



REGISTERED REPORT

ManyNumbers 3: A Multi-Lab Study of Demographic Correlates of Early Number Knowledge

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ABSTRACT

Large scale studies have documented socioeconomic (SES) and racial/ethnic disparities in children's standardized math achievement at kindergarten entry. These early math skills predict future mathematics achievement and career success. However, limited research has been conducted using large sample sizes to understand how SES and race/ethnicity are related to children's numerical skills at even younger ages. The current study aims to investigate sociodemographic variability in three fundamental areas of early numeracy: nonverbal numerosity discrimination, rote counting, and cardinal number word knowledge. In addition, we will examine if the relations between numerical skills might be explained by their shared correlations to sociodemographic factors and if differences in numerical skills between sociodemographic groups can be explained by variability in working memory. Finally, we also investigate whether childcare attendance moderates early sociodemographic differences in numerical abilities. To achieve these goals, data from children aged 2; 6–6; 0 will be gathered from ~ 45 US sites, drawn from a larger multi-lab international project (ManyNumbers project). The findings of this research will enhance our understanding of early emerging variability in numerical skills and provide insights into developing responsive and inclusive educational practices that support diverse learning needs in the early years.

1 | Introduction

Individual differences in math achievement in middle and high school are related to core numerical skills that emerge early in development (e.g., Ahmed et al. 2019; Duncan et al. 2007; Watts et al. 2014). According to previous studies, these differences are also related to the socioeconomic status (SES) and racial/ethnic background of children (Bai et al. 2021; Broer et al. 2019; Chmielewski 2019; Davis-Kean and Jager 2014; Hanushek et al. 2022; National Research Council 2009; Reardon 2011; Reardon et al. 2014; Reardon and Portilla 2016). Although previous studies have documented relations between demographic factors and overall math scores as early as kindergarten entry (Fryer and Levitt, 2004; Georges and Pallas 2010; Lee et al. 2007; Reardon and Portilla 2016), little is known about when and how relations between sociodemographic factors and specific numerical skills first arise in development (Bachman et al. 2022; Davis-Kean et al. 2022; Elliott et al. 2022; Scheuer et al. 2019).

In the present study, we deploy data from 45 US sites collected as part of the ManyNumbers project (Abreu-Mendoza et al. *n.d.* accepted in principle), including approximately 1000 children aged 2;6–6;0. In particular, we focus on three broad questions. First, we investigate how family SES and the racial/ethnic background of children are related to three numerical skills that are core to early numeracy: nonverbal discrimination of numerosities, rote counting skill, and cardinal number word knowledge. We are interested in how these different skills are related to one another. That is, how individual differences in some numerical skills are related to differences in other skills, especially in relation to sociodemographic factors like SES and race/ethnicity. Second, if factors like SES and race/ethnicity are

related to variability in early numerical skills, we ask whether such relations might be explained in part by individual differences in working memory. Finally, in a similar spirit, we ask how such correlations between numerical skills and SES, race/ethnicity might be moderated by experience in center-based childcare.

By taking this approach, we aim to investigate not only how core numerical skills are related to sociodemographic factors in early childhood, but also to address the theoretical question of how these skills interact, and why they are often interrelated in development. Are skills that require explicit training, like rote counting, more highly related to factors like SES or experience in center-based childcare, relative to, for example, the ability to perceive number in visual arrays? Are some skills more strongly constrained by individual differences in working memory than others? When SES is related to numerical skills, can this be explained by other factors, such as working memory or center-based childcare? In this study, we explore these questions, and the broader question of how sociodemographic variability relates to the emergence of core numerical skills in early childhood.

1.1 | Early Number Skills and Their Correlates

1.1.1 | Nonverbal Discrimination of Numerosities

Beginning in infancy, humans represent large approximate magnitudes using an Analog Magnitude System (AMS), which allows for reliable discrimination of arrays of objects, sounds, and events. In this system, the amount of error in a representation increases with magnitude (Cordes et al. 2001; Gibbon 1977) such

Summary

- Early mathematical skills are crucial for long-term academic and career achievement. SES and race/ethnicity-related disparities in math achievement emerge as early as preschool.
- Most studies use standardized math assessments that combine different numerical skills to assess achievement gaps, leaving uncertain which specific skills vary with demographic variables.
- We explore disparities in developmentally significant numerical skills and their relation to demographic variables. We also report relations between WM, childcare attendance and numerical skills.
- Data from approximately $N = 1080$ children aged 2;6–6;0 will be collected from ~ 45 US labs, including demographic information and numeracy measures.

that accuracy in comparing two sets depends on their ratio, rather than the absolute difference between them (Moyer and Landauer 1967; Treisman 1964). Previous studies find that the acuity of AMS representations increases throughout childhood into adolescence. For example, newborn infants discriminate magnitudes that differ by a 3.0 ratio while this ratio improves to 1.1 for teenagers (Feigenson 2011; Halberda and Feigenson 2008; Izard et al. 2009; Lipton and Spelke 2003; McCrink and Wynn 2007; Wang and Feigenson 2021; Xu and Arriaga 2007; Xu and Spelke 2000). By some accounts, individual differences in AMS acuity are related to later mathematics achievement both in children and adults (Bonny and Lourenco 2013; DeWind and Brannon 2012; Halberda et al. 2008; Inglis et al. 2011; Libertus et al. 2013; Lyons and Beilock 2011). Although some studies question this relation (Inglis et al. 2011; Price et al. 2012; Sasanguie et al. 2014), meta-analyses reveal small to moderate correlations between nonsymbolic number ability and math achievement both concurrently and longitudinally (Chen and Li 2014; Fazio et al. 2014; Schneider et al. 2017, though see Qiu et al. 2021).

A small number of studies have investigated the relation between AMS representations and sociodemographic factors such as SES and race/ethnicity, though these studies have typically been limited in sample size and geographic scope. For example, Bachman et al. (2022) analyzed data from nearly 150, 4-year-olds from the Pittsburgh area and observed a significant correlation between family SES and AMS acuity. They also found that Black and Hispanic children exhibited lower AMS acuity compared to their White peers when controlling family SES, age, and parental marriage status. Similarly, in a study of approximately 500 children from Orange County, CA, Sarnecka et al. (2023) found a small but significant relation between AMS acuity and SES. Other studies, however, have failed to find correlations between demographic factors like parental education and AMS acuity in preschoolers (Purpura and Simms 2018; Scalise et al., 2017; Slusser et al. 2019; vanMarle et al. 2014). No previous study has tested a large national sample of preschool-aged children to investigate the relation between AMS acuity and demographic factors like SES and race/ethnicity.

1.1.2 | Rote Counting Skill

Many children begin learning to count at around age 2 years and can count to 10 by 4 years of age (Cankaya et al. 2014; LeFevre et al. 2002; Sarnecka and Carey 2008). Initially, children recite the count list like the alphabet, as a rote sequence that lacks semantic content (Briars and Siegler 1984; Fuson et al. 1982; Le Corre and Carey 2007; Miller et al. 1995; Wynn 1990, 1992). This ability is often measured using the Highest Count task, in which children are asked to count as high as they can and the researcher records the highest number reached before the child makes an error. This measure—and other measures of rote counting fluency—is correlated with a wide range of numerical abilities, such as the acquisition of number word meanings (Marchand et al. 2022; Marušić et al. 2016), reasoning about relations between numbers (Cheung et al. 2017; Davidson et al. 2012), and later math achievement in elementary school (Koponen et al. 2013; Martin et al. 2014; Nguyen et al. 2016).

Multiple studies of US preschoolers find a significant relation between rote counting ability and SES, though these effects tend to be small, and based on relatively small sample sizes (Elliott et al. 2022; Saxe et al. 1987; Starkey et al. 2004). Meanwhile, almost no research has investigated how rote counting skill is related to race and ethnicity. In one study of kindergarten children that included a measure of counting, correlations due to race were reported but disappeared once covariates like SES, maternal age at first birth, and home environment were controlled (Fryer and Levitt, 2006). However, to our knowledge, no previous study has investigated whether effects due to race/ethnicity exist prior to commencement of formal education.

1.1.3 | Cardinal Number Word Knowledge

Although many children begin to recite number words by age 2, they do not associate these words with meanings until later, and do so in a gradual, protracted, fashion. Using the Give-a-Number task, in which children are asked to give different numbers of objects, Wynn (1990, 1992) found that children learn the meanings of the words “one,” “two,” and “three” in order, over the course of many months. First, they learn the meaning of “one” and can reliably give exactly one object, at which point they are often described as 1-knowers. After this, children require an additional 3–6 months to learn the meaning of “two,” then additional time to learn “three,” and sometimes “four,” and are called 2-, 3-, and 4-knowers respectively. Finally, after learning these first few numbers one at a time, children learn to use counting to label and construct larger sets, and at this point are often called cardinal principle-knowers (CP-knowers).

Several previous studies have investigated how number word learning is related to demographic factors, including race/ethnicity and SES. For example, Bachmann et al. (Bachman et al. 2022) found that SES was related to 4-year-olds’ performance on the Give-a-Number task, and that there were no additional differences due to race/ethnicity (see also Sarnecka et al. 2023; Scheuer et al. 2019). Relatedly, children’s understanding of counting principles,¹ which are thought to contribute to Give-a-Number performance, have also been found to vary by SES (Jordan et al. 2006). In contrast, Elliott et al. (2022) found no

relation between SES and Give-a-Number performance among 2-year-old children, though most parents in the study had undergraduate and graduate degrees, potentially limiting the study's ability to detect effects of SES. Finally, a large-scale study of over 3000 low-income children found a relation between race/ethnicity and number word knowledge (Manfra et al. 2014). In particular, they found that 3–5-year-olds identified as non-Hispanic and non-Black had the highest scores on a measure of number word meaning, followed by Black children and then Hispanic children. However, this study did not evaluate SES, and whether it might explain effects due to race/ethnicity.

1.2 | Relations Between Core Numerical Skills

Nonverbal number discrimination, rote counting, and cardinal number word knowledge are theoretically important because they measure constructs that form the core of early numeracy that emerge serially in the preschool period, are conceptually minimally overlapped but interrelated to each other (Cantlon et al. 2010; Geary et al. 2018; Moura 2026; Opfer et al. 2010; Piazza 2010; Starr et al. 2013; Wagner and Johnson 2011), and have been shown to be predictive of later math performance (see Nogues and Dorneles 2021, for a review). Nonverbal discrimination of numerosities is an ability humans are born with, which supports children's discrimination of quantities, and their intuitive understanding of ordinal relations and arithmetic operations (Feigenson et al. 2004), and may prepare their later acquisition of formal math skills (Chen and Li 2014; Fazio et al. 2014). Rote counting skill, on the other hand, typically develops around 2 years of age and can be taken as an indicator of number-related language input since children initially recite the count list like the alphabet, as a rote sequence that lacks numerical meanings (Briars and Siegler 1984; Fuson et al. 1982; Le Corre and Carey 2007; Miller et al. 1995; Wynn 1990, 1992). Finally, cardinal number word knowledge represents a major milestone in symbolic math learning, in which the rote count list is integrated with nonverbal numerical content, sometime between 3 and 5 years of age (Wynn 1990, 1992).

A substantial literature has investigated how the three component skills to be tested in the current study might be related (Cantlon et al. 2010; Opfer et al. 2010; Piazza 2010; Starr et al. 2013; Wagner and Johnson 2011). Some studies have reported significant correlations between the measures of the AMS and cardinal number knowledge (Mussolin et al. 2012; vanMarle et al. 2018; Wagner and Johnson 2011), while others have argued against such relations (Hyde et al. 2017; Negan and Sarnecka 2012; Soto-Calvo et al. 2015). Meanwhile, past studies have repeatedly found correlations between mastery of rote counting and cardinal number knowledge, raising the possibility that individual differences in rote counting ability may be more important to predicting cardinal number word learning than individual differences in cognitive skills like the AMS (Almoammer et al. 2013; Marchand et al. 2022; Marušić et al. 2016). What is less clear, however, is what explains these correlations, and to what degree they might be explained by sociodemographic factors, which, as already shown, might also be related to each component skill.

To begin to explore this question, in the present study we first ask which aspects of early numeracy are most strongly related

to sociodemographic factors—a question that remains unresolved due to inconsistent findings in the existing literature. Specifically, we will test whether skills that rely on exposure to number-related learning opportunities, like rote counting and cardinal number word knowledge, are more sensitive to sociodemographic factors than skills that are not explicitly trained in early childhood, like AMS acuity, an ostensibly perceptual skill. Then, we will test if numerical skills that are more related to sociodemographic factors are also more related to each other (i.e., the relation between rote counting and cardinal number word knowledge than each of these two skills' relation to AMS acuity) and how sociodemographic factors may explain relations among three numerical skills (if they exist). To achieve this goal, we will also conduct exploratory confounding analyses to examine whether SES or race/ethnicity explains the relation between numerical skills.

1.3 | Beyond Simple Correlations Between Early Number Skills, SES and Race/Ethnicity

Given the inconsistent findings regarding the associations between sociodemographic factors and three numerical skills, a central goal of the present study is to clarify whether early number skills are related to SES and race/ethnicity using a larger sample and more standardized measurements. However, to understand these relations, it is crucial to measure not only simple correlations, but also other factors that might explain them. Below we describe three ways in which simple correlations between early numerical skills and SES and race/ethnicity may be impacted by additional factors. In particular, we investigate (1) whether effects of race and ethnicity might be subsumed by effects due to SES, (2) whether relations between early numerical skills and SES and race/ethnicity can be explained by their shared association with domain-general working memory, and (3) whether such relations are weaker in children who attend center-based childcare (e.g., preschool).

1.3.1 | The Intersection Between SES and Race/Ethnicity

While race and ethnicity have been related to individual differences in mathematics achievement, some previous studies have argued that these may be explained by family SES (Charles et al. 2007; Mandara et al. 2009). Indeed, disparities in math performance may be related to sociodemographic factors and may increase over time (Baumert et al. 2012; Cameron et al. 2015; Caro et al. 2009; Hooper et al. 2010). However, some studies have found that much of the variance may be explained by correlated factors such as discrimination and low-quality education (Cameron et al. 2015; Conwell 2021; Crowder and Downey 2010; Fryer and Levitt, 2004; Grimm 2008; Hanushek and Rivkin 2006; Henry et al. 2019; Osborne 1997; Owens and Tom 2024; Paschall et al. 2018; Reardon et al. 2015; Reardon and Galindo 2009; Schmidt et al. 2021; Vanneman et al. 2009), and that the role of family SES itself may actually decline (Conwell 2021; Fryer and Levitt, 2004; Quinn 2015). For example, Fryer and Levitt (2004) found that among kindergarteners, family SES explained about 40% of the difference between Black and White children, whereas Conwell (2021) found that by high school it explained only 20% of this difference. Finally, previous research also finds that household income

moderates differences between Black and White children's math achievement, with some finding a greater difference among high-SES individuals (Lubienski 2002) and others reporting the opposite (Belkhir et al. 1995; Henry et al. 2020).

1.3.2 | Early Numeracy and Working Memory

What might explain relations between demographic variables like SES and race/ethnicity and early numerical skills? One possibility is that such relations are mediated by differences in executive functioning. A growing number of studies have associated mathematical skills with individual differences in executive functions, including inhibitory control, working memory, and cognitive flexibility (Ellefsen et al. 2020; Finders et al. 2021; Fitzpatrick et al. 2014; Friso-Van den Bos et al. 2013; Gordon et al. 2021; Lawson and Farah 2017; Lee and Bull 2016; Nguyen and Duncan 2019; Passolunghi and Costa 2016; St Clair-Thompson and Gathercole 2006; Van der Ven et al. 2012; Waters et al. 2021; Welsh et al. 2010; Willoughby et al. 2019). Evidence from large-scale studies suggests that, among these measures of executive functioning, working memory, measured at preschool or kindergarten, is the strongest predictor of math performance in primary school and middle school (Bull et al. 2008; Nguyen and Duncan 2019; Watts et al. 2014; also see Cortés Pascual et al. 2019, for a review). In particular, complex-span tasks that involve interference (e.g., performing a secondary task during encoding or processing distractors during retrieval) tend to show stronger correlations with math performance compared to simple span tasks (e.g., backward digit/block/word recall; see Conway et al. 2005; Peng et al. 2016; Unsworth and Engle 2007 for a review). Together, these findings suggest that a combination of short-term storage and executive functioning components explain important variance in math performance.

Although previous studies support a positive relation between working memory and early math achievement (Gordon et al. 2021; Purpura et al. 2017; Waters et al. 2021), they disagree over which math skills working memory is related to. Some studies have found positive correlations between measures of working memory and rote counting in 5–8-year-olds (Cirino 2011; Koponen et al. 2016; Koponen et al. 2018; Noël 2009; Passolunghi and Lanfranchi 2012; Simanowski and Krajewski 2019). Others have found that working memory may explain variability in preschoolers' cardinal number knowledge, as measured by the Give-a-Number task (Gordon et al. 2021) and the How Many task² (Cirino 2011), though some studies have argued that these skills are only weakly related to working memory during the preschool years (Purpura et al. 2017). Finally, some studies have found relations between visual working memory and AMS acuity at age 5 (Daubert and Ramani 2019), and that such correlations persist longitudinally, and exist in children as old as age 6 but not older children (Cirino 2011; Costa et al. 2011; Li et al. 2024; Ouyang et al. 2021; Skagerlund et al. 2024).

Critically, previous studies find that individual differences in working memory are related to both SES and racial/ethnic identity from preschool through middle school (Akhlaghipour and Assari 2020; Hackman et al. 2015; Lee and Bull 2016; Leonard et al. 2015; Little 2017; Noble et al. 2007; Philbrook et al. 2017). This

raises the question of whether working memory might explain differences in math achievement between different SES and race/ethnicity groups. For example, one previous study reported that, after controlling for verbal ability, baseline academic skills and other child- and family-level covariates, working memory mediated an association between parent education and children's arithmetic skill in first grade (Waters et al. 2021). Similarly, a study of 7–9-year-old Chinese children found that working memory and cognitive flexibility together fully mediated a relation between SES and math achievement (Poon et al. 2022). Thus, working memory may serve as a more proximal cause of variability in early numeracy, with environmental factors related to race/ethnicity and SES more distally related. Given the relatively stable correlation between sociodemographic factors and working memory from 2 months to 18 years of age (see Mooney et al. 2021; Nugroho et al. 2023 for a review), and given that sociodemographic disparities in math performance increase with child age (Baumert et al. 2012; Cameron et al. 2015; Caro et al. 2009; Hooper et al. 2010), working memory may explain a larger proportion of sociodemographic-related variation in children's math performance earlier in life. By comparing to what extent working memory mediates the relation between sociodemographic factors and different numerical skills, we address whether different explanations are merited for each component skill. For example, full mediation by working memory would imply a common underlying mechanism, with differences in association strength between sociodemographic factors and different numerical skills stemming from differences in working memory demands across numerical skills. In contrast, partial or null mediation would instead point to distinct pathways for each numerical skill.

1.3.3 | Early Numeracy and Center-Based Childcare

Given the persistent finding that mathematics achievement is related to SES and race/ethnicity (Bai et al. 2021; Broer et al. 2019; Chmielewski 2019; Hanushek et al. 2022; Reardon et al. 2014; Reardon and Portilla 2016), an important question is whether learning environments outside the home can mitigate differences between groups. Previous studies find that children who enroll in center-based childcare exhibit stronger language and quantitative skills relative to peers from similar backgrounds who experience home-based care (Ansari and Winsler 2012; Austin et al. 2011; Bassok 2010; Connell and Prinz 2002; cf. Baydar and Brooks-Gunn 1991; Votruba-Drzal et al. 2004). High quality childcare also appears to moderate risks associated with low income and low maternal education on math achievement during middle childhood (Dearing et al. 2009) and predicts higher high school completion rates at age 20 (Reynolds et al. 2004).

Previous studies debate whether relations between center-based childcare and cognitive outcomes vary by SES and race/ethnicity. Both the ECLS-K (Magnuson et al. 2007) and the National Longitudinal Survey of Youth (Caughy et al. 1994) report significant relations between prekindergarten or daycare attendance and math performance at kindergarten, especially for children from low-SES families. Using data from the Cost, Quality and Outcomes study (1995), Peisner-Feinberg and Burchinal (1997) found no moderating effect of maternal educational level on

the relation between childcare quality and pre-math scores measured at 4 years of age. Nevertheless, follow-up analyses that examined longitudinal math development from 4 to 8 years of age demonstrated a larger relation between childcare quality and children's math skills for children with mothers of lower educational level, an effect which remained consistent over time (Peisner-Feinberg et al. 2001).

1.4 | The Present Study

In the present study, we will explore how SES and race/ethnicity are related to three measures of early childhood numeracy: (1) the Dot Comparison task (nonverbal discrimination of numerosities), (2) the Highest Count task (rote counting), and (3) the Give-N task (cardinal number word knowledge), and whether SES and race/ethnicity explain interrelations between core numerical skills. In addition, we will explore whether relations between core measures of numeracy and SES and race/ethnicity are explained by working memory as well as how these outcomes are moderated by exposure to center-based childcare. Taking this approach we will ask the following questions:

1. **Relation Between SES, Race/Ethnicity, and Early Numeracy:** First, how are SES and race/ethnicity independently related to early numerical skills including nonverbal discrimination of numerosities, rote counting skills, and cardinal number word knowledge? Second, to what extent do SES and race/ethnicity interact with each other in predicting these skills?
2. **Relations Between Numerical Skills:** For each pair of numerical skills that show significant associations with one another and with sociodemographic variables, is their relation explained by confounding variables such as SES and race/ethnicity?
3. **Effects of Working Memory:** If SES and race/ethnicity are related to variability in early numerical skills, are these relations explained by their shared covariance with individual differences in working memory, or do these factors explain independent variance?
4. **Effects of Center-Based Childcare:** How is exposure to center-based childcare related to individual differences in early numerical skills? Does exposure to center-based childcare moderate the relations between different early numerical skills and demographic factors of SES and race/ethnicity?

By comparing how each component of early numeracy is related to sociodemographic variables, working memory, and center-based childcare, we can ask whether numerical skills might differ in their sensitivity to socioeconomic environment, access to numerically-relevant learning opportunities, or differences in domain-general cognitive capacity. Are symbolic skills like rote counting and cardinal number knowledge more related to differences in center-based care or SES than AMS acuity, or are such nonsymbolic skills equally related to sociodemographic factors? Do differences in the three numerical skills' susceptibility to sociodemographic factors explain why their interrelations vary?

2 | Method

2.1 | Participants

The current study is a part of the ManyNumbers project exploring children's early development of numerical skills, which involves participating sites across the world (Abreu-Mendoza et al. [n.d.](#) accepted in principle). Currently, 161 sites have joined, with sites potentially being added or dropping out over time, though we expect the final count to be around this number. In the present study, we will analyze ManyNumbers data collected from US sites and add to this an examination of how demographic factors are related to early numeracy in the US context. Each site will contribute data from at least 24 children between 2 years 6 months and 6 years 0 months, including at least 12 children under 3 years 6 months of age and 12 children over this age. Participants may be recruited from and tested in preschools, childcare centers, museums, libraries, in their homes, in laboratories or other IRB-approved locations with \$15/participant offered to sites as reimbursement.

To be included in data analyses for the current study, we will require that children (a) complete at least one of the three tests of numeracy (i.e., Dot Comparison, Highest Count, and Give-N tasks), (b) be within the age range of 2 years 6 months–6 years 0 months, (c) have no report of developmental disorder according to caregiver or teacher report, (d) to have at least one demographic variable needed for the calculation of the weighted SES index or the measure of race/ethnicity, and (e) to be proficient in the language of their testing site, such that they can follow verbal instructions. Children who fail to provide any responses in the Highest Count task, and at the same time fail the practice blocks of both Dot Comparison and Working Memory tasks—which involve extended verbal instructions—will be excluded, as per the protocol of Abreu-Mendoza et al. [n.d.](#) (accepted in principle).

2.2 | Power

Hierarchical models were used to construct power simulations for the entire project, which made it possible to account for within-site replications of previously reported effects and to detect varied effect size estimates across sites. With sites being the grouping variable, a random intercept model with one continuous variable, to simulate the effect of SES and working memory (WM), and one binary variable, to simulate the effect of race/ethnicity, childcare attendance etc., as well as their interactions as fixed effects was compared to random intercept models with each fixed effect removed. The variance of the random intercepts and the fixed coefficients were varied in simulations to test their impact on the power to detect fixed effects. Each simulated data set was fitted to the following random intercept model: $Y_{ij} = \beta_0 + b_i + \beta_1 N(0,1) + \beta_2 \text{Bin}(1, 0.15) + \beta_3 N(0,1) \text{Bin}(1,0.15) + \epsilon_{ij}$, where i denotes lab, j denotes a participant within a lab, b_i is the random effect, β_0 is the mean intercept value, which has been set to 0 in the simulated model, β_1 is the mean slope value of the normalized continuous variable, β_2 is the mean slope value of the binary variable that has 15% occurrences of "1," and β_3 is the mean slope value of the interaction term. The null hypothesis $\beta_k = 0$ ($k = 1, 2, 3$), was tested with the R package *simr* (Green and MacLeod 2016). The results of 1000 simulations showed that with 24 participants per

site and 30 sites in total, we will have ample power (> 0.80) to detect small to medium effect size ($\beta_k = 0.3$, Cohen's $f^2 = 0.08$, 0.03, and 0.02 for continuous variable, binary variable and their interaction respectively) of demographic variables on cognitive measures and random effect ($ICC = 0.3$).

2.3 | Assessments and Measures

All measures in this study are identical to those described by Abreu-Mendoza et al. [n.d.](#) (accepted in principle), and data from that study will be subjected to novel analyses here, focused on analyses of demographics, which are not analyzed in Abreu-Mendoza et al. [n.d.](#)

First, caregivers for all participants will be asked to provide the following demographic information (see Appendix 1 for complete form): (1) child's date of birth, (2) gender, (3) race and/or ethnicity, (4) their primary language and whether they are multilingual, (5) the type of institution they attend (daycare, pre-kindergarten/preschool, kindergarten, and other), and total months they have spent at them, (6) the number of people who live in the household, (7) the combined annual gross income of all members living in the household, (8) the gender and education level of up to two primary caregivers.

All participants will be asked to complete four tasks in the following order: (1) the Give-N task, (2) the Highest Count task, (3) the Dot Comparison task, and (4) the Visual Memory task. Children's caregivers will be asked to complete a demographics form, as described above. Children will be tested in person, one at a time in the language of their testing site, which we expect to be either English or Spanish in most cases. Children will complete the tasks in one or two sessions, no more than two weeks apart, with a total expected duration of approximately 45 min. Computerized tasks (Dot Comparison and Visual Memory tasks) will be implemented in PsychoPy v2022.2.5 (Peirce et al. 2019). Display size and device will vary depending on the location. Here we provide an abbreviated description of experimental methods; a detailed description can be found in Appendix 2 of the current report and in Abreu-Mendoza et al. [n.d.](#) (accepted in principle). A full set of stimuli, materials, and translations for all tasks will be available at: <https://osf.io/e4xb7/>.

2.3.1 | Give-N Task

As described in Abreu-Mendoza et al. [n.d.](#) (accepted in principle), a non-titrated version of the Give-N task will be used to assess children's knowledge of number word meanings. On each trial, children will be presented with 20 identically colored plastic ducks and a small plate or container and will be asked to "put N" on the plate with the noun of "ducks" omitted from the request (Almoammer et al. 2013; Marušić et al. 2016). Each child will be asked to give 1, 2, 3, 4, 5, 6, 8, and 10 ducks three times each in pseudo-randomized order.

2.3.2 | Highest Count Task

Children will be asked to count as high as they can, and the experimenter will record the highest number they reach before (1)

an error is made, (2) the child stops and refuses to count higher if prompted, or (3) 120 is reached.

2.3.3 | Dot Comparison Task

Children's ability to discriminate the magnitudes of large sets without counting will be measured with a computerized two-alternative forced-choice nonsymbolic number comparison task. A blue and a yellow dot array will be presented side by side on the screen for 2000 ms and the children will be asked to indicate which array has more dots. After taking two demonstrative sample trials and six practice trials with easy number ratios of 3.5 and 4.0 and feedback, children will advance to the test phase. The test session includes three blocks of 16 trials with no feedback. Each block will feature four trials of each of the four ratios, which will overlap partially across three age groups. Three-year-olds and younger will see ratios of 3.0, 2.5, 2.0, and 1.5. Four-year-olds will see ratios of 2.5, 2.0, 1.5, and 1.25. Five-year-olds will see ratios of 2.0, 1.5, 1.25, and 1.17. Average individual dot diameter, cumulative surface area, and cumulative perimeter each will be equated on one third of the trials. Within each type of control, convex hull will be equated in half of the trials and free to vary in the other half.

2.3.4 | Visual Memory Task

In this task, children will be asked to remember a series of familiar objects (Hartshorne 2008; Quirós-Godoy et al. 2022; Wechsler 2012). During the encoding phase, children will be shown 1, 2, 3, or 4 target pictures that are frequent in young children's vocabularies (e.g., ear, button, and banana). Depending on the number of targets, objects will appear on the screen for either 3 or 5 seconds. Next, during the probe phase, children will be shown a second set of pictures containing the target picture(s) from the encoding phase and 1–6 distractors. They will be asked to point to the images they saw during the encoding phase. Participants will complete a maximum of 34 experimental trials, divided into four blocks with increasing difficulty. To progress to the next block, participants must correctly answer at least 33% of the trials on the prior block. We chose to measure children's memory span in the presence of distractors, rather than using a simpler recall task such as an N-back, because identifying targets among distractors places greater demands on attentional control and interference resolution, which are believed to explain additional variance in children's numerical performance, beyond what is accounted for by the information maintenance and updating components of working memory (Conway et al. 2005; Peng et al. 2016; Unsworth and Engle 2007).

2.4 | Variable Coding

2.4.1 | Demographic Measures

All categorical variables will be dummy coded. For gender, male will be coded as 0 while female will be coded as 1. If sufficient data allow, we may also conduct exploratory analyses of additional genders (e.g., nonbinary). Analyses of race and/or ethnic group will focus on comparisons of Black, Hispanic/Latino, and White children and other groups that constitute more than 15% of the

sample (to ensure sufficient power). Participants who identified as more than one race/ethnicity and categories other than the above mentioned groups will be pooled together to create a new category of “Other,” (Reardon and Portilla 2016) though we will report descriptives for all groups (including different combinations of multiple races/ethnicities) with sample sizes larger than 10. For race/ethnicity, White will act as the statistical reference group, with dummy coding for Black, Hispanic/ Latino, and additional groups that constitute at least 15% of our sample. For primary language, English will be coded as 0 while non-English will be coded as 1. All continuous variables will be centered. Age will be measured in months from the date of testing. To compute parental education, the highest grade or degree of each parent will be converted into years of schooling (Sutin et al. 2017).³ Income-to-needs ratio will be approximated with the ratio of household income (coded as the lowest income of each interval) divided by poverty guideline for the family size (coded on an interval scale of 1–8). Both our measures of income and education are expected to approximate continuous and normal distributions. If this assumption is violated due to high skewness, we will instead use polychoric PCA, which treats these variables as ordinal. We will construct a weighted SES index by using the loadings onto the first principal component extracted from the principal component analysis of highest educational attainment (Davis-Kean 2005; Reardon 2011) of two caregivers (or the attainment of the single caregiver if only one is present) and income-to-needs ratio. We will also report the zero-order correlations of both caregivers’ education, income-to-needs ratio, as well as other demographics and cognitive measures. Previous studies showed that a single extracted component can explain about 70% of the variance in indicators like education, income, and occupation (Noble et al. 2007; Gunderson et al. 2018). If fewer than 10% of the data are missing for either of these two indicators, mean substitution technique will be used, since previous research shows minimal impact of imputation methods with missingness lower than 10% (Xiao et al. 2019). If more than 10% of data are missing, we will consider using multiple imputation to prevent estimation bias and preserve variance and covariance structure (Schafer and Graham 2002; Xiao et al. 2019). Total time spent in center-based childcare will be computed by summing months spent in all childcare (i.e., daycare, preschool/prekindergarten, or kindergarten) together. If we find more than 10% missing data in the measurement of duration,⁴ we will recode childcare attendance as 0 if the child has never experienced any childcare and 1 if the child has attended any of the three center-based childcare settings before.

2.4.2 | Cognitive Measures

Give-N Task. For primary analyses, children’s performance on the Give-N task will be measured as the proportion of correct trials to the number of trials completed (give_n_accuracy). Trials will be included in computing the overall accuracy only if all trials within a block were completed.

Highest Count Task. The highest number children reach before any error or omission will be log transformed (highest_count) because data from numberbank.org have shown it has nonlinear relations with other variables like age before transformation (Abreu-Mendoza et al. n.d. accepted in principle).

Dot Comparison Task. We will measure children’s nonsymbolic number discrimination acuity primarily with accuracy (i.e., proportion of correct trials) in the ratios that are common across all ages (1.5 and 2.0) (ams_accuracy) in our main analysis. Weber fraction (DeWind et al. 2015) will only be used in the exploratory analysis because our pilot studies find that it is not always possible to compute reliable Weber fraction estimates for participants with low accuracy (ams_weber).

Visual Memory Task. The number of trials on which children select all of the target pictures and none of the foil pictures will be used as a measure of visual memory task performance (vm_score).

2.5 | Statistical Models

Bayesian multilevel modeling (MLM) with random intercept and random slopes will be used to test our hypotheses with the brms package (Bürkner 2017) in R (Team 2010). If a model does not converge, we will follow standard pruning strategies (remove random slopes first and then random intercepts; The ManyBabies Consortium et al., C. et al. 2020). In the models described below, i represents the group index while j represents each subject tested at a site. Credible intervals of fixed effects will be constructed to test whether the relation between the predictors and the outcome variables is significant while credible intervals of variances of random coefficients will be examined to decide whether the effect of predictors vary by test sites.

All models will assume a normal distribution of task performance scores with the mean predicted by different predictors based on different hypotheses. The random coefficients are assumed to follow the common multivariate normal distribution with hyperparameters β_k and covariance matrix $\mathbf{T}$. Conjugate priors will be used for mean coefficients β_k , variances of coefficients τ_k as well as variances of outcome variable σ^2 so that the posterior distributions will be proper and in known forms. $\mathbf{T}$ is the covariance matrix of coefficients that can be decomposed into a correlation matrix and scaling matrices (Bürkner 2017). A non-informative LKJ prior with the shape parameter = 1 (default of brms) will be used as the prior distribution of the correlation matrix in a LKJ prior, which corresponds to a uniform distribution of the correlations where all correlation matrices are equally likely. If $\eta > 1$, extreme correlations become less likely, whereas $0 < \eta < 1$ results in higher probabilities for extreme correlations (Bürkner 2017).

Data Model:

$$Y_{ij} \sim N(\mu_{ij}, \sigma^2)$$

$$\mu_{ij} = \beta_{0i} + \beta_{1i}x_{1ij} + \beta_{2i}x_{2ij} \cdots + \beta_{Ki}x_{Kij}$$

$$(\beta_{0i} : \beta_{Ki}) \sim N((\beta_0 : \beta_K), \mathbf{T})$$

$$\mathbf{T} = \text{diag}(\tau) \Omega \text{diag}(\tau), \text{diag}(\tau) = \text{diag}(\tau_0, \tau_1, \dots, \tau_K)$$

Prior Model:

$$\beta_k \sim N(0, 10), k = 0, 1, \dots, K$$

$$\tau_k \sim \text{Inv-gamma}(1, 1), k = 0, 1, \dots, K$$

$$\sigma^2 \sim \text{Inv-gamma}(1, 1)$$

$$\Omega \sim \text{LKJ}(1)$$

1. Research Question 1: Does number task performance vary by SES and race/ethnicity? Does number task performance still vary by race/ethnicity with SES controlled and whether the potential disparities differ by SES level?

With Model 1a, we will examine if SES is significantly related to each of the four numerical measurements (Y_{ij}) (i.e., highest_count, give_n_accuracy, ams_accuracy, ams_weber) with age, gender and non-English primary language controlled. In Model 1b, we will explore if there are differences in numerical skills among Black versus White, Hispanic versus White, and Other versus White comparisons, with age, gender and non-English primary language controlled. Next, Model 1c will test if any observed effects of race/ethnicity remain when SES is included in the model. Model 1d will test whether any observed effects of race/ethnicity are moderated by SES.

$$M1a : Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) \\ + \beta_{3i}(\text{Gender}) + \beta_{4i}(\text{SES}) + \varepsilon_{ij}$$

$$M1b : Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) \\ + \beta_{3i}(\text{Gender}) + \beta_{4i}(\text{Black}) + \beta_{5i}(\text{Hispanic}) \\ + \beta_{6i}(\text{Other}) + \varepsilon_{ij}$$

$$M1c : Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) \\ + \beta_{3i}(\text{Gender}) + \beta_{4i}(\text{SES}) + \beta_{5i}(\text{Black}) \\ + \beta_{6i}(\text{Hispanic}) + \beta_{7i}(\text{Other}) + \varepsilon_{ij}$$

$$M1d : Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) \\ + \beta_{3i}(\text{Gender}) + \beta_{4i}(\text{SES}) + \beta_{5i}(\text{Black}) \\ + \beta_{6i}(\text{Hispanic}) + \beta_{7i}(\text{Other}) + \beta_{8i}(\text{Black} \times \text{SES}) \\ + \beta_{9i}(\text{Hispanic} \times \text{SES}) + \beta_{10i}(\text{Other} \times \text{SES}) + \varepsilon_{ij}$$

2. Research Question 2: If there is a relation between any two numerical skills, and both numerical skills are related to SES or race/ethnicity, is the correlation between the two numerical skills explained by SES or race/ethnicity?

We test the confounding effect of SES or race/ethnicity between one numerical skill (X_{ij}) and another numerical skill (Y_{ij}) by calculating the credible intervals of posterior samples of $\beta_{4i} - \alpha_{4i}$

in Model 2a and Model 2b. For each pair of numerical skills, we fit two models: one treating the first skill as the predictor and the second as the outcome, and another model reversing these roles.

M2a:

$$Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) + \beta_{3i}(\text{Gender}) \\ + \beta_{4i}(X_{ij}) + \varepsilon_{ij}$$

$$Y_{ij} = \alpha_{0i} + \alpha_{1i}(\text{Age}) + \alpha_{2i}(\text{Non-English}) + \alpha_{3i}(\text{Gender}) \\ + \alpha_{4i}(X_{ij}) + \alpha_{5i}(\text{SES}) + \omega_{ij}$$

$$M2b: Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) + \beta_{3i}(\text{Gender}) + \\ \beta_{4i}(X_{ij}) + \varepsilon_{ij}$$

$$Y_{ij} = \alpha_{0i} + \alpha_{1i}(\text{Age}) + \alpha_{2i}(\text{Non-English}) + \alpha_{3i}(\text{Gender}) \\ + \alpha_{4i}(X_{ij}) + \alpha_{5i}(\text{Black}) + \alpha_{6i}(\text{Hispanic}) + \alpha_{7i}(\text{Other}) \\ + \omega_{ij}$$

3. Research Question 3: If there are relations between numerical skills and SES or race/ethnicity, are these explained by their shared correlations with visual WM?

We will test the indirect effect of demographic variables (SES, race/ethnicity) on numerical task performance via visual WM by calculating the credible intervals of posterior samples of $\beta_{4i} - \alpha_{4i}$ in Model 3a, $\beta_{4i} - \alpha_{4i}$, $\beta_{5i} - \alpha_{5i}$ and $\beta_{6i} - \alpha_{6i}$ in Model 3b respectively.

M3a:

$$Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) + \beta_{3i}(\text{Gender}) \\ + \beta_{4i}(\text{SES}) + \varepsilon_{ij}$$

$$Y_{ij} = \alpha_{0i} + \alpha_{1i}(\text{Age}) + \alpha_{2i}(\text{Non-English}) + \alpha_{3i}(\text{Gender}) \\ + \alpha_{4i}(\text{SES}) + \alpha_{5i}(\text{vm_score}) + \omega_{ij}$$

$$M3b: Y_{ij} = \beta_{0i} + \beta_{1i}(\text{Age}) + \beta_{2i}(\text{Non-English}) + \beta_{3i}(\text{Gender}) + \\ \beta_{4i}(\text{Black}) + \beta_{5i}(\text{Hispanic}) + \beta_{6i}(\text{Other}) + \varepsilon_{ij}$$

$$Y_{ij} = \alpha_{0i} + \alpha_{1i}(\text{Age}) + \alpha_{2i}(\text{Non-English}) + \alpha_{3i}(\text{Gender}) \\ + \alpha_{4i}(\text{Black}) + \alpha_{5i}(\text{Hispanic}) + \alpha_{6i}(\text{Other}) \\ + \alpha_{7i}(\text{vm_score}) + \omega_{ij}$$

3. Research Question 4: Is center-based childcare attendance associated with higher scores on numerical tasks? If so, is such a relation stronger among children from lower SES and racial/ethnic minority groups?

In Model 4a, we will ask if children who attend center-based childcare score higher on numerical measures when age, gender and non-English primary language are controlled and if any observed effect of childcare attendance is stronger for children from lower SES groups. Model 4b will test if any observed effect of childcare attendance is stronger for children from racial/ethnic

minority groups.

$$M4a : Y_{ij} = \beta_{0i} + \beta_{1i} (Age) + \beta_{2i} (Non - English) \\ + \beta_{3i} (Gender) + \beta_{4i} (SES) + \beta_{5i} (Childcare) \\ + \beta_{6i} (Childcare \times SES) + \varepsilon_{ij}$$

$$M4b : Y_{ij} = \beta_{0i} + \beta_{1i} (Age) + \beta_{2i} (Non - English) \\ + \beta_{3i} (Gender) + \beta_{4i} (Black) + \beta_{5i} (Hispanic) \\ + \beta_{6i} (Other) + \beta_{7i} (Childcare) \\ + \beta_{8i} (Black \times Childcare) \\ + \beta_{9i} (Hispanic \times Childcare) \\ + \beta_{10i} (Other \times Childcare) + \varepsilon_{ij}$$

3 | Discussion

Findings from the current research may have both educational and theoretical significance. By exploring how SES and race/ethnicity are related to three key numerical skills, this study will contribute to theoretical discussions of why nonverbal numerosity discrimination, rote counting, and cardinal number word knowledge are related in development. Also, they will address which numerical skills are potentially more susceptible to the influence of sociodemographic factors. These questions, in turn, are relevant to understanding individual differences in mathematics achievement that exist from kindergarten to adulthood. Some numerical skills may be more related to demographic factors of SES and race/ethnicity than others, potentially making them more predictive of later achievement differences. Additionally, our data may provide important insights into why individual differences related to SES and race/ethnicity exist in early numeracy, by considering relations to working memory and childcare attendance. For example, it is possible that childcare attendance is more strongly related to numeracy outcomes in some sociodemographic/racial groups than in others. Finally, investigating the processes underlying relations between sociodemographic factors and early numeracy may inform the development of early interventions targeting mathematics performance across children from diverse backgrounds.

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Consent

No written consent has been obtained from the patients as there is no patient identifiable data included in this case report/series.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Upon publication, we will share raw data, materials, and code needed to replicate the findings of the final manuscript.

Endnotes

¹ For example, the ability to maintain one-to-one correspondence between number words and objects while counting (Gelman and Gallistel 1978).

² In this task, children were asked to report the total number of items presented in object arrays immediately after they were asked to count out the items.

³ Elementary school = 6; Middle school = 9; High school diploma = 12; 2 yr degree at a college/trade school = 14; 4 yr degree from a college/university = 16; Master's or professional degree = 18; Doctoral degree (Ph.D., M.D., etc.) = 20.

⁴ If parents simply report that their child has ever attended childcare but fail to provide the duration for every instance, this child will be excluded from analyses related to childcare attendance.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: desc70184-sup-0001-Appendices.docx