eighth grade (Grimm, 2008). In addition, specific early literacy skills (e.g., vocabulary and print knowledge) were found to be influential in math development (e.g., Purpura & Napoli, 2015; Purpura et al., 2011). Purpura and Reid (2016) observed that math language (e.g., "more," "many," and "fewer") is more proximal to numeracy skills than general language. Vanbinst et al. (2020) suggest that early reading and early arithmetic have a shared underlying cognitive basis for Flemish children. Furthermore, English literacy (second strongest to working memory) predicted Singaporean 11-year-olds' algebraic word problem solving skills (Lee et al., 2009) and bilingualism is beneficial for children's math reasoning and problem-solving skills (Hartanto et al., 2018). Peng and colleagues' (2020) meta-analysis results affirmed that more complicated language and math skills were associated with stronger relations between language and math.

Early numeracy and later math achievement

Early numeracy is a common term that is comprised of skills such as verbal counting, recognizing number patterns, comparing numerical magnitudes, manipulating quantities, and adding and subtracting objects. The associations between children's ENS and their later math achievement have been well documented (e.g., Clerkin & Gilligan, 2018; Duncan et al., 2007; Raghubar & Barnes, 2017). While preliteracy skills were more strongly related to word reading, sensitivity to relative quantity was more strongly related to first-grade math (Chu et al., 2016). Basic numerical cognition was predictive of later procedural calculation skills and word problem development (Fuchs et al., 2010) and most strongly related to the ability to solve applied math problems (Jordan et al., 2010). Students who received early numeracy intervention improved their second-grade math performance (Bryant et al., 2021). Similarly, advanced counting competencies (Nguyen et al., 2016) and fluency in solving addition problems (Geary, 2010) were found to be strong predictors of fifth-grade math achievement. A meta-analysis of longitudinal studies revealed that number acuity may prospectively predict later math performance and is also retrospectively associated with early math performance (Chen & Li, 2014). Nevertheless, studies demonstrated that early math and reading skills positively influence each other in later school years (e.g., Cirino et al., 2018; Hooper et al., 2010) but when deficient also displayed comorbidities with each other.

Mediation effects

Some studies have employed more complex statistical techniques to identify and explain the mechanism or procedure that underlies an observed relation between ENS and math achievement via a third hypothetical variable (i.e., a mediator). For example, Purpura et al. (2017) detected that the relation between early math and literacy skills is mediated by children's mathematical language skills and partially mediated by print knowledge (Purpura & Napoli, 2015). Math language mediates the relation between the direct home numeracy environment and numeracy skills (King & Purpura, 2021) and language abilities impact formal math skills partially through informal math skills (). In addition, verbal analogies were indirectly related to arithmetic knowledge through symbolic number skill (Vukovic & Lesaux, 2013) and reading comprehension skills may be partially mediating the relation between problem solving ability and growth in math (Vista, 2013).

It appears that the extant studies barely, if ever, explored how ELA and ENA directly or indirectly enhanced later math performance nor inquired into how ELA and ENA progress into ELS and ENS which in turn advance later math achievement. Furthermore, insufficient research has been undertaken examining whether a third variable influences the strength or direction of the relations between ENS and math achievement. For instance, if found to be significant, ELS can cause an amplifying or weakening effect between ENS and math achievement as the child's ELS level increases (i.e., moderation). Hence, the question as to whether children with weaker ELS might rely more on ENS to solve math problems remains unexplored. This study will explore the moderation effect of ELS for ENS on G4M. For instance, whether the effect of ENS on G4M becomes less pronounced for children possessing stronger ELS.

HRL and math achievement

Many studies have confirmed the relation between home resources and children's school achievement. Increases in school resources are consistently associated with improvements in math achievement for all groups, regardless of their individual resources (McConney & Perry, 2010). In China, increased levels of family and school resources were favorably related to student math achievement, and the association became more pronounced for levels of school resources in rural areas (Xue et al., 2020). In Japan, the student level of resources (i.e., number of books, computer access, paternal, and maternal educational levels) were positively related to student math achievement, whereas the school level of resources (i.e., rural and economically disadvantaged) were inversely related to student math achievement (Takashiro, 2017). In contrast, in Australia correlations between math performance and resources are far weaker in the nonmetropolitan schools than for those in the metropolitan areas (Murphy, 2019). In Tennessee, the higher the percentage of disadvantaged (determined by the percentage of students receiving federally subsidized free and reduced-priced lunches) the lower the achievement was. Hence, it appears there is a locale difference. Students with few resources in rural areas outperformed their economically disadvantaged nonrural peers. The author surmised that it is possible that support in the economically disadvantaged rural locales provides a sense of community not found in other economically disadvantaged areas which enables rural students to achieve higher in math than their nonrural peers (Hopkins, 2005). Furthermore, the effect of cognitive activation on math achievement was transmitted through self-efficacy which was moderated by resources at both the student level and the teacher level (Li et al., 2020, 2021).

Researchers tested the Information Distortion Model (IDM) and hypothesized that in Australia children with a few resources would have higher academic interest compared to those with many resources and who were academically equally prepared. Results support the model and indicate that children with a few resources had higher numeracy interest than those who were equally prepared with many resources (Parker et al., 2021). In contrast, in China few family resources were shown to hamper middle school student math achievement, however high levels of subjective social mobility can buffer the adverse effects of low family resources on math achievement. Subjective social mobility reflects students' personal beliefs in their ability to attain a higher social and economic status in the future and is regarded as a motivational resource (Zhang et al., 2020). Math and reading ability heightened future adult SES attainment (Ritchie & Bates, 2013). Further studies examining the underlying mechanism of family resources and its impact on academic achievement, as well as the varying influences on student achievement in different locales (e.g., rural vs. urban) in a cross-culture paradigm (e.g., European descents vs. Asian countries) are necessary. It appears that children with few resources in rural areas of mostly European descent countries (e.g., Australia and U.S.) outperformed their urban counterparts, whereas the reverse association was observed in Asian countries (e.g., China and Japan).

Confidence in math

Studies examining confidence and math achievement often focused on the reciprocal relations between the two. Typically, math self-efficacy improved math achievement and earlier math achievement was a consistent predictor of later confidence and interest, suggesting a reciprocal relation between confidence and math performance (e.g., Arens et al., 2017; Ganley & Lubienski, 2016; Grigg et al., 2018; Schöber et al., 2018; Sewasew et al., 2018). Nonetheless, Vogt et al. (2020) analyzed the NICHD SECCYD data and reported that children who scored higher on applied problems at 54 months had lower non-ability-based confidence (or overconfidence) at age 15 than those with a lower achievement. The associations between non-ability-based confidence and earlier development were similar for boys and girls. NICHD (2006) reported that the participants in SECCYD were comprised of "76.4% white, 12.7% African-American, 6.1% Hispanic…" (p. 30). Hence, caution is needed in generalization of the findings as the Hispanic group was underrepresented with whites overrepresented. In a cross-cultural study, self-rating in math and absence of disappointment with poor performance were associated with better performance in the English group, whereas no significant relationships between attitudes and performance were detected among Chinese first graders (Dowker et al., 2019). Fourth through sixth graders who perceived their classroom environments as more caring, challenging, and mastery oriented had significantly higher levels of math self-efficacy, which favorably impacted math performance. Note that the participants consisted of "Latino/a (62%) and Caucasian (31%) students" (Fast et al., 2010, p. 731). Students from a sample of "5th grade to early college students (41% female, 80% white)" (Rice et al., 2013, p. 1028) with greater social support for math and science from parents, teachers, and friends had more constructive attitudes and a higher sense of their own competence. Marked overconfidence was observed within the world regions that had lower scores on measures of cognitive ability whereas less inflated levels of overconfidence were noted among the high-achieving world regions based on samples from 33 nations (Stankov & Lee, 2014). Erickson and Heit (2015) cautioned that both overconfidence and anxiety can adversely affect metacognitive ability and can lead to math avoidance. Another cross-cultural study reported that teachers with greater self-efficacy in teaching math had higher job satisfaction and class levels of math achievement and interaction quality. At the student level, a higher individual self-concept advanced math achievement, and individual perceptions of interaction quality enhanced self-concept (Perera & John, 2020). It appears that the extant studies have given minimal attention as to whether the effect of ENS on later math achievement is transmitted through confidence (i.e., mediation). Furthermore, whether the effect of ENS on later math achievement becomes more pronounced for children with stronger ELS (i.e., moderation effect) is a topic deserving more comprehensive research.

The present study

The review of the existing studies on related topics has shown that complex relations among multiple variables influence students' math achievement. However, few studies have explored moderators of ENS on later math performance and whether the effects might be inordinately impacted by the levels of the moderator (e.g., mean and $\pm$ 1SD). For example, the effect of ENS on math might become less pronounced as children's ELS increased. In addition, whether the effect of ENS is transmitted through other variables (e.g., confidence) to enhance later math performance and if this effect may be stronger for children with stronger ELS (i.e., moderated mediation) deserves comprehensive study. This study uses the TIMSS 2019 data in a cross-linguistic and cross-cultural framework to examine the variables comprising (1) home environment support and (2) student engagement and attitudes that lead to the differing outcomes in students' fourth-grade math achievement. Specifically, this study targeted the top eight performing countries on variables in home environment support including ELA, ENA, ELS, ENS, and HRL, as well as student engagement and attitudes (e.g., SCM), and fourth-grade math plausible values as the outcome variable. The hypotheses explored in this study are as follows:

H1: Home environment support, student engagement, and attitudes are predictors of G4M. In particular, ELS are more effective than ENS in predicting G4M.

H2: Home environment support and student engagement and attitudes are intercorrelated.

H3: There are conditional direct effects of ENS on G4M.

a) ELS have a direct effect on G4M.

b) ENS have a direct effect on G4M.

c) ELS moderate the effect of ENS on G4M, and the effect of ENS on G4M is more prominent for children with weaker ELS

d) HRL (a covariate) have a direct effect on G4M.

H4: There are conditional indirect effects of ENS on G4M (i.e., ENS $\rightarrow$ SCM $\rightarrow$ G4M).

a) ENS have a direct effect on SCM.

b) ELS have a direct effect on SCM.

c) ELS moderate the effect of ENS on SCM, and the effect of ENS on SCM is more pronounced for children with stronger ELS.

d) SCM have a direct effect on G4M.

e) SCM mediate the relation between ENS and G4M, and the effect is more evident for children with stronger ELS.

f) HRL (a covariate) have a direct effect on SCM.

Note that HRL serve as a covariate to control for ENS differences on SCM and G4M. The conceptual and statistical moderated mediation model diagrams are exhibited in Fig. 1.

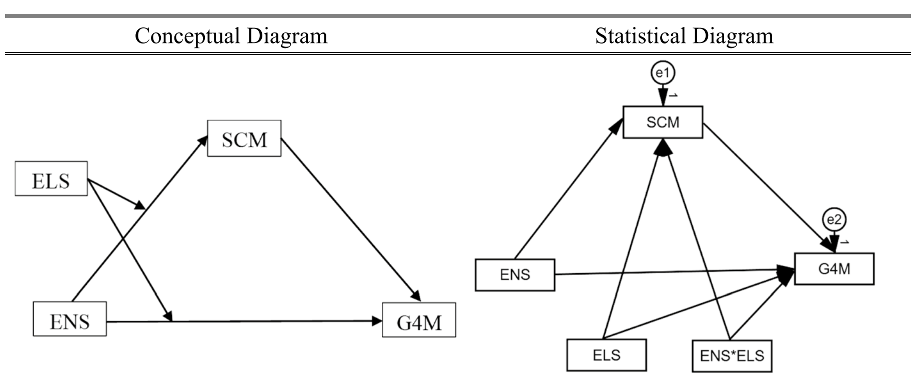
Methods

Participants

UNESCO's International Standard Classification of Education (ISCED) 2011 (UNESCO, 2012) provides an internationally accepted classification scheme for describing levels of schooling across countries. All students enrolled in the grade that represents 4 years of schooling counting from the first year of ISCED Level 1 (providing the mean age at the time of testing is at least 9.5 years) are eligible to participate in TIMSS. Approximately 600,000 students from 64 countries and 8 benchmarking systems (e.g., Hong Kong Special Administrative Region, SAR) participated in TIMSS, 2019. Approximately 32,000 participants from the top eight performing countries were included in the present study and their mean PVs are shown in Fig. 2.

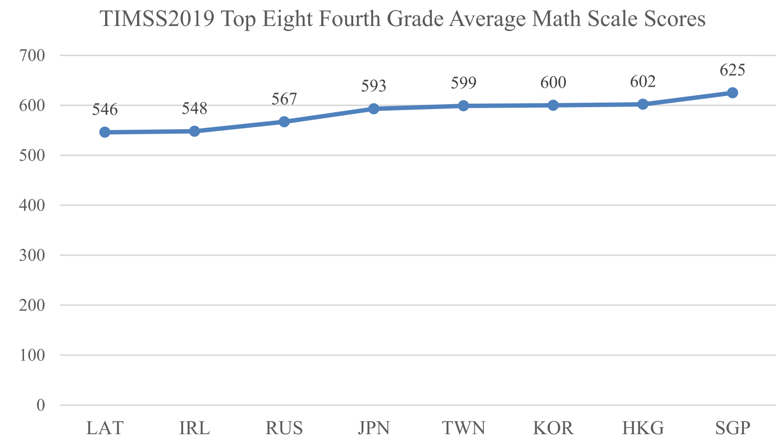
Assessments

The TIMSS, 2019 assessment migrated to eTIMSS, a digital version of the assessment administered to students on computers and tablets. eTIMSS also included a novel section consisting of problem solving and inquiry tasks (PSIs) designed to exploit the digital environment to its fullest. About half the participating countries chose to transition to eTIMSS. The eTIMSS participating countries also administered the



Note: Predictor: ENS = Early numeracy tasks (skills) beginning school/SCL;
Moderator: ELS = Early literacy tasks (skills) beginning school/SCL;
Mediator: SCM = Students confident in mathematics/SCL;
Covariate: HRL = Home Resources for Learning/SCL;
Outcome variable: G4M = Fourth-grade mathematics

Fig. 1 Moderated Mediation Diagrams. Predictor: *ENS* Early numeracy tasks (skills) beginning school/SCL, Moderator: *ELS* Early literacy tasks (skills) beginning school/SCL, Mediator: *SCM* Students confident in mathematics/SCL, Covariate: *HRL* Home Resources for Learning/SCL, Outcome variable: *G4M* Fourth-grade mathematics



Note: SGP = Singapore; HKG = Hong Kong; KOR = Korea; TWN = Taiwan; JPN = Japan; RUS = Russia; IRL = Ireland; LAT = Latvia

Fig. 2 TIMSS 2019 Top Eight Fourth Grade Average Math Scale Scores. *SGP* Singapore, *HKG* Hong Kong, *KOR* Korea, *TWN* Taiwan, *JPN* Japan, *RUS* Russia, *IRL* Ireland, *LAT* Latvia

paper version of their trend items to a sample of schools, providing a bridge that helped link the two test-taking modes. For TIMSS, 2019, comparing the item statistics for eTIMSS and paperTIMSS was integral in identifying items that were psychometrically equivalent under the IRT scaling. This process enabled the eTIMSS and paperTIMSS achievement results to be reported on the same achievement scale (i.e., fourth-grade math). The TIMSS assessment was categorized into content and cognitive domains. The content domains were comprised of (1) numbers, (2) geometric shapes and measures, and (3) data display, while the cognitive domains consisted of (1) knowing, (2) applying, and (3) reasoning. Constructed response items were scored independently by two trained scorers and TIMSS, 2019 trend scoring reliability for human scored items was 97%. The agreement across items was 98% or higher across countries, whereas within-country scoring reliability was 98% (Fishbein et al., 2020).

TIMSS utilized Item Response Theory (IRT) models to compute proficiency scores to provide valid comparisons across student populations based on broad coverage of the achievement domain. These test items were arranged in blocks that were assembled into student booklets that contained different (but systematically overlapping) sets of item blocks. Because each student received only a fraction of the achievement items for 72 min test time, statistical and psychometric methods were required to link these different booklets together so that student proficiency could be reported on a comparable numerical scale even though no student answered all the tasks. IRT was well suited to handle such data collection designs in which not all students were tested with all items. In addition, TIMSS used the three-parameter logistic (3PL) for multiple-choice items, the 2PL IRT model for constructed response items worth 1 score point, and the generalized partial credit model for constructed response items worth up to 2 score points (von Davier, 2020).

Home Environment Support

Participating countries (except U.S. and England) administered an early learning survey to the parents/guardians and a questionnaire to students, both of which were linked to the achievement booklet. The scales were constructed using the partial credit model IRT scaling methods. Each context scale separated students into regions corresponding to high, middle, and low values on the construct using the combinations of responses. Partial credit IRT scaling was based on a statistical model that related the probability that a student would respond to an item to that student's math ability on the underlying construct. The average Cronbach's alpha reliability coefficients for countries with data is approximately 0.88 for the early literacy and numeracy activities and the early literacy and numeracy tasks scales, and 0.70 for the home resources for learning scale (Yin & Fishbein, 2020).

Early literacy activities scale (9 items).

This survey asked parents, "*Before your child began elementary school, how often did you or someone else in your home do the following activities with him/her?*" Such an item included in this scale is "*Play with alphabet toys (e.g., blocks with letters of the alphabet).*" Students whose parents "*often*" engaged in five activities with them while "*sometimes*" doing the other four activities scored 10.8 or higher. Those whose parents "*never or almost never*" did five activities with them while "*sometimes*" doing the other four activities scored 6.2 or lower. All others *sometimes* engaged them in early literacy activities.

Early numeracy activities scale (9 items)

This survey asked parents, "*Before your child began elementary school, how often did you or someone else in your home do the following activities with him/her?*" Such an item included in this scale is "*Play games involving shapes (e.g., shape sorting toys, puzzles).*" Students whose parents "*often*" engaged in five activities with them while "*sometimes*" doing the other four activities scored 11.0 or higher. Those whose parents "*never or almost never*" did five activities with them while "*sometimes*" doing the other four activities scored 6.6 or lower. All others *sometimes* engaged them in early numeracy activities.

Early Literacy tasks scale (7 items)

This survey asked parents, "*How well could your child do the following when s/he began the first grade of elementary school?*" Such an item included in this scale is "*Write words other than his/her name*." Students whose parents rated "*very well*" to four tasks and "*moderately well*" to the other three tasks scored 11.2 or higher. Those whose parents rated "*not very well*" to four tasks while "*moderately well*" to three tasks scored 8.8 or lower.

Early numeracy tasks scale (5 items)

This survey asked parents, "*Could your child do the following when s/he began the first grade of elementary school?*" Such an item included in this scale is "*Recognize written numbers*." Students whose parents' responses were "*very well*" to two tasks and "*moderately well*" to one task and "*yes*" to two tasks scored 11.7 or higher. Those whose parents' responses were "*not very well*" to two tasks and "*moderately well*" to one task and "*no*" to two tasks scored 8.1 or lower (P. Foy, Personal Communication, July 26, 2021).

Home resources for learning scale (5 resources, 22 items)

One of the five resource questions comprised of this scale asked parents, "*Highest level of occupation of either parent (parents).*" Such an item included in this resource subscale was "*Professional (corporate manager or senior official, professional, or technician or associate professional).*" Students with *many resources* scored 11.8 or higher, having more than 100 books at home and both home study supports, more than 25 children's books at home, at least one parent having finished university, and at least one parent having a professional occupation. Students with *few resources* scored 7.4 or lower, having 25 or fewer books at home and neither of the home study supports, 10 or fewer children's books at home, neither parent having achieved beyond upper-secondary education, and neither parent owning a small business or holding a clerical or professional occupation. All others had *some resources.*

Student engagement and attitudes

Confidence in mathematics scale (9 items)

This scale asked students, "*How much do you agree with these statements about mathematics?*" Such an item included in this scale is "*I am good at working out difficult mathematics problems.*" Those *very confident* in mathematics scored 10.7 or higher reporting "*agree a lot*" with five statements and "*agree a little*" with the other four. Students *not confident* in mathematics scored 8.5 or lower reporting "*disagree a little*" with five statements and "*agree a little*" with the other four. All others were *somewhat confident* in mathematics (Yin & Fishbein, 2020). The average Cronbach's alpha reliability coefficients for the students confident in math scale for these eight countries is 0.87.

Data analysis

The present study employed the IEA IDB Analyzer (Version 4.0.42, IEA, 2021) and PROCESS Macro (v4.0, 2022) (Hayes, 2022) in conjunction with IBM SPSS 28 (2022) to test on the public-use version of the TIMSS, 2019 data. The proportions of the sample are approximately 8% from Hong Kong, 18% from Singapore, and 12% from each of the remaining six countries with relatively similar contributions. IDB Analyzer was utilized to compute descriptive statistics and bivariate correlations. A moderated mediation model (Hayes, 2017, model 8) was constructed to estimate the conditional effect of ENS on SCM (mediator) varied as a function of ELS (moderator). In addition, the conditional direct effect of ENS on G4M is also dependent upon the levels of ELS. An index of moderated mediation was used to test the significance of the moderated mediation. Confidence intervals did not contain zero between the lower and upper limits of the 95% confidence intervals indicating that the direct and indirect effects were conditional on the level of the moderator (ELS). The number of bootstrap samples for percentile bootstrap confidence intervals was 5,000.

Results

Descriptive statistics and correlations

The average bivariate correlations comprised of mostly Asian and European students showed that ELS ($r=0.36$) were effective than ENS ($r=0.21$) in predicting G4M and ELA and ENA were inadequate indicators of G4M (rs $=0.16$ and 0.15). SCM dominated with the highest impact in G4M ($r=0.44$) with HRL also prominent ($r=0.39$). Hypothesis 1 has been supported.

Bivariate correlations between home learning environment and student attitudes showed that children who were proficient in ELS were also likely to be proficient in ENS ($r=0.30$). ELS benefitted from both ELA ($r=0.34$) and ENA ($r=0.32$) while ENS were facilitated ineffectively from ELA and ENA (rs $=0.09$ and 0.11), and ENA evolved more to ELS ($r=.\ 32$) than ENS ($r=0.11$). Parents with many HRL engaged in more early literacy ($r=0.30$) and numeracy ($r=0.25$) activities with their children than their counterparts who possessed fewer HRL, and parents engaged both activities with their children in proportional amounts ($r=0.77$). HRL enriched children's ELS ($r=0.34$) more than ENS ($r=0.16$), and inadequately boosted SCM ($r=0.19$). Children who engaged in more ELA and ENA with their parents were not much more confident in math (rs $=0.14$ and 0.15). In a similar vein, students with more HRL, and who entered school with higher levels of ELS and ENS, were not more confident in math with rs $=0.17$, 0.11, and 0.19 respectively. A correlation matrix with home environment support, student attitudes, and plausible values (PVs) is exhibited in Table 1. Hypothesis 2 has been supported. Note that ELA and ENA were not included in further analysis mostly due to the weak correlation coefficients with G4M.

Moderated mediation

ENS → SCM

A moderated mediation model was tested using the PROCESS macro (Hayes, 2022) in SPSS to estimate the conditional direct and indirect effects of ENS on G4M through SCM (i.e., mediator) as moderated by ELS. All variables were standardized prior to entering the analysis to facilitate interpretation of any effects resulting in the estimation of standardized coefficients (β). Betas are comparable in magnitude within a model as well as between studies with higher absolute β coefficients presenting stronger effects. Results from the present study exhibited that ENS and ELS both had direct effects on SCM (βs $=0.05$ and 0.10 ps <0.001, respectively) signifying that ELS had a stronger

Table 1 Correlation Coefficients Between Home Environment Support and Plausible Values (PV) and Student Attitudes

	Math PV	ELA	ENA	ELS	ENS	HRL	SCM
ELA	0.16	–					
ENA	0.15	0.77	–				
ELS	0.36	0.34	0.32	–			
ENS	0.21	0.09	0.11	0.30	–		
HRL	0.39	0.30	0.25	0.34	0.16	–	
SCM	0.44	0.14	0.15	0.17	0.11	0.19	–

All correlations are significant at the 0.01 level (2-tailed). *ELA* Early literacy activities scale, *ENA* Early numeracy activities scale influence on SCM than ENS. Moreover, ELS moderated the relations between ENS and SCM (β = 0.02, $p < 0.001$) suggesting that the effect of ENS on SCM became more pronounced for students with stronger ELS (β = 0.07, $p < 0.001$) than those with lower ELS (i.e., mean and -1SD) (βs = 0.05 and 0.03, respectively, *p*s < 0.001). The results suggested that there were conditional effects of the focal predictor (ENS) at different levels of the moderator (i.e., ± 1SD and mean ELS) on SCM. Furthermore, HRL was significantly associated with SCM (β = 0.13, $p < 0.001$).

ENS → SCM → G4M

ENS, SCM, and ELS had direct effects on G4M (βs = 0.09, 0.28, and 0.16, respectively, *p*s < 0.001) indicating that ELS was a much more prominent predictor of G4M than ENS despite SCM having the strongest effect on G4M. ELS moderated the relations between ENS and G4M (β = -0.04, $p < 0.001$) suggesting that the effect of ENS on G4M was more evident for those with weaker ELS (βs = 0.13 and 0.09, respectively, *p*s < 0.001) than those with stronger ELS (β = 0.06, $p < 0.001$). The results suggested that there were conditional direct effects of the focal predictor (ENS) varying with different levels of the moderator (ELS) on G4M implying that students who possessed stronger ELS utilized strategies more than ENS to solve fourth grade math problems. Further, HRL had a strong direct effect on G4M (β = 0.20, $p < 0.001$). Sub-hypotheses (*a*) through (*d*) of H3 have been supported, suggesting that there are conditional direct effects of ENS at different levels of ELS on G4M.

The estimation of the moderated mediation models suggested that SCM was a mediator of the relation between ENS and G4M and had significant direct effects on G4M (ENS → SCM → G4M: Index of moderated mediation = 0.0056, *BootSE* = 0.0013, *BootLLCI* = 0.0030, *BootULCI* = 0.0081). That is, the effect of ENS on G4M was transmitted through SCM. This denotes that (1) children who have stronger ENS had higher math achievement at fourth grade, (2) this relationship was explained by stronger SCM, and (3) this effect was stronger for children with stronger ELS. Sub-hypotheses (*a*) through (*f*) of H4 have been supported suggesting that there are conditional indirect effects of ENS on G4M transmitted through SCM at different levels of ELS.

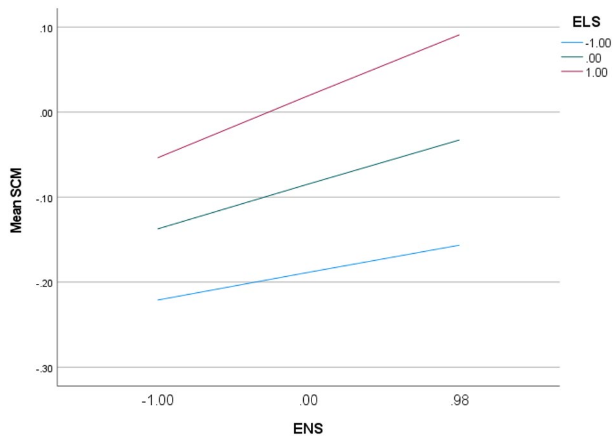
In summary, the results indicate that (1) the mechanism linking ENS to G4M through a mediator SCM is related to ELS, and (2) the conditional direct effects of ENS on G4M vary at different levels of ELS suggesting that literacy skills might enhance students' approaches in analyzing, interpreting, and solving math problems. The findings suggest that students with lower ELS benefitted more from ENS whereas those with higher ELS relied less on ENS to solve fourth-grade math problems. The full moderated mediation model with estimations of conditional direct and indirect effects are presented in Table 2. The hypotheses that have been explored and supported are summarized in Table 3.

Discussion

IEA TIMSS has employed advanced techniques in methodology to derive the scale scores of home environment support and student engagement and attitudes and subcategories in cognitive and content domains. This has provided data for researchers to explore multifaceted relations among variables using advanced statistical techniques to

Table 2 Full model of moderated mediation analysis

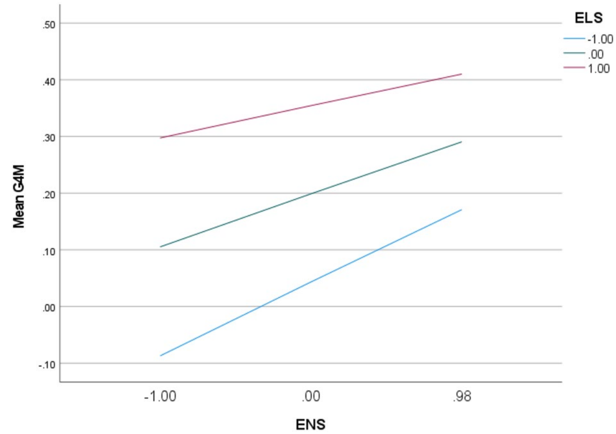
	β	*s.e*	*t*	*p*	*LLCI*	*ULCI*
Outcome variable: SCM						
Covariate: HRL						
Moderator: ELS						
ENS	0.05	0.0055	9.61	< 0.001	0.04	0.06
ELS	0.10	0.0059	17.70	< 0.001	0.09	0.12
ENS × ELS	0.02	0.0047	4.33	< 0.001	0.01	0.03
HRL	0.13	0.0056	24.06	< 0.001	0.12	0.15
Conditional Effects of the Focal Predictor (ENS) at Values of the Moderator (ELS):						
ELS						
− 1.00	0.03	0.0075	4.37	< 0.001	0.02	0.05
0.00	0.05	0.0055	9.63	< 0.001	0.04	0.06
1.00	0.07	0.0069	10.51	< 0.001	0.06	0.09



	β	*s.e*	*t*	*p*	*LLCI*	*ULCI*
Outcome variable: G4M						
Covariate: HRL						
Moderator: ELS						
ENS	0.09	0.0046	20.49	< 0.001	0.09	0.10
SCM	0.28	0.0046	59.75	< 0.001	0.27	0.29
ELS	0.16	0.0049	31.75	< 0.001	0.15	0.17
ENS × ELS	− 0.04	0.0039	− 9.43	< 0.001	− 0.04	− 0.03
HRL	0.20	0.0047	43.10	< 0.001	0.19	0.21
Conditional Effects of the Focal Predictor (ENS) at Values of the Moderator (ELS):						
ELS						
− 1.00	0.13	0.0062	20.99	< 0.001	0.12	0.14
0.00	0.09	0.0046	20.47	< 0.001	0.09	0.10
1.00	0.06	0.0058	9.82	< 0.001	0.05	0.07

Table 2 (continued)

	β	*s.e*	*t*	*p*	*LLCI*	*ULCI*



Conditional direct effects of ENS on G4M:						
ELS						
− 1.00	0.13	0.0062	20.99	< 0.001	0.12	0.14
0.00	0.09	0.0046	20.47	< 0.001	0.09	0.10
1.00	0.07	0.0058	9.82	< 0.001	0.05	0.07
Conditional indirect effects of ENS on G4M:						
Indirect effect						
ENS → SCM → G4M						
ELS	β	*BootSE*	*BootLLCI*	*BootULCI*		
− 1.00	0.0090	0.0020	0.0051	0.0129		
0.00	0.0146	0.0015	0.0117	0.0177		
1.00	0.0202	0.0020	0.0163	0.0243		
Index of moderated mediation:						
	Index	*BootSE*	*BootLLCI*	*BootULCI*		
ELS	0.0056	0.0013	0.0030	0.0081		

LLCI lower limit confidence interval, *ULCI* upper limit confidence interval. If the 95% confidence interval does not include the null value (0), then there is a statistically significant difference between the groups ($p < .05$)

test models with moderated and mediated relations with the intent of improving math teaching and learning around the world. This study adds greater understanding of math learning and how early literacy and numeracy skills influence G4 math performance. The participants were comprised of mostly Asian and European students with results showing that ELS were stronger than ENS in predicting G4M and lend support to extant studies including Aragón et al. (2016), Birgisdottir et al. (2020), Purpura et al. (2011), and Yang et al. (2021). In contrast, it appears that the results from this study did not confirm children's early numeracy skills as the strongest predictor of their later math achievement that have been reported by others (e.g., Bryant et al., 2021; Duncan et al., 2007; Raghubar & Barnes, 2017). Parents reported engaging in higher frequencies of ELA than ENA before their children started school, which is coherent with recent findings by Napoli et al. (2021). Both parent–child ELA and ENA developed into ELS, while bafflingly neither ELA nor ENA advanced into ENS which did not confirm that home numeracy environment predicted ENS (e.g., Clerkin & Gilligan, 2018; Fazio et al., 2014; Segers et al., 2015; Siegler, 2016; Susperreguy et al., 2020). Parents with many HRL

Table 3 The hypotheses have been explored and supported

H1	Home environment support, student engagement, and attitudes are predictors of G4M. In particular, ELS are more effective than ENS in predicting G4M
H2	Home environment support and student engagement and attitudes are intercorrelated
H3	There are conditional direct effects of ENS on G4M
a)	ENS have a direct effect on G4M
b)	ELS have a direct effect on G4M
c)	ELS moderate the effect of ENS on G4M, and the effect of ENS on G4M is more prominent for children with weaker ELS
d)	HRL (a covariate) have a direct effect on G4M
H4	There are conditional indirect effects of ENS on G4M (i.e., ENS → SCM → G4M)
a)	ENS have a direct effect on SCM
b)	ELS have a direct effect on SCM
c)	ELS moderate the effect of ENS on SCM, and the effect of ENS on SCM is more pronounced for children with stronger ELS
d)	SCM have a direct effect on G4M
e)	SCM mediate the relation between ENS and G4M, and the effect is more evident for children with stronger ELS
f)	HRL (a covariate) have a direct effect on SCM

All hypotheses are supported

engaged in moderately more ELA than ENA with their children than those with fewer HRL. In addition, HRL contributed more to ELS than ENS although children's proficiencies in ELS and ENS were correlated. The findings that HRL fostered G4 math achievement are consistent with previous studies (e.g., McConney & Perry, 2010; Xue et al., 2020). Moreover, higher individual SCM advanced math achievement, in agreement with existent studies (e.g., Perera & John, 2020).

The positive moderation effect of the ELS on the relations between ENS and SCM indicate that the effect of ENS on SCM becomes more pronounced for children possessing stronger ELS. The negative moderation effect of the ELS on the relations between ENS and G4M appears to be in line with results from Fuchs et al. (2016) and Peng et al. (2020). The results suggest that children with weaker ELS utilized more ENS to assist them when approaching math problems whereas those with stronger ELS employed strategies more than ENS to answer math problems. Findings from this study suggest that children's strategies to solve math problems might be enhanced by their literacy skills. Future studies that explore the dynamics between ELS and ENS and their combined influences and strengths on math achievement are urgently needed. In addition, studies to uncover how ELS help children answer math problems deserve comprehensive examination. It is necessary to separate ELS into different levels (e.g., $\pm 1SD$ and mean) when examining relations between ENS and math attainment. Moderated mediation analysis is an informative technique for assessing whether direct and indirect effects are conditional on values of a moderating variable such as ELS.

Limitations

The limitations of this study include characteristics of design or methodology that impacted or influenced the interpretation of the findings. For instance, parents reported low percentages of early literacy and numeracy activities with their children before school in the top five performing East Asian countries. Intriguingly, how Asian children have mastered their early literacy and numeracy skills and excelled to the top in international assessments remain undetermined. Likewise, low percentages of East Asian students reported that they were confident in math, nevertheless their performance was exceptional. In addition, participating countries included in this study were comprised of mostly Asian and European students and as such the findings should not be generalized to black and Hispanic children's math learning. Future studies should explore whether the conditional direct and indirect effects are equal or more evident in black and/or Hispanic children's math learning. If so, parents and educators should try to strengthen children's literacy skills in tandem with numeracy skills to enhance their later math achievement. It would also be beneficial if the results of this moderated mediation model can be replicated using large-scale U.S. data which often include participants from more diverse ethnic backgrounds.

Implications

Both ELA and ENA advanced to children's ELS and ELS are stronger than ENS in predicting children's math achievement. Moreover, HRL have a stronger association with ELS than ENS. This study seeks to prompt awareness among parents and educators and should foster children's literacy skills in concert with numeracy skills thanks to the critical role of ELS in their later math achievement. Most critically, parents are urged to engage in comparable levels of early literacy and numeracy *practices* utilizing instantaneous everyday situations with their children before entering school to enhance their children's literacy and numeracy skills regardless of the availability of learning resources they can provide. However, whether strengthening literacy skills for students from disadvantaged groups with few resources can narrow the achievement gap deserves comprehensive studies.

Conclusion

Results from this study suggest that children's early literacy skills have a critical role in their later math achievement in a cross-linguistic and cross-cultural framework. The effect of ENS on SCM becomes more pronounced when the level of ELS increases whereas the effect of ENS on SCM diminishes for those with weaker ELS. In addition, the effect of ENS is transmitted through SCM, and confidence has a strong effect on G4M. In contrast, the effect of ENS on G4M diminishes when the level of ELS increases. It appears that children with weaker ELS employ ENS whereas those with stronger ELS utilize strategies more than ENS to tackle math problems. This suggests that children's math problem solving strategies might be advanced by their early literacy skills. Furthermore, ELS are more effective than ENS in predicting children's G4 math achievement. The main takeaways from this study are: (1) ELS have a stronger effect on G4M than ENS; (2) HRL impact more on children's ELS than ENS; (3) both early literacy and numeracy activities have progressed to ELS but demonstrated limited advancement to ENS, a missing link; (4) SCM emerged as the strongest predictor of G4M; (5) students with stronger ELS and ENS are more confident in math; and (6) The moderated mediation analysis revealed that (a) ELS have stronger direct effects on G4 math achievement than ENS; (b) the effects of ENS on G4M become more pronounced for children with weaker ELS (i.e., conditional effects); and (c) the effect of ENS on G4 math achievement is transmitted through SCM (ENS → SCM → G4M) and the effect is more prominent for those who had more proficient ELS (i.e., conditional indirect effects). Findings from the conditional direct and indirect effects of ENS on G4M suggest that children who had more proficient ELS utilize strategies beyond just ENS to solve G4 math problems and that children's strategies to solve math problems may be enhanced by the proficiency of their literacy skills. Parents and educators should facilitate children's literacy skills and numeracy skills to enhance their later math achievement.

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Isabelle Chang, the sole author. The author read and approved the final manuscript.

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Availability data and materials
The datasets generated and/or analyzed during the current study are available in the TIMSS 2019 International Database repository, https://timss2019.org/international-database/.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Not applicable.

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