What matters most?
Examining socioeconomic disparities
and predictors of early math ability

by

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Abstract

The academic achievement gap across socioeconomic status extends from school readiness throughout formal schooling, and academic success predicts later life outcomes. Recent research has turned to predictors of school readiness mathematics ability, as it has been shown to be the greatest predictor of later academic achievement. Previous studies have contested the strongest predictors of math ability, and have been tested in inconsistent populations. The present study examined the strongest predictors of early math ability in both low- and high-SES groups. We found that cardinal number knower level uniquely predicted math ability, irrespective of SES. Additionally, we found that vocabulary mediates the relationship between SES and math abilities. These findings suggest that SES affects math abilities through vocabulary and, ultimately, through cardinal number knower level.
Introduction

Nation-wide testing has revealed an academic achievement gap across race, family income level, and parental educational attainment (National Center for Educational Statistics, 2013). This achievement gap can be seen through early academic indicators even before students enter kindergarten (Lee & Burkam, 2002), and remains present throughout elementary school and beyond (National Center for Educational Statistics, 2013; Sirin, 2005). This school readiness gap has enormous implications for later achievement, as competence at school entry predicts rate of skill growth throughout elementary school (Jordan, Kaplan, Ramineni, & Locuniak, 2009).

This school readiness gap has huge implications, as individual differences in early math skills have been shown to serve as a strong predictor of later academic success (Duncan et al., 2007). A growing literature suggests that variations in math ability may be due to a number of external factors, including home environment (LeFevre et al., 2009; Melhuish et al., 2008), socioeconomic status (SES) (Jordan & Levine, 2009), and classroom teacher characteristics and pedagogical style (Mashburn et al., 2008).

These environmental factors may influence a number of cognitive abilities that underlie formal academic skills, including executive functioning (EF), general vocabulary, and math (Jordan & Levine, 2009; Noble, McCandliss, & Farah, 2007).

Formal academic math skills rely on both the evolutionarily conserved “number sense,” hereafter referred to as the approximate number system (ANS), and explicitly taught symbolic number representation. The ANS is a nonverbal system of number representation that is shared with nonhuman animals and develops beginning
at birth, continuing through infancy and childhood, and into adulthood (Droit-Volet, Clément, & Fayol, 2008; Halberda & Feigenson, 2008; Izard, Sann, Spelke, & Streri, 2009; Xu & Spelke, 2000). Systems of symbolic number representation vary from culture to culture, are usually rooted in language, and serve to supplement the ANS with number words and formalized computations (Carey, 2009). Prior research suggests these two systems are functionally intertwined and build upon one another, especially in formal academic instruction (Barth, La Mont, Lipton, & Spelke, 2005; Barth, La Mont, Lipton, Dehaene, Kanwisher, & Spelke, 2006; Gilmore, McCarthy, & Spelke, 2007). The current study investigates how various cognitive factors, including ANS acuity and number word knowledge—a component of early symbolic math abilities—predict formal mathematical abilities in both low- and high-SES groups, and whether these predictors differ in each group.

Previous research has suggested the ANS is predictive of academic math abilities, including tests of school readiness and the SAT (review in Feigenson, Libertus, & Halberda, 2013); however, recent findings call this into question (Fuhs & McNeil, 2013; Gilmore et al., 2013). A number of other cognitive skills including vocabulary and EF have been suggested as mediators of the relationship between ANS and academic math, especially in children from low-income families (Fuhs & McNeil, 2013). This longitudinal study further explores the association between the ANS and mathematical abilities, and how that association differs by SES. The outcomes of this study may have great implications for early childhood education and for narrowing the math achievement gap.
The School Readiness Gap

School readiness is a multidimensional construct that suggests children are ready to enter kindergarten prepared to learn. It is made up of behavioral, emotional, cognitive, and knowledge components and involves not only children, but also factors that influence children’s early development including families, communities, and other learning environments (Blair, 2002; Maxwell & Clifford, 2004). Children from low-income families—especially those who grew up in poverty—tend to perform significantly worse on tests of school readiness. These children have significantly lower IQs and score lower on academic achievement tests from as early as age 1 than children of middle- and high-income families (Gottfried, Gottfried, Bathurst, Guerin & Parramore, 2003). In fact, a review of literature documenting gaps in school readiness suggests that there is about a one standard deviation difference in school readiness across racial and ethnic lines (Rock & Stenner, 2005).

These gaps in achievement have been recorded for over 30 years, and are prevalent across grade levels. The National Center for Education Statistics (2013) has reported marked gaps in academic achievement across the U.S. since as early as 1980. Nationwide testing of randomized samples of students has consistently shown gaps in educational achievement between students of different ethnicities and income levels.

Given previous research suggesting that SES affects the overall construct of school readiness as well as academic achievement more broadly, some recent studies have turned to individual components of school readiness, including math, language, and EF. However, few studies have addressed the ways in which these factors may mediate the effects of SES on school readiness, and more specifically math abilities.
In this study, we seek to replicate prior findings of the effect of SES on each math, language, and EF, and will explore the interactions and mediating effects of these components.

**Symbolic and Nonsymbolic Math**

A meta-analysis of 6 longitudinal studies containing nearly 36,000 preschool students suggested that early math and literacy abilities are a stronger predictor of later academic achievement and educational attainment than social, emotional, and attentional skills (Duncan et al., 2007). While there has been a push for early literacy and socioemotional development across America (Phillips, Gormley, & Lowenstein, 2009), Duncan and colleagues’ study brings attention to early math abilities as an equally important focus in early education. Both literacy and math were found to be statistically significant predictors, but math was found to be a stronger predictor than literacy in regression analyses.

As a result, it is important we determine the strongest predictors of math readiness so as to inform the development of interventions to improve early math skills. Extensive research has suggested the ANS as a predictor and correlate of academic math abilities across grade levels, including assessments of early math achievement and the SAT (review in Feigenson et al., 2013). Here, we further investigate this relationship and between the ANS and early math readiness, as well as various other components of early math. We also investigate how these components develop differently in children of low- and high-SES families.

**Approximate Number System.** Research has revealed differences in the acuity of the ANS, yet it is unclear how these differences arise. The ANS is
responsible for imprecise, approximate representations of numerical magnitudes, and is shared with non-human animals including rats, pigeons, dolphins, and other primates (review in Dehaene, Dehaene-Lambertz, & Cohen, 1998). These mental representations of number tend to be distributed around the number they are meant to represent, with higher values producing more error than lower values, such that estimates of 20 would be less accurate than estimates of 10, but that an infinite number of estimates should converge on the target value (Halberda & Feigenson, 2008). This is in accordance with Weber’s Law, which predicts that the discriminability between numbers is a function not of the absolute numbers, but of the ratio between them (i.e., 5 is as discriminable from 10 as 10 is from 20).

Acuity of the ANS is not fixed throughout development, but improves over time. Research with human infants has revealed that newborns can discriminate 3:1 ratios in visual and auditory stimuli (Izard, Sann, Spelke, & Streri, 2009). Infants and young children have much more noisy ANS representations than do adults, such that 6-month olds can discriminate visual and auditory stimuli that differ by a ratio of 2:1 (Xu & Spelke, 2003), and that ratio becomes more refined as children approach adulthood. Cross-culturally, adults can discriminate ratios of 9:10, with some adults able to quickly discriminate a ratio of 11:12 (Halberda & Feigenson, 2008). However, human adults hit their peak of numerical acuity around age 30, and then decrease in ability. A large online study of 10,000 people ranging in age from 11-85 revealed that ANS acuity improves throughout traditional school years, and declines after people turn 30 (Halberda, Ly, Wilmer, Naiman, & Germine, 2012).
Within a single age group, however, there can be considerable variation in ANS acuity. In the Internet study by Halberda and colleagues (2012), there are large individual differences in precision within each group, and further research will address these individual differences.

Part of the variance in ANS acuity is thought to be a result of environmental influence. In a large-scale study of monozygotic and dizygotic 16-year-old twins in England and Wales, Tosto and colleagues (2014) concluded that while ANS acuity was modestly heritable, the majority of variance was explained by non-shared environmental factors. However, the authors did not discuss the environmental factors responsible for this variance.

Some recent research is delving into the origin of the individual differences in ANS acuity. Some have proposed that this may be partially due to degree of education. Piazza and colleagues (2013) tested the ANS acuity of adult and child members of the Mundurucú in the Amazon. They found that the average ANS acuity of adults was markedly worse than that of Italian adults, but that the difference was largely a product of education. Upon further analysis, they found Mundurucú adults who did not attend any formal schooling had ANS acuity twice as acute as Italian adults, and comparable ANS acuity to Italian kindergarteners. This was compared to Mundurucú adults who had attended some schooling who were found to have only slightly less refined ANS acuity than Italian adults.

Other research has suggested an individual’s ANS acuity is stable across a short span of time, such that discrimination abilities for visual cues at 6 months predicted discrimination abilities at 9 months (Libertus & Brannon, 2010). Extending
those results even further, discrimination abilities at 6 months also predicted ANS acuity at 3.5 years (Starr, Libertus, & Brannon, 2013). However, this evidence is not mutually exclusive with the suggestion that education improves ANS acuity. All published research on the stability of the ANS over time has focused only on children before they enter formal schooling. Further research will be needed to determine the stability of the ANS through in later years, and whether specific educational exposure can improve ANS acuity.

Additionally, ANS acuity has been suggested to be malleable and, indeed, can be improved with training within a given individual. DeWind and Brannon (2012) demonstrated testing adults on a dot comparison task across multiple sessions with feedback improves their ANS acuity. However, they found that while an individual’s reaction time improved after each of 6 sessions, ANS acuity improved only after the first session. This raises the question as to whether improved ANS acuity after only the first session may have simply been a product of practice effects given that it was participants’ first time engaging with the task.

While numerical acuity is thought to be stable, there has been no established cause of differences in ANS acuity. This present study will determine whether SES affects ANS acuity.

**Symbolic Math and its Relation to the ANS.** Informal, approximate numerical representations are complemented by understanding of exact, symbolic number words and is an important component of early math. Thus, it is important to investigate the role of cardinal number knowledge in early math abilities and how it differs across SES.
In the process of understanding symbolic number words, children learn a set of symbols as placeholders, which are later assigned meaning. Thus, children first learn to say the count list (usually numbers 1 through 10) before they understand the meaning of each number (Carey, 2009; Fuson, 1988).

In learning the meaning of number words, children then go through distinct “knower levels” in which they sequentially understand the meaning of each number (Fuson, 1988; Gelman & Gallistel, 1978; Wynn, 1990, 1992; Sarnecka & Carey, 2008). That is, a child who is a “2-knower” will understand the meaning of both “one” and “two,” but not of numbers higher than 2. After reaching the 3 or 4-knower level, it is thought that children become cardinal principle knowers (CP-knowers) and understand the general successor function that each number in the count list is simply one more than the one before it (i.e., each new number in the count list is simply the previous number \( n+1 \)), as well as the cardinal principal in which they recognize that the last number counted is the total number of objects in a set (Carey, 2009; Gelman & Gallistel, 1978). This entire process from learning to recite the count list to becoming a CP-knower may take around three years, until a child is 5 years old (Wynn, 1992).

Sarnecka and Carey (2008), in a follow-up to Wynn’s (1990, 1992) studies of children’s knower levels, found performance on other assessments of numeracy corresponded with knower level. The authors tested children on memorization of the count list, one-to-one correspondence, understanding of the prompt “how many,” and understanding that moving forward in the count list reflects adding to a set whereas moving backward reflects subtracting from a set and found that, while nearly all
children were able to recite the count list to 10, there were significant differences in performance on the other task by knower level, controlling for age. The authors found that children performed significantly better as CP-knowers than as subset knowers.

As in previous studies, Sarnecka and Carey suggest that CP-knowers should be able to represent any number up to which he or she can count. However, this has been called into question with recent research. Davidson, Eng, and Barner (2012) found that children who are CP-knowers do not have a firm understanding of the successor function even for low numbers as assessed by a task that asked children whether adding one bead to a box of existing beads would result in the box holding \( n + 1 \) beads. The suggestion that CP-knowers do not have an understanding of higher numerosities has been extended with the task that is typically used to assess knower level. In this experiment, children who were described as CP-knowers were asked for 10 and 14 objects. Nearly all CP-knowers were able to produce 10 objects, while just half were able to accurately produce 14, even if they could confidently count to 15 or higher (Sarbh, Taggart, & Shusterman, in prep).

According to Common Core State Standards, an understanding of cardinality is a foundational skill all kindergarten students should know, as it underlies most formal mathematical operations and lays the basis for future academic math (National Governors Association Center for Best Practices, Council of Chief State School Officers, 2010), which is also in accord with teachers’ beliefs about the importance of counting and cardinality (Lee & Ginsburg, 2007). However, an emerging line of research has found ANS acuity to both correlate with and be predictive of symbolic mathematical skills, including those measured on academic achievement tests such as
measures of school readiness and the SAT, suggesting that the numerical approximation might be an equally important standard (review in Feigenson et al., 2013).

This predictive value of the ANS on symbolic math abilities may support the hypothesis that understanding of exact quantity emerges from mapping nonsymbolic representations onto number words. Mundy & Gilmore (2009) demonstrated that 6- to 8-year-old children are able to match approximate representations to symbolic ones, and vice versa. Children were given a mapping task in which they were presented with either a discrete number word, and were asked to choose which of two arrays of dots represented that word, or were given an array of dots and asked to choose which of two Arabic numerals represented that array. This demonstrates a bidirectional association of approximate and symbolic numeracy.

The ANS was also found to have a place in formal mathematical operations, as well. Gilmore, McCarthy, and Spelke (2007) found non-symbolic processing can assist in symbolic arithmetic, even before children have learned formal mathematical operations. The authors suggested that in the absence of formal principles of addition and subtraction, 5- and 6-year-old children can still perform approximate two-digit operations and comparisons. Participants had to compare two numbers of objects added together versus one other number and choose which was more. Findings were in accord with Weber’s law, such that children became less accurate as the ratio between the numbers being compared equaled 1.

The link between ANS acuity and symbolic math abilities extends from infancy: Starr, Libertus, and Brannon (2013) found that ANS acuity at 6 months
predicts ANS acuity, math abilities as measured by the Test of Early Mathematics Ability, 3rd Edition (TEMA-3), and knower level at 3.5-years old, but did not predict general intelligence (IQ). Furthermore, the correlations between ANS at 6 months and both ANS and math abilities at 3.5 years held even when controlling for IQ, suggesting a unique role of ANS acuity as an early predictor of symbolic math abilities.

However, the directionality of the link between the ANS and symbolic math is still unclear. While some research has suggested the ANS supports the emergence of and learning in symbolic math, other research has claimed the opposite. Using a 6-week longitudinal study, Shusterman, Slusser, Halberda, and Odic (under review) found that an increase in knower level, especially the jump from 1-knower to 2-knower and in becoming a CP-knower, corresponded with refinement of the ANS. However, this study still relies upon correlational evidence and did not suggest a direct causal link.

Research on training the ANS has tried to suggest that improvements in the ANS result in improvements in symbolic math. Park and Brannon (2013) found that by training the ANS in ten sessions using approximate dot addition and subtraction animations, they would see a corresponding improvement on three-digit addition and subtraction problems in adults. However, adults who received training in either a general knowledge or number-ordering task did not see improvement on addition and subtraction problems.

Hyde, Khanum, and Spelke (2014) extended the findings by Park and Brannon (2013) by introducing an ANS training paradigm to first grade children, and
similarly found improvement in arithmetic abilities. Researchers chose to train four different skills in a single session: non-symbolic addition, line length addition, numerical comparison, and brightness comparison, each of which has been presented as a possible contributor to academic math abilities. Subjects who participated in number-specific conditions (non-symbolic addition and numerical comparison) performed better on a worksheet that tested symbolic math abilities than subjects who participated in either of the other two conditions. Interestingly, there was significant improvement on the speed of completion, but only marginally significant improvement on accuracy.

There is inconclusive evidence as to the directionality of the link between ANS acuity and symbolic math abilities, but there is clearly some interplay of the two. However, it is unclear whether the strength of that link differs among children from different socioeconomic backgrounds. On the one hand, the ANS is thought to be fairly stable and unaffected by factors outside of formal education, but are thought to predict academic math achievement. Yet, children from low-income families consistently perform more poorly than their middle- and high-income peers on math achievement tests. This study will clarify the effect of SES on ANS acuity, cardinal number knowledge, and academic math achievement.

**Language Skills**

A strong explanatory theory of the effect of SES on school readiness claims that differences in cognitive abilities as students enter school are an effect of language skills in early childhood. A seminal study by Hart and Risley (1995) concluded that amount of linguistic input varies as a function of social class. In their study, they
extrapolated from a series of observations in 42 families that by the time two given children are 3 years old, a child from a professional family will have heard 30 million words more than a child from a family on welfare. This was determined by observations in which children from welfare families hear an average of 616 words per hour, children from working-class families hear 1,251 words per hour, and children of professional families hear 2,153 words per hour; researchers assumed a 100-hour week given a 14-hour waking day.

Hart and Risley (1995) then proposed that amount of language input should influence vocabulary size. Using a series of assessments, they found that children of professional families had an average vocabulary of 1,116 words, as compared to 525 in children of welfare families, controlling for age at which children started to speak as well as age at time of testing.

This finding has been validated in more recent studies looking at the effect of parental education on child language size, finding that children of parents with college degrees have a significantly larger expressive vocabulary than those of parents with no high school diploma. This association was primarily found to be an effect of the level of the mother’s education, and the study assumed the mother to be the primary caregiver for the child. The study did not account for families in which the father was the primary caregiver. The same effect of mother’s education on expressive vocabulary size was seen cross-culturally with families in China (Hoff & Tian, 2005).

Language abilities have also been suggested as a mediator between home environment and school readiness. Using a large sample of twins, Forget-Dubois and
colleagues (2009) suggested that variation in linguistic ability partially accounts for the relationship between SES and school readiness. However, both SES and school readiness were also strongly correlated with general cognitive ability (IQ), but it was not examined as a mediator. The study also did not examine subsections of the general school readiness assessment, so it may be that language ability only mediated the relationship between SES and the language-specific portions of school readiness.

It is still unclear how variations in linguistic abilities affect other domains of school readiness; however, some studies have suggested language is a foundational component of math abilities.

**Language and its Relations to Math.** In this study, we investigate the various predictors of academic math abilities across SES. However, development of formal math skills is inextricably linked to language and, in particular, number-specific language input: without language specific to exact quantities, people do not develop an understanding of cardinality or equinumerosity. This has been explored in both cross-linguistic and US-specific contexts.

**Cross-Linguistic Number Acquisition.** Frank and colleagues (2008) found that in a society whose language does not express exact quantities above 2, participants could match numbers of objects with present sets, but were unable to match previously presented sets. Researchers concluded that because there was no way to represent exact quantity, there was no way participants could give consistent responses. They therefore had to rely on systems of approximate number to represent the set.
However, in similar research with a different society that expresses exact quantities for only 1 through 5, ANS acuity was slightly less refined than in a society that expresses quantities for a wider range of numbers. Using a dot comparison task, researchers found Mundurucú adults had slightly worse ANS acuity than French adults (Pica, Lemer, Izard, & Dehaene, 2004). Later research suggested this difference in ANS acuity may be an effect of education, as Mundurucú adults attend on average less school than French adults, although it is unclear in formal education improved ANS acuity (Piazza et al., 2013).

For a full conceptual understanding of cardinality, there must also be a rich understanding of language. Older adults who learned Nicaraguan Sign Language had a worse conceptual grasp on numeracy than young adults and children who learned Nicaraguan Sign Language earlier in life, which may indicate an effect of time of exposure to language discussing quantity. However, the older adults also did not have as strong an understanding of the language as their younger peers, so math abilities may have simply covaried with language in this study (Flaherty & Senghas, 2011).

*Number Acquisition in the US.* Additionally, in a population of children born deaf that later received hearing aids or cochlear implants, time of language input was an important factor in the development of numeracy. Oral-deaf children developed concepts of numeracy on a similar trajectory as hearing children from the time they began receiving linguistic input, suggesting they developed an understanding of number concepts later as a function of later language input (Lange, Berkowitz, & Shusterman, in prep).
In a normally hearing population that speaks English, researchers have seen an effect of specific linguistic input. Gunderson and Levine (2011) suggested that number word acquisition is predicted by number-specific language in the home. They found that the more number words a child’s primary caregiver uses, the faster the child develops an understanding of number and the cardinal principle. Further, the amount of parent number talk was significantly correlated with SES, such that children of higher-SES families heard more number words than those from lower-SES families.

Additionally, Negen and Sarnecka (2012) found that both receptive and expressive vocabulary correlate with knower-level, suggesting that number word knowledge as described by knower-level may simply be a function of general word knowledge.

There is a clear language deficit in children from low-income families, and clear role of language in the development of mathematical concepts. Here, we ask whether language mediates the relationship between family SES and academic math achievement.

**Executive Function**

Executive function is a construct of higher order processes that regulate and control aspects of behavior including include working memory, attention shifting, and inhibitory control (Miyake, Friedman, Emerson, Witzki, & Howarter, 2000). Classroom learning inherently demands all three components, and are therefore an important part of our investigation.
Noble, Norman, and Farah (2005) found significant differences between low- and middle-income kindergarteners’ performance on EF tasks. In a follow-up study, Noble, McCandliss, and Farah (2007) investigated differences in individual components of EF across SES. The authors found that SES predicted variance in both working memory and cognitive/inhibitory control—systems implicated in school abilities—but not reward processing.

Prior studies have established relations between EF and early math (Bull & Scerif, 2001), early literacy (Swanson, 1999), and broader academic performance (Duckwork & Seligman, 2005). It has thus been hypothesized that SES might affect academic performance through its effect on EF.

In a recent study, Fitzpatrick, McKinnon, Blair, and Willoughby (2014) found that in addition to correlating independently with SES, EF also correlated with a number of school readiness abilities including early math, early literacy, general intelligence, and processing speed. The two-part study included a battery of EF assessments, a tablet-based test of reaction time, the Raven’s Colored Progressive Matrices as a measure of IQ, two subtests of the Woodcock-Johnson Test of Achievement III testing math and word-identification skills, and the picture-identification subtest of the Woodcock-Johnson Test of Cognitive Abilities that measured vocabulary. The authors found using regression analyses that age, SES, IQ, and EF—but not processing speed—each predicted outcomes on all three Woodcock-Johnson subtests. Controlling for IQ and age, EF partially mediated the relationship between SES and all subtest scores; however, controlling for EF and age, IQ did not. This suggests a unique role of EF in mediating the academic achievement gap, and
further studies may examine EF as a causal mechanism for improving school achievement.

In further analyses in the same study, vocabulary also mediated the relationship between SES and both math and word identification. Including vocabulary as a factor in regressions on math and word-identification subtests, the authors found that EF still served as a predictor of math, but not word identification. It is still unclear what causes the individual differences EF across SES in this study. The authors postulate that language abilities may support EF development, though it clearly does not account for all variance in EF. They also note that EF differences may be may have been a result of preschool experience: SES was categorized as either “high SES” or “low SES” based upon enrollment in one of three private preschools with high tuition, or one of three needs-based preschools. The preschools use different curricula, and the authors note the high-income preschools all use a Montessori curriculum, which has been previously shown to improve EF (Fitzpatrick, McKinnon, Blair, & Willoughby, 2014).

Additional research that featured home observation with 4- and 5-year-olds revealed differences in EF across SES, and correlations between SES, EF, and math abilities. Controlling for EF, the author found the correlation between SES and math abilities to no longer be significant, suggesting that EF may mediate the relationship between home environment and math-specific abilities (Dilworth-Bart, 2012).

The role of EF in the relationship between ANS acuity and math abilities is contested. Fuhs and McNeil (2013) reported the previously established association found in other studies (Libertus, Odic, & Halberda, 2008; Libertus et al., 2011, 2013)
to be mediated entirely by receptive vocabulary and inhibitory control in a low-income population. Fuhs and McNeil found the association between ANS and TEMA-3 scores to be weaker than previously reported in middle-income populations. They also did not test in a middle-income population; however, Gilmore and colleagues (2013) similarly describe inhibitory control—and not ANS acuity—as correlating with math achievement. Here, researchers question the task demands of the ANS acuity paradigm because it requires sustained attention and intensive processing for a long period of time. They explain that this may be especially salient in a low-income population whose EF abilities are markedly worse (Noble et al., 2005).

However, when Libertus and colleagues (2013) controlled for both attention and memory—two parts of the EF construct—they continued to find a significant relationship between ANS acuity and TEMA-3 scores.

Finally, some evidence suggests that language skills may be crucial to the development of executive function. Noble and colleagues (2005) ran a large battery of tests on each of five neurocognitive correlates of kindergarten skills including executive function, language, spatial abilities, memory, and visual skills. They found that SES significantly predicted only EF and language abilities—a composite of vocabulary, phonological awareness, and grammar measures. In controlling for the language composite score, the authors found that language mediated the relationship of SES with EF. SES thus appeared to predict language skills, which in turn support the development of EF. However, this is in contest with Fuhs and McNeil’s (2013) finding that there is an additive effect of vocabulary and EF in mediating the
relationship between ANS acuity and math abilities. It is possible that the broader test of language abilities in Noble, Norman, and Farah’s study may mediate a greater amount of the relationship between ANS and math abilities than just the measure of vocabulary used in Fuhs and McNeil’s study vocabulary.

**The Current Study**

This study aims to fill the gap in published literature about differing predictors of math achievement across socioeconomic status. The majority of research on predictors of early math abilities has been published with children from middle- and high-income families (Gilmore et al., 2013; Libertus et al., 2013). Minimal research has been undertaken with children from low-income families, and less still has compared predictors of math achievement across socioeconomic status. Some research has posited a mediating effect of language and EF (Fuhs & McNeil, 2013; Gilmore et al., 2013), which have been shown to differ across SES level (Noble et al., 2005).

As is the precedent in much of the related research, we use the TEMA-3 to measure early mathematic abilities (Libertus et al., 2011). This standardized assessment includes measures of both informal (approximate) and formal (taught in school) skills, and scores of the TEMA-3 are highly correlated with other tests of early math abilities, including Woodcock-Johnson subtests (Ginsburg & Baroody, 2003). We expect to see a significant difference in TEMA-3 scores across SES as a validation of the math achievement gap as early as preschool and kindergarten.

Ultimately, this study will explore which of the tested cognitive domains predict math abilities as children enter formal schooling, and whether those domains
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differ across SES. To do that, we designed a two-phase, longitudinal study to assess the predictive value of number word knowledge, ANS acuity, and general vocabulary on early math abilities.

The pretest battery included three elements. The Give-a-Number (Give-N) task measures children’s understanding of cardinal number words (Sarnecka & Carey, 2008; Wynn, 1990, 1992). Number word knowledge develops with appropriate linguistic input, but little published research has addressed difference in development across SES. The Panamath task is a dot comparison estimation task measures children’s approximate number system acuity (Feigenson & Halberda, 2008). ANS acuity is thought to be fairly stable, and develops naturally from infancy to adulthood, though it can be honed with explicit training. Finally, the Peabody Picture Vocabulary Test, 4th edition (PPVT-4) measured children’s general receptive vocabulary (Dunn & Dunn, 2007). Previous research has shown significant differences in receptive vocabulary across SES (Hart & Risley, 1995, 2003).

The posttest battery included six elements, and required two testing sessions. Session one tested children’s math abilities using Give-N, Panamath, and the TEMA-3. Session two tested children’s executive function, using two behavioral regulation tasks, and vocabulary, using the PPVT-4. The role of EF as a predictor of math abilities is contested, and has been tested in both middle- and low-income children (Fuhs & McNeil, 2013; Gilmore et al., 2013; Libertus et al., 2013). The present study is unique in its analysis of whether the association between EF and math knowledge differs across SES levels.
We expect to find a correlation of SES with each of our measures, and that these associations are driven by both language and EF. We know there is an effect of SES on both language skills and executive function and that the two are correlated. Previous studies have also suggested language as a mediator of SES and EF (Noble et al., 2005; Noble et al., 2007). Prior research has shown a gradient of receptive vocabulary across SES and a correlation between cardinal number knowledge and vocabulary (Hart & Risley, 1995; Negen & Sarnecka, 2012).

We thus present our main questions and hypotheses to bridge the gap in research spanning across SES.

Our first question asks whether there are indeed SES disparities in our measures. Extensive research has revealed a gap in both early math (Jordan & Levine, 2009), early language skills (Hart & Risley, 1995; Noble et al., 2005), and EF (Noble et al., 2007). However, very little research has addressed whether there are SES disparities in cardinality (Jordan, Huttenlocher, & Levine, 1992), and no published research has yet addressed whether there are differences in ANS acuity across low- and high-SES.

Our second question asks what the strongest predictors of math abilities are, irrespective of SES. Previous research has posited ANS acuity as a predictor of math abilities and has explored the role of expressive vocabulary, memory, and attention (Libertus et al., 2013), and emerging research has suggested a role for EF (Gilmore et al., 2013), but no published research has tested knowledge level as a predictor of math abilities.
Finally, our third question asks whether there are mediators of the relationship between SES and math, and whether those mediators differ by SES group.

Our first hypothesis suggests that language is an important mediator of the relationship between SES and math. This builds upon Noble and colleagues’ (2005) finding that language stands as a mediator of SES and outcome domains, including executive function. This also follows from Negen and Sarnecka’s (2009) finding that vocabulary correlates strongly with number word knowledge. We expect to find that language skills mediate the relationship between SES and TEMA-3 scores.

Our second hypothesis reconciles the findings that the relationship between ANS and TEMA-3 is mediated in a low-SES population (Fuhs & McNeil, 2013), but not in a high-SES population (Libertus et al., 2013). For this, we present a model of moderated mediation and suggest that vocabulary and executive function mediate the relationship between ANS acuity and math abilities only in a low-income population and not a middle- to high-income population.

Methods

Participants

Participants were tested at preschool and daycare centers in San Jose, Calif. and Middletown, Conn., and in the Cognitive Development Labs at Wesleyan University. 154 children (78 F, $M_{age} = 4$ years, 3 months, range = 3 years, 0 months – 6 years, 2 months) were tested at time 1, and 65 (31 F, $M_{age} = 5$ years, 1 month, range = 3 years, 8 months – 7 years, 9 months) have completed post-test at time of this
writing. All children received a sticker for their participation, and families who came into the lab received a $5 travel reimbursement.

**Measures**

This longitudinal study involved two testing sessions one year apart. In both sessions, participants were tested on an indicator of early symbolic, cardinal numeracy, and one of ANS acuity, as well as one of receptive vocabulary. In the second session, participants were additionally tested on a test of early math achievement, and some children were tested on two tests of EF. Parents were asked to complete a questionnaire of family demographic information including average annual income, parent employment, race/ethnicity, and the child’s school experience. All testing procedures are described below.

**Symbolic math.** Using the Give-a-Number (Give-N) task adapted from Wynn (1992) and described by Sarnecka and Carey (2008), children were asked to count 15, then 20 plastic fish to test their knowledge of the count list. Children were then asked to put a number of fish in a bowl (referred to as the fish’s “swimming pond”) in sets of 1-8. Whether or not the child was correct, he would be asked to “count and check to make sure it’s [n].” Corrections were allowed if the child recognized an error.

Number-knower level was determined using a titration method following (Wynn, 1992) in which children had to give the correct number of fish 2 of 3 times for the highest number of understanding. That is, if a child gave the incorrect number of fish when asked for 5, he would be asked for 4 fish. If he gave the correct amount

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1 Data collection is still in progress.
2 EF battery was added approximately halfway through posttesting. Additional data collection is still under way, and will include EF.
for 4 at least 2 times, and gave the incorrect amount for 5, he was classified as a 4-knower. Children were asked for $n$ fish in the following order: 1, 4, 6, 8, then 7, though an incorrect answer prompted to ask for a set of $(n – 1)$. A child was classified as a CP-knower if he got every 2 of 3 for each number correct.

**ANS acuity.** Using an adaptation of the Panamath non-symbolic task described by Halberda and Feigenson (2008), children compared two sets of dots in order to determine which had more. Blue and yellow dots were presented on the left and right sides of a computer screen, respectively, and children were asked to either press the key with the sticker of the corresponding color, or say and point to the side with more dots and allow the experimenter to press the button. Children received immediate feedback for all trials through sounds of different tones: a high-pitched beep signified a correct answer, while a low-pitched beep indicated an incorrect answer. Children completed six training trials, followed by 60 test trials.

The number of dots on each side of the screen ranged from 4 to 15 such that the ratio was one of four ratio bins: 1:2, 2:3, 3:4, and 6:7. Test trials were randomly assigned by the computer program, and half the trials had more yellow dots, while half had more blue dots. On half the trials, the two sides were equated for average dot size; on the other half, the two sides were equated for total surface area.

Performance was measured by total percent correct on the 60 test trials. Though a number of other indices including Weber fraction—a psychometric function that estimates the ratio of numerosities between which an individual can discriminate—numerical ratio effect—the slope of the ratio-accuracy or ratio-reaction
time graphs—have been used to describe ANS acuity in previous studies, percent correct is thought to be the most stable measure (Inglis & Gilmore, 2014).

**Receptive vocabulary.** Using the PPVT-4 (Dunn & Dunn, 2007), we measured the size of children’s receptive vocabulary. Children were asked to point to one of four pictures on a page that showed a specified noun or verb (e.g., “Can you point to ball?”). The test was completed when a child responded incorrectly 8 times in a given set of 12 items, following protocol in the PPVT-4 manual.

**Mathematical ability.** To test math ability, we used Form B of the TEMA-3 (Ginsburg & Baroody, 2003). This test measures counting abilities and Arabic numeral recognition, number-comparisons, and calculation skills. Performance on the TEMA-3 correlates highly with performance on other achievement tests including the Woodcock-Johnson III (Woodcock, McGrew, & Mather, 2001).

**Executive function.** Executive function was measured using two tasks of behavioral regulation.

The Elephant-crocodile task is adapted from the Bear-dragon executive function task (Carlson & Moses, 2001), and the Dots task (Davidson, Amso, Anderson, & Diamond, 2006). Children were introduced to two puppets, an elephant and a crocodile, who would push one of two ‘buttons.’ Children were asked to press the same button the elephant puppet pressed, and the opposite button from the one the crocodile puppet pressed. The experimenter first introduced the rule for the elephant, and gave two practice trials in which children were given feedback, followed by four test trials with no feedback. The experimenter then introduced the rule for the crocodile, and again gave two practice trials with feedback followed by four test trials.
without feedback. The last part block included mixed trials in which the elephant and crocodile pressed buttons in a fixed, pseudorandom order for 12 trials with no correction. Each response was coded as correct (0 points), self-correct, in which a child changed his response after touching a button (1 point), and incorrect (2 points), such that a child who responded correctly to each trial earned a score of 0 points and a child who responded incorrectly to each prompt earned a score of 24 points.

The second task, the Head-Toes-Knees-Shoulders task (HTKS) is a measure of inhibitory control developed by Ponitz and colleagues (2008). In this task, children were asked to respond to the opposite of what the experimenter asks. For instance, if a child was told, “touch your head,” he would touch his toes. The task had three phases. In phase one, participants were asked to touch the opposite of their head and shoulders. There were six practice trials with feedback, and 10 test trials without feedback. In phase two, the experimenter added shoulders and knees, and there were five practice trials. For the ten test trials, the experimenter told the child to touch his head, shoulders, knees, or toes, and the child was expected to do the opposite. In the final phase, the rules changed such that ‘head’ corresponded with ‘knees,’ and ‘shoulders’ correspond with ‘toes.’ As in phase one, children were presented with six practice trials with feedback, and ten test trials. Children would only move to the next phase if they scored more than 4 points. Each response was coded as ‘correct’ (2 points), ‘self-correct,’ in which the child made discernable movement toward the wrong body part before moving to the correct body part (1 point), or ‘incorrect’ (0 points), such that a child who responded correctly to each trial earned a score of 60
points and a child who responded incorrectly to each prompt earned a score of 0 points.

**Parent questionnaire.** Parents were given a brief, one-page questionnaire (Appendix A) including questions regarding parental education, income, and occupation, as well as the child’s preschool experience.

Parental education was defined as the highest level of education reached by each parent or primary caregiver, and was self-reported as 1 of 7 bins. Parents were also given the option to not report their highest level of education. Education was treated as an ordinal variable in most analyses.

Income-to-needs ratio was defined as the mean of the indicated income bin, or exact income when reported, divided by the poverty threshold for a family of that size, such that a score of 1 indicates a family at the poverty line.

Parental occupation was defined on a 5-point scale of occupational prestige (National Center for O*NET Development, 2014). Each classified by the US Census Bureau was ranked, such that the score corresponded with amount of preparation needed for a given job.

**Data Analytic Strategy**

To answer our research question about the differing predictors of math achievement across SES, we first needed to establish the presence of SES disparities in math achievement. We then wanted to control for those SES differences in order to suggest predictors of math achievement irrespective of SES. Finally, we wanted to determine whether there were differences in those predictors or mediators between SES groups. As some measures (TEMA-3, PPVT-4) provided standardized scores
that accounted for age, but others (knower level, ANS, EF) did not, we used raw scores in all analyses in which we also controlled for age.

**Hypothesis 1: Vocabulary mediates the relationship between SES and math.** To address this hypothesis, we ran hierarchical linear regression models. We needed to first establish that SES predicted each math measure. We concluded a mediation effect if introducing our measure of vocabulary made SES a non-significant predictor.

**Hypothesis 2: Vocabulary mediates the relationship between ANS and TEMA-3 in low SES, but not high SES.** Similar to hypothesis 1, we needed to establish that ANS was a significant predictor of TEMA-3 scores in both a low- and high-SES population as had been established in previous research (Libertus et al., 2013; Fuhs & McNeil, 2013). We again ran hierarchical linear regressions, and determined whether ANS was no longer a significant predictor of TEMA-3 when vocabulary was included as a mediator in each group.

**Results**

**Descriptive Statistics**

Descriptive results are summarized in Table 1. All analyses were performed on the subset of the participants who completed the tasks included in the given analysis (i.e., we did not replace missing data). As the number of participants who completed the EF tasks at both pre- and posttest is comparatively small (N = 27; N = 25, respectively), we chose not to include EF in any analyses except for pairwise correlations so as to not limit the power in our analyses.
Sex Differences. Descriptive statistics by sex are summarized in table 2. We ran independent-samples t-tests on each of the measures and found only significant sex differences on posttest PPVT-4 score ($p = .008$) with girls outperforming boys (girls $M = 118.71$, boys $M = 106.84$). We did not separate any analyses by sex.

Table 1
Summary of Descriptive Statistics

<table>
<thead>
<tr>
<th>Measure</th>
<th>Task</th>
<th>Time 1 N</th>
<th>Time 1 Mean</th>
<th>Time 2 N</th>
<th>Time 2 Mean</th>
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<td>Task</td>
<td></td>
<td>(SD)</td>
<td></td>
<td>(SD)</td>
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<td>55</td>
<td>5.65</td>
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<td></td>
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<td>(0.89)</td>
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<td>56</td>
<td>73.73</td>
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<td>(17.58)</td>
<td></td>
<td>(14.18)</td>
</tr>
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<td>—</td>
<td>54</td>
<td>106.24</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>(11.56)</td>
</tr>
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<td>113.47</td>
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<td>(15.01)</td>
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<td>Head-Toes</td>
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<td>—</td>
<td>25</td>
<td>29.24</td>
</tr>
<tr>
<td></td>
<td>Knees-Shoulders</td>
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<td>(15.15)</td>
</tr>
<tr>
<td></td>
<td>Buttons (%)</td>
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<td>Level</td>
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<td>Average Job Zone</td>
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<td></td>
<td></td>
<td></td>
<td>(1.15)</td>
</tr>
<tr>
<td></td>
<td>Income-to-Needs</td>
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<td></td>
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<td></td>
<td></td>
<td>(2.01)</td>
</tr>
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Table 2

Summary of Descriptive Statistics by Sex

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<thead>
<tr>
<th>Pre/Post Test</th>
<th>Measure</th>
<th>Task</th>
<th>Male N</th>
<th>Male Mean (SD)</th>
<th>Female N</th>
<th>Female Mean (SD)</th>
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<tr>
<td>Pre</td>
<td>Age</td>
<td></td>
<td>24</td>
<td>4.08 (0.67)</td>
<td>31</td>
<td>4.07 (0.64)</td>
</tr>
<tr>
<td></td>
<td>Knower Level</td>
<td>Give-N</td>
<td>25</td>
<td>4.32 (2.23)</td>
<td>30</td>
<td>3.93 (2.03)</td>
</tr>
<tr>
<td></td>
<td>ANS</td>
<td>Panamath</td>
<td>25</td>
<td>59.48</td>
<td>28</td>
<td>64.78</td>
</tr>
<tr>
<td></td>
<td>Accuracy</td>
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<td></td>
<td>(20.02)</td>
<td></td>
<td>(15.06)</td>
</tr>
<tr>
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<td>Vocabulary</td>
<td>PPVT-4</td>
<td>24</td>
<td>113.83</td>
<td>31</td>
<td>113.45</td>
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<tr>
<td></td>
<td>Score</td>
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<td></td>
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<td></td>
<td>(14.94)</td>
</tr>
<tr>
<td>Post</td>
<td>Age</td>
<td></td>
<td>25</td>
<td>5.08 (0.64)</td>
<td>31</td>
<td>5.08 (0.78)</td>
</tr>
<tr>
<td></td>
<td>Knower Level</td>
<td>Give-N</td>
<td>25</td>
<td>5.64 (1.04)</td>
<td>30</td>
<td>5.67 (0.76)</td>
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<tr>
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<td>Panamath</td>
<td>25</td>
<td>74.17</td>
<td>31</td>
<td>37.37</td>
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<tr>
<td></td>
<td>Accuracy</td>
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<td></td>
<td>13.31</td>
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<td>(15.05)</td>
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<tr>
<td></td>
<td>Math Abilities</td>
<td>TEMA-3</td>
<td>24</td>
<td>106.42</td>
<td>30</td>
<td>106.10</td>
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<tr>
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<td></td>
<td>(11.45)</td>
<td></td>
<td>(11.85)</td>
</tr>
<tr>
<td></td>
<td>Vocabulary</td>
<td>PPVT-4</td>
<td>19</td>
<td>106.84</td>
<td>24</td>
<td>118.71</td>
</tr>
<tr>
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<td></td>
<td>(15.93)</td>
<td></td>
<td>(12.16)</td>
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<tr>
<td></td>
<td>EF</td>
<td>Head-Toes-Knees-Shoulders</td>
<td>13</td>
<td>27.38 (17.79)</td>
<td>12</td>
<td>31.25 (12.12)</td>
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<tr>
<td></td>
<td>Buttons (%)</td>
<td></td>
<td></td>
<td>82.75 (21.99)</td>
<td>13</td>
<td>85.94 (17.34)</td>
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<tr>
<td>SES</td>
<td>Average</td>
<td></td>
<td>25</td>
<td>3.78 (1.18)</td>
<td>31</td>
<td>3.77 (1.08)</td>
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<td>Education Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average Job Zone</td>
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<td>21</td>
<td>2.98 (1.36)</td>
<td>30</td>
<td>2.95 (1.02)</td>
</tr>
<tr>
<td></td>
<td>Income-to-Needs</td>
<td></td>
<td>22</td>
<td>3.87 (2.34)</td>
<td>27</td>
<td>3.65 (1.72)</td>
</tr>
</tbody>
</table>
**Socioeconomic Status.** Each of our measures of SES strongly was intercorrelated. We entered each parent’s education level, average parent education, each parent’s occupational prestige, average occupational prestige, and family income-to-needs ratio into a factor analysis, and found that average parent education loaded the most strongly onto the extracted component (r = .894). We also found that average parent education correlated most strongly with each other SES variable. As this is a longitudinal study and we are interested in developmental trends, we wanted to choose the most stable measure of SES. We thus chose to use average parent education as our measure of SES. Parent education has genuinely be found to predict family income and occupational status (Leibowitz, 1974), and has been shown to predict child achievement outcomes more strongly than family income (Davis-Kean, 2005). This may be a product of the volatility of family income over time (Duncan, Brooks-Gunn, Yeung, & Smith, 1998).

**Question 1: Are there SES disparities in early math achievement?**

We ran a one-way ANOVA to determine whether there were SES disparities in math achievement. We categorized average parent education into tertiles of high (N = 20), middle (N = 18), and low (N = 18) education, such that the middle group had post-high school experience (community college or a four-year university), the high group had post-baccalaureate experience (masters or doctoral), and the low group a high school degree or lower. TEMA-3 score significantly differed across groups, $F (2, 51) = 5.031, p = .01$. Tukey post-hoc comparisons revealed significant differences between low- and middle-SES groups ($p = .032$) and between low- and high-SES groups ($p = .016$), but not between middle- and high-SES groups ($p =
.994). We thus chose to collapse our SES tertiles into only low-SES (N = 25) and middle- and high-SES (N = 31), such that low-SES reflected less than a four-year college degree, and high-SES was a four-year degree or more. Independent-samples t-tests confirmed that there were significant differences in TEMA-3 scores between the two groups, $F(1, 52) = 7.112, p = .01$.

We next explored SES differences in vocabulary measures. We ran independent-samples t-tests and found significant SES disparities in both pre- and posttest PPVT ($p = .006$ and $p = .005$, respectively).

To test for SES disparities in measures that did not standardize scores for age, we ran partial correlations controlling for age at time of testing. Because we assumed a directional hypothesis such that SES affects outcome measures, we used a 1-tailed standard of significance. We found that average parent education level correlated significantly with pretest knower level ($p = .039$), pretest ANS accuracy ($p = .035$), and head-toes-knees-shoulders performance ($p = .034$). Parent education level did not significantly correlate with posttest ANS accuracy ($p = .241$).
**TEMA-3 Score in Low- and High-SES Groups**

![TEMA-3 Score in Low- and High-SES Groups](image1)

**Figure 2**

**PPVT-4 Score in Low- and High-SES Groups**

![PPVT-4 Score in Low- and High-SES Groups](image2)

**Figure 3**
Knower Level in Low- and High-SES Groups

Figure 4

ANS Accuracy in Low- and High-SES Groups
Question 2: What factors predict early math abilities?

We ran correlations in which we controlled for average parent education level in order to analyze the factors that predict early math abilities independent of SES. Pearson’s correlation coefficients are presented in Table 3.

Table 3
Partial Correlations, Controlled for Parent Education

<table>
<thead>
<tr>
<th></th>
<th>Knower Level at T1</th>
<th>ANS at T1</th>
<th>ANS at T2</th>
<th>TEMA at T2</th>
<th>PPVT at T1</th>
<th>PPVT at T2</th>
<th>HTKS at T2</th>
<th>Age at T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knower Level at T1</td>
<td>—</td>
<td>.478**</td>
<td>.670**</td>
<td>.406**</td>
<td>.314*</td>
<td>.244</td>
<td>.728**</td>
<td>.670**</td>
</tr>
<tr>
<td>ANS at T1</td>
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<td>—</td>
<td>.456**</td>
<td>.323*</td>
<td>.306*</td>
<td>.302†</td>
<td>.334</td>
<td>.611**</td>
</tr>
<tr>
<td>ANS at T2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>.566**</td>
<td>.307*</td>
<td>.457**</td>
<td>.652*</td>
<td>.550**</td>
</tr>
<tr>
<td>TEMA at T2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>.336*</td>
<td>.325*</td>
<td>.408*</td>
<td>.207</td>
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<td>PPVT at T1</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>.299</td>
<td>.315*</td>
<td>—</td>
</tr>
<tr>
<td>HTKS at T2</td>
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</table>

†  p < .08
*  p < .05
** p < .01
Our variable of interest, performance on the TEMA-3, was significantly correlated with knower level, ANS accuracy at both pre- and posttest, PPVT score at both pre- and posttest, and EF, before controlling for age.

We wanted to know which measures were correlated with one another even when age was partialled out, since older children would be expected to perform better across a range of measures. The results are presented with Pearson’s coefficients in table 4.

Controlling for age, ANS acuity at pretest no longer correlated with TEMA-3 score (p = .177), EF was no longer correlated with TEMA-3 scores (p = .091), and PPVT-4 score at posttest was only marginally correlated with TEMA-3 score (p = .053). TEMA-3 score was still significantly correlated with ANS accuracy at posttest, knower level, and PPVT-4 score at pretest.
Table 4

Partial Correlation, Controlled for Age and Parent Education

<table>
<thead>
<tr>
<th></th>
<th>Knower Level at T1</th>
<th>ANS at T1</th>
<th>ANS at T2</th>
<th>TEMA at T2</th>
<th>PPVT at T1</th>
<th>PPVT at T2</th>
<th>HTKS at T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knower Level at T1</td>
<td></td>
<td>0.140</td>
<td>0.464**</td>
<td>0.487**</td>
<td>0.429**</td>
<td>0.034</td>
<td>0.518*</td>
</tr>
<tr>
<td>ANS at T1</td>
<td></td>
<td>0.219</td>
<td>0.251</td>
<td>0.225</td>
<td>0.170</td>
<td>-0.050</td>
<td></td>
</tr>
<tr>
<td>ANS at T2</td>
<td></td>
<td>0.595**</td>
<td>0.380**</td>
<td>0.369*</td>
<td>0.445*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEMA at T2</td>
<td></td>
<td>0.391**</td>
<td>0.253</td>
<td>0.365</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPVT at T1</td>
<td></td>
<td></td>
<td>0.780**</td>
<td>-0.055</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPVT at T2</td>
<td></td>
<td></td>
<td></td>
<td>0.014</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† p < .08
* p < .05
** p < .01
We ran a hierarchical linear regression model to determine the relative predictive power of ANS accuracy, pretest PPVT-4 score, and pretest knower level. In our first step, we included only the background variables: age at pretest and average parent education. In each subsequent step, we added one variable, beginning with ANS accuracy, then PPVT-4, and finally knower level.

As seen in Table 5, after controlling for age and parent education, pretest ANS acuity does not significantly predict TEMA-3 performance as had been suggested in previous literature (Libertus et al., 2013). In step three, PPVT-4 does predict TEMA-3 scores. However, when knower level is added into the model in step four, it stands as a unique predictor. This suggests knower level is the strongest predictor of math abilities irrespective of SES.

---

3 We chose not to include EF in the model, as relatively few subjects completed the EF battery during post-test. Only a subset of our sample was tested on the EF battery, as it was not included in the original research design. Additionally, when preliminary analyses were performed with the subset of participants that completed the EF battery, the previously established predictors of math ability in this study were not significant. Later analyses will include EF.
Table 5

*Summary of Hierarchical Regression Analysis for Variables Predicting TEMA-3*

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td>.247</td>
</tr>
<tr>
<td>Age at T1</td>
<td>1.44</td>
<td>2.61</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>-1.47</td>
<td>2.82</td>
<td>-0.09</td>
<td></td>
</tr>
<tr>
<td>ANS at T1</td>
<td>0.16</td>
<td>0.11</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td>.075</td>
</tr>
<tr>
<td>Age at T1</td>
<td>2.73</td>
<td>1.35</td>
<td>0.27*</td>
<td></td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>0.10</td>
<td>0.11</td>
<td>0.08</td>
<td>0.38*</td>
</tr>
<tr>
<td>PPVT-4 at T1</td>
<td>0.17</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 3</strong></td>
<td></td>
<td></td>
<td></td>
<td>.082</td>
</tr>
<tr>
<td>Age at T1</td>
<td>-5.13</td>
<td>3.06</td>
<td>-0.32</td>
<td></td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>2.02</td>
<td>1.31</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>ANS at T1</td>
<td>0.10</td>
<td>1.00</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>PPVT-4 at T1</td>
<td>0.11</td>
<td>0.08</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Knower Level</td>
<td>2.49</td>
<td>1.01</td>
<td>0.44**</td>
<td></td>
</tr>
</tbody>
</table>

†  p < .08
*  p < .05
** p < .01
Question 3: Do predictors of math ability differ by SES?

Hypothesis 1: Vocabulary mediates the relationship between SES and math. We ran a series of models to investigate whether language mediates the relationship between SES and math abilities. Here, we treated SES as a part of our analyses rather than as a control variable. For pretest measures, we ran hierarchical regression models to determine whether the relationships between SES and knower level, and SES and ANS accuracy were mediated by vocabulary.

We hypothesize that the strong effect of SES on vocabulary may drive the consequent difference in knower level. To test this, we ran a hierarchical linear regression and found that average parent education and age together accounted for approximately 47.3% of the variance in knower level, confirming that SES is a significant predictor of knower level. However, when PPVT-4 is added into the model, education level is no longer a significant predictor of knower level. Vocabulary and age stand as the only unique predictors of knower level. Results are presented in Table 6.
Table 6

Summary of Hierarchical Regression Analysis for Variables Predicting Knower Level

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td>.492</td>
</tr>
<tr>
<td>Age at T1</td>
<td>2.06</td>
<td>0.30</td>
<td>0.69**</td>
<td></td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>0.39</td>
<td>0.19</td>
<td>0.21*</td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td></td>
<td></td>
<td></td>
<td>.089</td>
</tr>
<tr>
<td>Age at T1</td>
<td>1.40</td>
<td>0.36</td>
<td>0.47**</td>
<td></td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>0.20</td>
<td>0.19</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>PPVT-4 at T1</td>
<td>0.03</td>
<td>0.36</td>
<td>0.36**</td>
<td></td>
</tr>
</tbody>
</table>

† p < .08
* p < .05
** p < .01

SES predicted neither pre- or posttest ANS accuracy, controlling for age ($p = .09; p = .482$, respectively).

We also wanted to examine whether vocabulary mediated the relationship between SES and TEMA-3. We performed a hierarchical regression and confirmed that parent education accounted for approximately 14.1% of the variance in TEMA-3 scores. However, when we added PPVT-4 in the second block, the relationship between education level and TEMA-3 was only marginally significant, but vocabulary remained significant. Results are presented in Table 7.
Table 7

Summary of Hierarchical Regression Analysis for Variables Predicting TEMA-3

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
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<td></td>
<td></td>
<td>.162</td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>3.53</td>
<td>1.27</td>
<td>.040**</td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td></td>
<td></td>
<td></td>
<td>.089</td>
</tr>
<tr>
<td>Avg. Parent Ed.</td>
<td>2.547</td>
<td>1.30</td>
<td>.29†</td>
<td>0.29†</td>
</tr>
<tr>
<td>PPVT-4 at T2</td>
<td>0.23</td>
<td>0.11</td>
<td>.32*</td>
<td></td>
</tr>
</tbody>
</table>

† p < .08  
* p < .05  
** p < .01

Hypothesis 2: Vocabulary mediates the relationship between ANS and TEMA in low SES, but not high SES. To test our hypothesis of moderated mediation, we split our sample by education level, such that low-SES did not have a college degree (N = 25) and high-SES had a college degree or more (N = 31). We performed hierarchical regressions in each of the two groups, with TEMA-3 score as our dependent variable, and age and ANS accuracy as our independent variables in the first step, and adding PPVT-4 in the second step.

As seen in Table 8, in the low-SES group, ANS accuracy was initially a significant predictor of TEMA-3. However, when PPVT-4 was added into the regression, ANS accuracy was no longer a significant predictor. In the high-SES group, ANS accuracy was again a significant predictor of TEMA-3 score, and adding
PPVT-4 into the regression, ANS accuracy was still significant. Thus, vocabulary mediates the relationship between ANS and TEMA only in a low-SES group.

Table 8

*Summary of Hierarchical Regression Analysis for Variables Predicting TEMA-3 in low- and middle/high-SES groups*

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td>.219</td>
</tr>
<tr>
<td>Age at T2</td>
<td>-3.47</td>
<td>4.24</td>
<td>-0.21</td>
<td></td>
</tr>
<tr>
<td>ANS at T2</td>
<td>0.44</td>
<td>0.20</td>
<td>0.56*</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td>.041</td>
</tr>
<tr>
<td>Age at T1</td>
<td>-6.19</td>
<td>5.04</td>
<td>-0.37</td>
<td></td>
</tr>
<tr>
<td>ANS at T2</td>
<td>0.37</td>
<td>0.21</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>PPVT-4 at T2</td>
<td>0.12</td>
<td>0.12</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td>.366</td>
</tr>
<tr>
<td>Age at T2</td>
<td>-4.43</td>
<td>2.74</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>ANS at T2</td>
<td>0.54</td>
<td>0.17</td>
<td>0.73**</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td>.008</td>
</tr>
<tr>
<td>Age at T1</td>
<td>-3.37</td>
<td>3.61</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>ANS at T2</td>
<td>0.56</td>
<td>0.18</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>PPVT-4 at T2</td>
<td>-0.06</td>
<td>0.13</td>
<td>-0.14</td>
<td></td>
</tr>
</tbody>
</table>

†  p < .08
*  p < .05
** p < .01
Discussion

The goal of this study was to determine differing predictors of math abilities using a more inclusive and diverse sample than in previous literature. Our findings contribute to the literature by suggesting different mediators of the relationship ANS acuity and early math abilities in low- and high-SES children, as well as by qualifying findings in related literature on predictors of early math abilities.

Our first question asked whether there were SES disparities in each of our measures. Previous research has shown disparities in early math (Jordan & Levine, 2009) and language skills (Hart & Risley, 1995; Noble et al., 2005). We replicate both of these findings and found significant differences in TEMA-3 scores and PPVT-4 scores at both pre- and posttest, and additionally saw SES disparities in knower level and in ANS acuity at pretest, but not at posttest.

The narrowing of the gap in ANS accuracy from age 4 to age 5 may reflect improved attentional skills or understanding of directions, and further analysis may reveal that SES differences in ANS acuity at age 4 is actually an effect of vocabulary or EF. It may also reflect a role of schooling in improving ANS acuity. As most children tend to enter preschool between the ages of 3 and 4, most of the children in our study at pretest had spent little time in their preschool setting. Perhaps constant verbal and visual numeric input in preschool classrooms increases acuity, whereas home input might be more variable. Thus, early differences in ANS acuity across SES may arise as a product of in-home experience rather than classroom experience.

Previous research has suggested differences in both how and how much parents from low- and middle-SES families talk to their children (Hart & Risley,
1995; Lareau, 2003). As we found that pretest ANS acuity correlated with child vocabulary, it may be that individual differences in ANS acuity have some basis in language.

The effect of ANS acuity on math achievement has been contested. Some studies have suggested that ANS acuity is a strong and stable predictor and correlate of early math achievement, as well as of other symbolic math skills (review in Feigenson et al., 2013), whereas others have suggested that other factors, and not ANS acuity, predict early math abilities (Fuhs & McNeil, 2013; Gilmore et al., 2013).

We wanted to determine the strongest predictors of early math abilities, irrespective of SES. In further examining this disputed topic, we found that cardinal number knower level is the only significant predictor of early math abilities in preschool children of math abilities a year later, overshadowing both ANS accuracy and receptive vocabulary as other potential predictors. This has implications for further research and for early childhood education. For example, these findings motivate shifting the focus from ANS training paradigms (Hyde et al., 2014) to training cardinal number knowledge. However, there has been little research on training cardinality that can be used in preschools (Mix, Sandhofer, Moore, & Russell, 2012).

Given that we found significant SES disparities across measures of early numeracy and math skills, and that predictors of these school readiness-based math abilities were correlated differently than existing research suggests, we further examined possible models of mediation of the relationship between SES and math abilities. Here, we hypothesized two possible outcomes. Our first hypothesis
suggested that language mediates the relationship between SES and math. Previous research has found that amount of number words spoken to a child—specifically those in reference to present sets of 4-10 objects—predicts his or her cardinal number knowledge (Gunderson & Levine, 2011). Gunderson and Levine found that SES predicted both vocabulary and cardinal number knower level. We replicated these findings, and extend them to suggest that vocabulary mediates the relationship between SES and knower level such that more and/or higher quality number talk in the homes and classrooms of children from higher socioeconomic backgrounds as compared to their less privileged peers may engender greater math abilities across the board as they prepare to enter school. Though vocabulary itself was not a significant predictor of TEMA-3 scores, it may be that knower level emerges as a subset of general vocabulary. In accordance with this, we replicated Negen and Sarnecka’s (2012) finding that knower level is significantly correlated with general vocabulary. This in connection with Gunderson and Levine’s (2011) study suggests that there may be a causal influence of language, and specifically number-specific language input, on number. It may be that developing interventions—possibly in the form of lessons and curricula for preschool teachers, or games for parents to play with their kids—that highlight and attend to discussion of numbers may improve children’s cardinal number knowledge, which in turn may improve their math abilities. The development of these interventions for low-SES schools might markedly narrow the math achievement gap.

In following with the finding that vocabulary mediated the relationship between SES and knower level, and that knower level is the strongest predictor of
TEMA-3 score, we found that vocabulary mediated the relationship between SES and TEMA-3 scores, while neither knower level nor ANS accuracy effectively mediated this relationship. This further suggests that early academic math abilities are rooted in language abilities more than in abilities unique to numerical representations, such as approximate number discrimination.

We also sought to reconcile Fuhs and McNeil’s (2013) finding that the relationship between ANS and TEMA-3 scores are mediated by vocabulary and EF in a low-SES population with Libertus and colleagues’ (2013) finding that it is not mediated in a middle- and high-SES population. We hypothesized that mediators of ANS and math abilities would differ by SES because of in-home experiences. Fuhs and McNeil postulated that the strength of the association between ANS and TEMA-3 might depend on exposure to math-related stimulation, and numerous studies have found that children from low-SES families are not as regularly engaged with math activities as their middle- and high-SES peers (Bradley & Corwyn, 2002; Saxe, Guberman, & Gearhart, 1987).

Indeed, we found that in a low-SES group, concurrent vocabulary mediated the relationship between ANS and TEMA-3, but in a high-SES group, it did not. This may be a result of the significant gap in PPVT-4 score by group, which replicates findings of a previously established language gap (Hart & Risley, 1995). It may also simply be a product of the association of knower level with SES. Given that our findings suggest knower level is the strongest predictor of TEMA-3 score, controlling for SES, and that knower level correlates with vocabulary, it may be that the higher proportion of CP-knowers in the high-SES group can explain the lack of mediation.
We thus propose a model based on our data of the effect of SES on TEMA-3 scores. We suggest that SES affects math abilities through language and knower level. We saw significant SES differences in both vocabulary and knower level, but that vocabulary mediated the relationship between SES and knower level, but knower level did not mediate the relationship between SES and vocabulary. We also found that knower level was the strongest predictor of TEMA-3 scores. Our model is presented in figure 5.

Figure 5

*Proposed Model of the Effect of SES on TEMA-3*

Limitations

Certain limitations should be mentioned. First, and perhaps more importantly, we were not able to use EF in analyses at time of writing because so few participants had completed the EF battery. It is possible that EF may, as has been seen in previous studies, more effectively mediate the relationship between SES and math abilities (Fitzpatrick et al., 2014) or the relationship between ANS and math abilities (Fuhs & McNeil, 2013; Gilmore et al., 2013). It may also be that EF plays a unique role in the development of the ANS and/or the development of cardinality.

We also cannot account for preschool or home environment differences in our analyses. We recruited from a broad range of preschools—some
needs-based, some private, and some public—and cannot make a claim about individual differences that may have arisen as a product of school environment. We do not know whether various preschools used different curricula that prioritize certain skills over others, or whether the length of the school day had any effect on outcome measures. Similarly, we did not account for in-home differences. While we did measure SES, we were not able to investigate cases of single-parent homes, presence of a non-parental primary caregiver, or the amount of time a given parent was or was not in the home. Furthermore, we do not have measures of language input or number-specific language input from these sources.

One other finding that must be addressed is the sex difference in vocabulary. We found that, while all participants started with the same vocabulary as measured by the PPVT-4 at a mean age of 4.08, girls developed a greater receptive vocabulary over the course of a year, such that their PPVT-4 score was nearly 8 standardized points higher than boy’s. This is consistent in gender differences in language development, and may reflect a language capacity difference (Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991). However, while there is a possibility that the sex differences in vocabulary were partially responsible for our other findings, we did not control for sex in any of our analyses.

Conclusion

School readiness abilities—particularly math skills—are highly predictive of later academic achievement (Duncan et al., 2007), and academic success predicts greater health benefits, higher salaries, and a lesser chance of committing a crime (Nores, Belfield, Barnett, & Schweinhart, 2005; Freudenberg & Ruglis, 2007).
Children from socioeconomically disadvantaged families enter kindergarten with significantly lower math and verbal abilities than their socioeconomically advantaged peers. Our data motivate interventions in classrooms that attend to verbal abilities, especially those that focus on numeracy and cardinality. Enhancing number-specific verbal skills may reduce early disparities in math abilities. This may help to narrow the academic achievement gap and ensure the high educational attainment of our country’s children.
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Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. (2006). Non-symbolic arithmetic in adults and young children. *Cognition, 98*(3), 199-222.


Davidson, K., Eng, K., & Barner, D. (2012). Does learning to count involve a semantic
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What matters most? Examining socioeconomic disparities and predictors of early math ability

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Lange, R., Berkowitz, T., & Shusterman, A. (in prep). The role of language in the development of number concepts: evidence from and towards an understanding of oral deaf cognition.


What matters most? Examining socioeconomic disparities and predictors of early math ability

*Science, 14*(6), 1292-1300.


What matters most? Examining socioeconomic disparities and predictors of early math ability

psychology, 41(1), 49-100.


What matters most? Examining socioeconomic disparities and predictors of early math ability


Appendix A: Family Background Questionnaire

*Parent/Caregiver Information*  
Date: _________________

1. Who are your child’s primary caregivers? (Please list all below).

<table>
<thead>
<tr>
<th>Name</th>
<th>Relationship to Child</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Please mark the highest level of education obtained by you and your child's other parent/caregiver.

<table>
<thead>
<tr>
<th>Doctorate</th>
<th>You?</th>
<th>Second Caregiver?</th>
<th>Additional Caregiver?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor or Undergraduate Degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Associate's Degree/ Community College</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High school diploma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than high school diploma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No schooling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (specify ____________)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefer not to answer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. What is the current occupation for: You? ____________________________

Other parent(s)/Caregiver(s): ____________________________

4. Please write your total household income here: ____________________________

or mark your total household income below

- [ ] less than $10,000
- [X] $10,000 to less than $20,000
- [X] $20,000 to less than $30,000
- [X] $30,000 to less than $40,000
- [X] $40,000 to less than $50,000
- [X] $50,000 to less than $60,000

- [ ] $60,000 to less than $70,000
- [ ] $70,000 to less than $80,000
- [ ] $80,000 to less than $90,000
- [ ] $90,000 to less than $100,000
- [ ] more than $100,000
- [ ] Don’t know/Prefer not to answer
Child Information

5. How many total people live in your household? __________________

6. Does your child have any siblings? □ No  □ Yes (please list all siblings below)

<table>
<thead>
<tr>
<th>Date of Birth</th>
<th>Gender</th>
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</table>

7. What is your child’s racial/ethnic background?
   □ White/European American
   □ Latino/Hispanic
   □ African American/African
   □ Asian American/Asian
   □ Middle Eastern
   □ Mixed backgrounds, specify______________
   □ Other, specify ________________
   □ Prefer not to answer

8. Did your child attend a preschool or daycare center? □ No  □ Yes
   a. If yes, which?
      ______________________________________________________
   b. Approximately how many hours per week did your child spend in the preschool/daycare? ________________________________

9. Where does your child currently attend school?
    __________________________________________
    a. What grade is s/he in? ______________

10. What language(s) do you speak with your child at home? __________________________
    a. What was your child’s first language? __________________________