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Maternal Education Prospectively Predicts Child Neurocognitive Function: An Environmental Influences on Child Health Outcomes Study

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All participants consented to participate in their local ECHO cohort and to have their information shared with the ECHO consortia. Both a central and cohort-specific Institutional Review Board monitored human subject activities at each cohort site and at the centralized ECHO Data Analysis Center. All adult participants provided informed consent for themselves and their child, and children provided assent. Deidentified data from the ECHO program are available through Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) Data and Specimen Hub (DASH; https://dash.nichd.nih.gov/). DASH is a centralized resource that allows researchers to access data from various studies via a controlled-access mechanism. Researchers can now request access to these data by creating a DASH account and submitting a Data Request Form. The NICHD DASH Data Access Committee will review the request and provide a response in approximately 2–3 weeks. Once granted access, researchers will be able to use the data for 3 years. See the DASH Tutorial (https://dash.nichd.nih.gov/resource/tutorial) for more detailed information on the process.

Santiago Morales served as lead for conceptualization, data curation, formal analysis, visualization, writing–original draft, and writing–review and editing. Maureen E. Bowers and Lauren Shuffrey contributed equally to conceptualization. Maureen E. Bowers, Lauren Shuffrey, Katherine Ziegler, Sonya Troller-Renfree, Alexis Hernandez, Stephanie C. Leach, Monica

A large body of research has established a relation between maternal education and children's neurocognitive functions, such as executive function and language. However, most studies have focused on early childhood and relatively few studies have examined associations with changes in maternal education over time. Consequently, it remains unclear if early maternal education is longitudinally related to neurocognitive functions in children, adolescents, and young adults. In addition, the associations between changes in maternal education across development and more broadly defined neurocognitive outcomes remain relatively untested. The current study leveraged a large multicohort sample to examine the longitudinal relations between perinatal maternal education and changes in maternal education during development with children's, adolescents', and young adults' neurocognitive functions ($N = 2{,}688$; $M_{\text{age}} = 10.32$ years; $SD_{\text{age}} = 4.26$; range = 3–20 years). Moreover, we examined the differential effects of perinatal maternal education and changes in maternal education across development on executive function and language performance. Perinatal maternal education was positively associated with children's later overall neurocognitive function. This longitudinal relation was stronger for language than executive function. In addition, increases in maternal education were related to improved language performance but were not associated with executive functioning performance. Our findings support perinatal maternal education as an important predictor of neurocognitive outcomes later in development. Moreover, our results suggest that examining how maternal education changes across development can provide important insights that can help inform policies and interventions designed to foster neurocognitive development.

Public Significance Statement

Using a large multicohort sample, we examined the longitudinal relations between perinatal maternal education and changes in maternal education with their children's neurocognitive functions. Perinatal maternal education was associated with their children's later neurocognitive function. This longitudinal relation was stronger for language than executive function. Increases in maternal education were related to improved language performance but were not associated with executive function. Early maternal education is an important predictor of later child neurocognitive outcomes. Changes in maternal education also provide unique associations with child neurocognition.

Keywords: maternal education, socioeconomic status, neurocognitive outcomes, executive function, language

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Neurocognitive abilities, such as executive functions and language, are an important predictor of academic outcomes and societal adjustment (Moffitt et al., 2011; Ursache et al., 2012). A wealth of evidence shows that socioeconomic status (SES) is associated with neurocognitive function across development. Starting from early development, children from higher SES backgrounds tend to score higher on standardized cognitive batteries than children from more disadvantaged SES environments (Duncan & Magnuson, 2011; Lawson et al., 2018; Pace et al., 2017). Thus, understanding the associations between early SES and changes in SES during childhood with neurocognitive development may offer important insights into the SES disparities observed in cognitive, academic, and socioemotional outcomes, and lend insights into potential malleable processes to target in early intervention efforts.

SES is often conceptualized as a composite of parental education, family income, and social positioning (e.g., occupational prestige; Duncan et al., 2015). Although most studies do not differentiate between each of the SES components, it has been suggested that family income and parental education should be examined separately as they may influence children's neurocognitive functions in different ways (Duncan & Magnuson, 2012). Moreover, examining the impacts of individual SES components (e.g., maternal education) can provide more useful information for intervention and policy efforts, as intervening on an SES composite would be more difficult than individual components (Duncan & Magnuson, 2012).

Maternal education is the most commonly used SES indicator and has been suggested to more accurately and reliably reflect the SES of the family (Bornstein et al., 2003; Hoff et al., 2012).

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Theoretically, as mothers become more educated, they gain new skills and knowledge that can benefit the development of their children's neurocognitive function. For example, maternal education is thought to increase several learning experiences (Magnuson et al., 2009; Pace et al., 2017; Romeo et al., 2022). Moreover, maternal education is also thought to increase their educational expectations for children, which have been linked to children's neurocognitive development (Magnuson et al., 2009; Taylor et al., 2004). From a developmental perspective, high levels of maternal education in early development might be particularly important for the development of children's neurocognitive functions. Although neurocognitive functions follow a protracted development across childhood and adolescence, neurocognitive skills develop most rapidly during the first 5 years of life, potentially setting the foundation for later developmental trajectories (Best & Miller, 2010; Morales & Fox, 2019; Zelazo et al., 2013). Empirically, maternal education seems to be the most consequential component of SES for children's neurocognitive and academic outcomes compared with household income or neighborhood measures (Dickinson & Adelson, 2014; Hackman et al., 2014; Magnuson et al., 2009; Muñez et al., 2021; Rindermann & Ceci, 2018; Romeo et al., 2018). Moreover, developmental science and interventions highlight the role of early family environments in the development of neurocognitive functions and later achievement, providing a critical developmental window for potential intervention (Heckman, 2006). For these reasons, we focus on the associations of early maternal education and changes in maternal education with neurocognitive functions.[1]

Neurocognitive functions include several abilities, such as executive function, memory, attention, and language, that can be investigated as separate and relatively independent skills. However, in addition to investigating individual skills, neurocognitive functioning can also be organized into general cognitive dimensions by creating various composites. One approach includes creating an overall composite measure of neurocognitive function, given that different individual skills are significantly correlated across individuals (Akshoomoff et al., 2013). This measure is thought to provide a broad assessment of cognitive function. Several studies have examined relations between maternal education, and SES more broadly, and overall measures of cognitive function (e.g., Cermakova et al., 2023; Rindermann & Ceci, 2018).

Although the relations between maternal education and neurocognitive functions have been studied by examining an overall neurocognitive composite, they have been most commonly studied as executive functions and language skills. Executive functions are a set of cognitive processes used to guide goal-directed behavior (Nigg, 2017). Subdomains of executive functions have been postulated to be skills, including inhibitory control, cognitive flexibility, and working memory (Diamond, 2013; Miyake et al., 2000). In prior research, the relations between maternal education (and SES more broadly) and executive functions have been inconsistent. Several studies have found that higher SES is associated with higher scores on tests of executive functions (e.g., Blair et al., 2011; Hackman et al., 2015; Noble et al., 2005). However, other studies have not found such a relation (e.g., Engel et al., 2008; Wiebe et al., 2008). A similar pattern has been found with maternal education specifically, such that some studies find a relation (e.g., Blair et al., 2011), while others do not (e.g., Cameron et al., 2012). A recent meta-analysis showed a small ($r = .16$), but significant, relation between SES and executive functions (Lawson et al., 2018). Importantly, when examining a composite of several executive functions, the relation between executive functions was stronger for studies in which participants had wider ranges of SES (Lawson et al., 2018). While not definitive, the findings by Lawson et al. (2018) suggest that the relations between SES and executive function may be small in magnitude and strongest among the most economically disadvantaged participants.

In contrast, the influence of maternal education (and SES more broadly) on language performance has been found more consistent and is larger in magnitude, with maternal education being associated with higher scores for children in standardized assessments of language (Hoff, 2006; Romeo et al., 2018, 2022; Rowe, 2012; for a review, see Pace et al., 2017). Studies examining verbal abilities together with executive function and other nonverbal problem-solving and reasoning abilities found that verbal abilities are more strongly associated with maternal education, and SES more broadly (Anum, 2022; Hackman et al., 2021; Rindermann et al., 2010). However, to the best of our knowledge, the differential links between maternal education and executive functioning and language abilities have not been examined in a unified framework across childhood, through adolescence, and into young adulthood. Such an investigation is essential for both understanding the emergence of SES-related differences in cognition as well as informing future educational policy and interventions aimed at reducing socioeconomic disparities in cognitive, academic, and socioemotional outcomes.

Most of the evidence that has established the relation between maternal education and neurocognitive functions comes from small-scale, cross-sectional associations. The available longitudinal evidence examining trajectories of language and executive functions suggests that SES is associated with the initial levels (i.e., early development), but not the rate of developmental change of language and executive functions (Hackman et al., 2014, 2015; Hughes et al., 2009; Romeo et al., 2022). This has been consistently found across childhood and adolescence. For example, SES during infancy and toddlerhood was associated with lower executive functioning by 4.5 years and this difference was constant through middle to late childhood (Hackman et al., 2015). In another study, maternal education was associated with lower language and executive function at 3 years but was not associated with the development of these neurocognitive functions from 3 to 5 years (Romeo et al., 2022). Similarly, studies have found that the relation between SES and executive function remains relatively stable across development (Hackman et al., 2015; Last et al., 2018; Lawson et al., 2018). These studies suggest that SES differences in neurocognitive functions are relatively constant across development and do not show significant accumulation effects across time (i.e., increases in SES differences with increasing age) or "catch-up" (i.e., reductions in SES differences with increasing age).

[1] Although we focus on maternal education, when reviewing the literature, we discuss SES as a broader construct if the prior studies used a composite to measure SES and maternal education was not examined in isolation.

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Importantly, most studies examining relations with maternal education have treated maternal education as a static construct. However, understanding changes in maternal education can help provide a more direct link between the effects of maternal education on neurocognitive functions and inform intervention efforts and public policies. For example, examining the extent to which maternal education changes are associated with different neurocognitive functions of children can provide valuable insights for designing intervention initiatives focused on improving children's outcomes through enhancing their socioeconomic circumstances. Previous studies evaluating increases in maternal education have focused on language and academic outcomes (Magnuson, 2003, 2007; Magnuson et al., 2009; Rosenzweig & Wolpin, 1994) but not executive functions. For instance, one study found that increases in maternal education in early childhood were related to increases in toddler's language outcomes (Magnuson et al., 2009). However, to the best of our knowledge, no study has examined associations between changes in maternal education and executive function. Moreover, previous studies have only assessed associations in early childhood (12 years and younger).

Together, these longitudinal studies suggest that SES-related differences in neurocognitive functions emerge early in development and remain relatively stable across childhood. However, the few studies examining changes in maternal education during childhood suggest that increases in maternal education are associated with better performance on verbal neurocognitive assessments. Importantly, most of these studies have focused on early childhood. Consequently, it remains unclear if early maternal education longitudinally predicts differences in neurocognitive functions across childhood and into adulthood. In addition, the relations between changes in maternal education and more broadly defined neurocognitive outcomes remain relatively untested (i.e., studies have specifically tested executive function or language). Finally, no longitudinal studies have evaluated the differential effects of early maternal education and changes in maternal education across development on overall, as well as executive functioning and language performance.

Current Study

The current study leveraged a large multicohort with an accelerated longitudinal design to investigate the relations between maternal education and neurocognitive functioning across a wide age range. As mentioned above, we focused on maternal education as our index of SES because it is the most reliable and commonly used indicator of SES. Moreover, maternal education allows for an easier comparison across geographic regions, compared to other measures like income. Finally, the income measure in our sample had considerable amounts of missing data. Thus, we only utilize maternal education in the current study. To investigate the associations between maternal education, changes in maternal education, and neurocognitive functioning, we examined relations between perinatal maternal education and changes in maternal education between the perinatal period and when neurocognition was measured, which occurred once per participant between early childhood and young adulthood (3–20 years; Figure 1). Specifically, we examined if the effects of changes in maternal education were significant above and beyond the effects of perinatal maternal education.

First, we examined relations between perinatal maternal education and changes in maternal education with an overall composite of neurocognitive performance. We hypothesized that higher levels of perinatal maternal education would predict higher neurocognitive functioning across ages. Moreover, using a latent change score, we hypothesized that children, adolescents, and young adults whose mothers' education levels increased over time would score higher on the neurocognitive assessments in childhood than children whose mothers' education levels did not increase.

Second, to examine the relations between perinatal maternal education and specific dimensions of neurocognition, we determined whether the relations between perinatal maternal education and changes in maternal education differed between executive functioning and language performance. We hypothesized that the relations with maternal education would be stronger for language than executive function. Similarly, we expected that the relations with changes in maternal education would be stronger for language than executive function.

Finally, to better understand developmental effects, we explored if the effects of perinatal maternal education and changes in maternal education on neurocognition differed between younger and older participants, as well as between males and females.

Method

Participants

Data for this article were collected as part of the National Institutes of Health's (NIH's) Environmental influences on Child Health Outcomes (ECHO) Program. The program's goal is to investigate the effects of early environmental exposures on child health and development by combining data from 69 longitudinal studies across the United States (Blaisdell et al., 2022; Gillman & Blaisdell, 2018). Participants in the current study included individuals with available NIH Toolbox data collected during childhood, adolescence, and/or young adulthood (ages 3 and 20 years; henceforward, called "participants"). The sample consisted of 2,875 participants with data based on at least one assessment from the NIH Toolbox: The early cognition childhood composite or the fluid or crystallized composites. Of those participants, 1,712 participants had longitudinal data on their mothers' education levels in the perinatal period and later in development when neurocognitive data were collected. A small subset of participants had mothers ($n = 136$) who reported decreases in maternal education between the perinatal period and the later assessment. Given that educational attainment does not decrease and because our interest was on increases in maternal education across development, these participants were excluded from the analysis. In addition, participants from cohorts contributing fewer than 20 mother–child dyads to the analysis were also excluded ($n = 51$), leading to a final sample of 2,688 participants (1,437 male; 1,228 female; 23 missing sex information; $M_{\text{age}} = 10.32$ years; $SD_{\text{age}} = 4.26$). Participants had the following age distribution: $n = 622$ (3–6 years); $n = 761$ (7–10 years); $n = 1{,}014$ (10–15 years), and $n = 291$ (16–20 years).

The approximate geographical locations of the participants enrolled in the study are shown in Figure 1. As shown in Table 1, the race composition of the participants in the sample was 61.8% White, 19.3% African American, 11.9% multiracial, 2.6% Asian, 0.9% American Indian, 0.3% Native Hawaiian, and 1.5% other races. A small percentage (1.7%) of participants reported "I do not know" for race or had missing race information. In addition, 17.4% of participants were Hispanic or Latinx. Finally, mothers' highest level of education was

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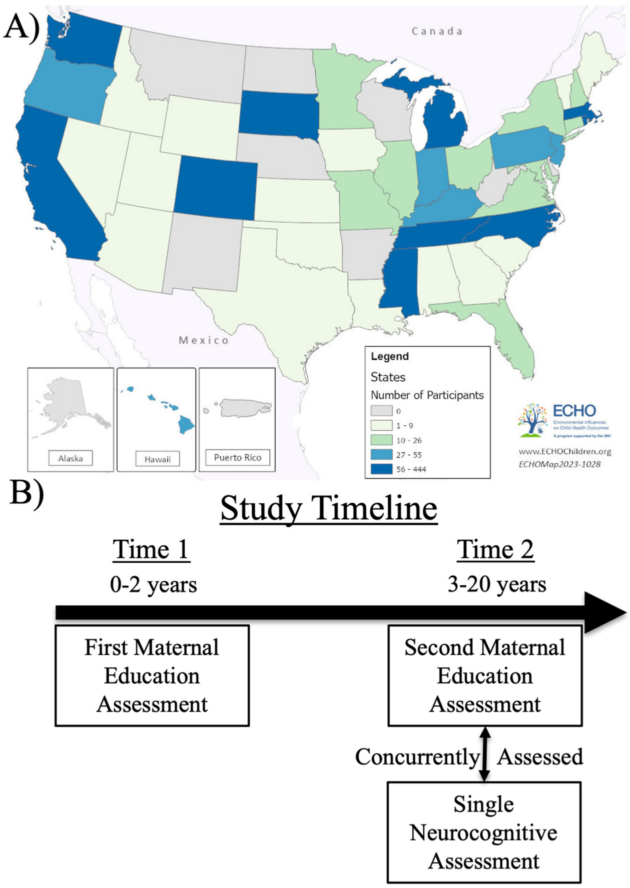
Figure 1
Participant Enrollment by United States State and Study Timeline



Note. (A) Participant enrollment by U.S. state; (B) study timeline. The map does not utilize exact addresses due to confidentiality concerns. Thus, this representation of the different states is only an approximation. The list of ECHO cohorts included in this article can be found in the online supplemental materials. ECHO = Environmental influences on Child Health Outcomes. See the online article for the color version of this figure.

reported as: 18.9% had a graduate school degree; 19.8% had a college degree; 22.7% had some college or an associate degree; 10.3% had a high school degree; 4.6% did not complete high school; and 23.8% had missing education information. As shown in Table 1 and Figure S1 in the online supplemental materials, all participants had an overall score on the NIH Toolbox, 78.0% had a crystallized score, and 77.6% had a fluid score. For maternal education, 57.1% had perinatal maternal education data and 76.2% had maternal education at the time of NIH Toolbox data collection. Because of the significant amount of missing data, we utilized a statistical approach that maximizes the available data and reduces potential biases associated with missing data, along with several sensitivity analyses (see Statistical Analyses section). Moreover, of the mothers with longitudinal maternal education data, 24.1% increased their education levels between the perinatal period and later in development when neurocognitive performance was assessed, and the remaining 75.9% had no change in education level. Of the mothers who increased maternal education ($N = 321$ with complete data), 18.7% increased from less than high school ($M_{\text{increase}} = 1.73$, $SD_{\text{increase}} = 0.88$, $\text{Max}_{\text{increase}} = 4$); 43.6% increased from high school or equivalent ($M_{\text{increase}} = 1.23$, $SD_{\text{increase}} = 0.53$, $\text{Max}_{\text{increase}} = 3$); 22.4% increased from some college, or an associate/trade school degree ($M_{\text{increase}} = 1.25$, $SD_{\text{increase}} = 0.44$, $\text{Max}_{\text{increase}} = 2$); and 15.3% increased from a college degree to a graduate degree. In the online supplemental materials, we have added more detailed patterns of change, illustrating that mothers of older children tended to have larger increases in their education.

Table 1
Sociodemographic Characteristics of Child Participants Across ECHO Cohorts

Variable	*n*	%
Sex		
Female	1,228	45.7
Male	1,437	53.5
Missing	23	0.9
Race		
White	1,661	61.8
African American	519	19.3
Multiracial	319	11.9
Asian	71	2.6
American Indian	25	0.9
Native Hawaiian	7	0.3
Other race	40	1.5
Missing	46	1.7
Ethnicity		
Non-Hispanic Latinx	2,212	82.3
Hispanic Latinx	468	17.4
Missing	8	0.3

Note. ECHO = Environmental influences on Child Health Outcomes.

All participants consented to participate in their local ECHO cohort and to have their information shared with the ECHO consortia. Both a central and cohort-specific Institutional Review Board monitored human subject activities at each cohort site and at the centralized ECHO Data Analysis Center. All adult participants provided informed consent for themselves and their child, and children provided assent.

Measure

A link to the ECHO Cohort Data Collection Protocol Version 2.0 is available in the online supplemental materials. This link includes a detailed description of the original measures and harmonization procedures.

Maternal Education

Maternal education was measured twice. First, during the perinatal period and a second time when neurocognitive functioning was assessed. Perinatal maternal education was measured by harmonizing maternal reports of education during pregnancy or infancy into the following five categories: 1 = *less than high school*; 2 = *high school degree, general educational development (GED), or equivalent*; 3 = *some college, associate degree, or trade school*; 4 = *bachelor's degree*; and 5 = *graduate degree (master's, doctorate, or professional)*. Maternal education during childhood was measured using the NIH Toolbox registration. The mothers' total number of years of education was recoded to correspond to the 5-point scale in our measure of perinatal maternal education.

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Neurocognitive Performance

Participants' neurocognitive performance was assessed in childhood, adolescence, or young adulthood using the NIH Toolbox Cognition Battery. This battery includes the Picture Vocabulary Test, Oral Reading Recognition Test, Dimensional Change Card Sort (DCCS) Test, Flanker task, Picture Sequence Memory Test, List Sorting Working Memory Test, and Pattern Comparison Processing Speed Test. Performance on these tests is combined into the following composite scores: (a) crystallized cognition which assesses language by combining Picture Vocabulary and Oral Reading Recognition; (b) fluid cognition which assesses executive function by combining DCCS, Flanker, Picture Sequence Memory, List Sorting Working Memory, and Pattern Comparison Processing Speed; and (c) the Early Childhood Cognition Battery, which captures overall neurocognitive function by combining two assessments of each domain (DCCS, Flanker, Picture Sequence Memory, and Picture Vocabulary) allowing the inclusion of more young participants who only completed those assessments (Akshoomoff et al., 2013; Bauer & Zelazo, 2013). To estimate the composites, participants had to complete all the measures for that battery. Participants were included in the analysis if they contributed at least one composite. Of the 2,688 participants included in the analyses with the overall composite (largest sample), 2,063 participants completed all the assessments. Sensitivity analyses demonstrated similar results when limiting our analyses to only participants who completed the entire NIH Toolbox Cognition Battery (see the online supplemental materials). For participants who had more than one assessment, only their first assessment was included. The NIH Toolbox's age-corrected standardized scores were used. However, in our sensitivity analyses (see the online supplemental materials), we obtained similar results using uncorrected scores.

Statistical Analyses

To test our hypotheses, we conducted two separate latent change score models (Kievit et al., 2018). Conceptually, the latent change score is identical to a difference score. However, the latent change score models have several advantages (as described in detail in Kievit et al., 2018). First, because latent change score models utilize latent variables, they can better account for measurement error in the observed scores. Moreover, latent change scores can be included in larger models to examine broader hypotheses, explicitly modeling relations with the first timepoint and change under a structural equation modeling (SEM) framework. Finally, another advantage is that by taking advantage of SEM, latent score models can efficiently handle missing data using full information maximum likelihood (FIML), compared to traditional difference scores. The first model tested the effects of maternal education on overall neurocognitive functions. The second model examined the specific influences of maternal education on executive functioning and language performance, which were allowed to covary with each other. To investigate the longitudinal effects of early-life maternal education on neurocognitive performance across childhood, we evaluated the main effects of perinatal maternal education on the neurocognitive scores (overall, or fluid and crystallized scores depending on the model). Moreover, to test if increases in maternal education were associated with improved neurocognitive functions in children, we evaluated the effects of the maternal education latent change score on neurocognitive outcomes (overall, or executive function and language scores depending on the model).

Finally, to determine if these effects differed by age, we examined if the effects of perinatal maternal education significantly differed between children who completed the neurocognitive assessments earlier in childhood ($\leq$10 years old) compared with those who completed the assessments later childhood, adolescence, or young adulthood ($>$10 years old). We decided to use age 10 as the cutoff because that is considered the start of adolescence (World Health Organization, 2022) and is a cutoff commonly used across recent studies to differentiate between childhood and adolescence (e.g., J.-B. Li et al., 2019; Miller et al., 2021). Moreover, age 10 was the mean and median age of the sample, resulting in groups that were approximately the same size. In a multigroup analysis, a chi-square difference test was used to compare differences in the effects of maternal education between the two groups. If a significant difference across models was found, we conducted additional follow-up multigroup analyses constraining one regression path at the time across groups to systematically compare each regression path and determine which path significantly differed between the two groups (Satorra & Bentler, 2001). In two sensitivity analyses, we further examined potential interactions with age (see below).

All models controlled for children's race and ethnicity as they were significantly associated with the neurocognitive outcomes. Race was dummy-coded as three variables for Black, Mixed race, and all other races combined as Other race, with White as the reference group (since this group comprised most of the sample). Ethnicity was coded as: 1 = *Hispanic/Latinx* and 0 = *non-Hispanic/Latinx*. All predictors and covariates were allowed to covary, except between two binary predictors. Models were estimated using FIML estimation to reduce potential bias in the parameter estimates due to missing data (Enders & Bandalos, 2001). This approach allowed for the inclusion of all participants with data on one or more variables (as opposed to listwise deletion). To account for departures from multivariate normality in the presence of missing data, models were fit using a maximum likelihood with a robust variance estimator (MLR; Yuan & Bentler, 2000). Model fit was evaluated using a combination of fit indices, including the chi-square test, comparative fit index (CFI ≥ 0.90), root-mean-square error of approximation (RMSEA ≤ 0.06), and standardized root-mean-squared residual (SRMR ≤ 0.08; Hu & Bentler, 1999). All statistical analyses were conducted in R Version 4.1.0 using deidentified data in a virtual private network hosted by the Research Triangle Institute.

Sensitivity Analyses

To assess the consistency and reliability of our findings in light of various methodological choices, we performed the subsequent seven sensitivity analyses: (a) controlled for an early measure of income. This was not included in the main analyses because it was only available in early childhood and in a subset of participants ($n = 751$); (b) examined the analyses with uncorrected neurocognitive scores, rather than age-corrected scores; (c) tested the potential effects of different cohorts by only utilizing a subset of cohorts and using multilevel models (MLMs) rather than SEM models. The MLMs allowed us to also examine a different way of creating changing scores compared to the latent change scores and accounting for missing data; (d) further examined the effects of different ways of handling missing data by conducting the main SEM models using listwise deletion rather than FIML and a separate analysis only

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including the participants who completed the entire NIH Toolbox Cognition Battery; (e) further tested other ways of capturing change in maternal education by regressing neurocognitive outcomes on maternal education at the second timepoint controlling for perinatal maternal education (first timepoint); (f) assessed in greater detail the interaction with age by utilizing smaller age groups to examine more specific potential effects by using the following age bins: 3–6, 7–10, 11–15, and 16–20 years; (g) further investigated the age effects by extracting scores for the latent change variable and using them as an observed variable to model linear changes with continuous age.

Results

Descriptive Results

Descriptive statistics and the correlations among all study variables are presented in Table 2. As expected, maternal education was longitudinally and concurrently related to all the neurocognitive scores (overall, executive function, and language). Notably, statistically comparing the correlation coefficients using Williams' test (Steiger, 1980) revealed that the relations between maternal education and language scores were significantly larger than the associations between maternal education and executive function scores (perinatal maternal education: $t = 3.11$, $p = .002$; childhood maternal education: $t = 4.77$, $p < .001$).

Associations Between Maternal Education and Overall Neurocognitive Function

When examining the relations between maternal education and overall neurocognitive performance, the latent change score model had a good model fit (CFI = 1.00, Tucker–Lewis index [TLI] = 0.94, RMSEA = 0.05; SRMR = 0.01). The model revealed that maternal education significantly increased between the two assessments ($b = 0.96$, $\beta = 1.53$, $p < .001$). Testing our specific hypotheses, as shown in Figure 2 and Table 3, we found that early-life maternal education had a significant longitudinal relation with overall neurocognitive performance ($\beta = .32$, $p < .001$). However, we found that changes in maternal education were not significantly associated with children's overall neurocognitive performance ($\beta = -.01$, $p = .635$).

Finally, to determine if these relations differed by child age, we examined if the associations between perinatal maternal education or changes in maternal education and neurocognitive performance significantly differed between individuals who completed the neurocognitive assessments in early childhood (≤10 years old) compared with those who completed the assessments in late childhood, adolescence, or young adulthood (>10 years old). As expected, we observed differences in the average levels of maternal education change, such that mothers of older children increased education levels more than younger children (Table S7 in the online supplemental materials), $t(869.94) = 6.85$, $p < .001$. Because of this difference, we allowed means and variances to vary across groups and only examined differences in the regressions of interest. A chi-square difference test revealed that the regressions involving maternal education were significantly different between groups, $\Delta\chi^2(2) = 6.56$, $p = .038$. Probing these differences by testing one regression at a time demonstrated that increases in maternal education were related to higher overall neurocognitive scores for older individuals (>10 years; $\beta = .08$, $p = .036$), but not for younger individuals (≤10 years; $\beta = -.05$, $p = .145$), interaction, $\Delta\chi^2(1) = 6.71$, $p = .001$. Moreover, the effects of perinatal maternal education did not differ between younger and older participants, $\Delta\chi^2(1) = 0.16$, $p = .686$.

Associations Between Executive Functioning and Language Performance

When examining associations between maternal education and executive functioning and language performance, the latent change score model had adequate model fit (CFI = 1.00, TLI = 0.92, RMSEA = 0.05; SRMR = 0.01). Examining our specific hypotheses, as shown in Figure 3 and Table 3, we found that early-life maternal education had a significant longitudinal effect on language ($\beta = .38$, $p < .001$) and executive functioning ($\beta = .27$, $p < .001$) composites. A follow-up chi-square difference test revealed that the associations between perinatal maternal education and language was significantly stronger than the association between maternal education and executive function, $\Delta\chi^2(1) = 10.61$, $p = .001$. In addition, increases in maternal education over time were related to higher language scores ($\beta = .08$, $p = .003$), although we did not observe a similar relation with executive function ($\beta = .04$, $p = .224$). However, the associations between change in maternal education did not significantly differ between executive function and language, $\Delta\chi^2(1) = 2.82$, $p = .093$. Finally, when examining if these relations differed by age, the chi-square difference test did not reveal a significant difference in the regressions involving maternal education between younger and older groups, $\Delta\chi^2(4) = 4.24$, $p = .375$. This result suggests that the relations between perinatal maternal education and changes in maternal education with executive function and language did not significantly differ by age.

Finally, in an exploratory analysis, we examined potential sex differences using multigroup SEM analyses, similar to the ones

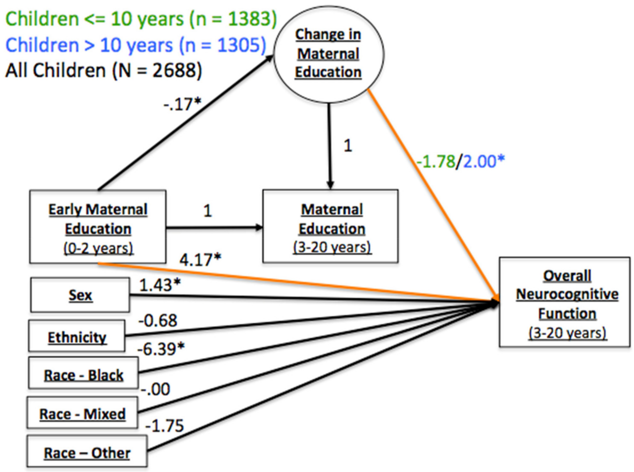
Table 2
Means, Standard Deviations, Sample Size, and Correlations for Each Measure of the Study

Variable	*M*	*SD*	*N*	Min	Max	1	2	3	4
1. Overall composite (NIH Toolbox)	94.54	17.83	2,688	43	146	—			
2. Executive function (NIH Toolbox)	89.68	18.40	2,085	28	146	.86	—		
3. Language (NIH Toolbox)	101.58	17.35	2,098	54	158	.63	.43	—	
4. Perinatal maternal education	3.19	1.24	1,535	1	5	.36	.29	.38	—
5. Childhood maternal education	3.50	1.17	2,049	1	5	.33	.29	.40	.86

Note. Maternal reports of education were coded as follows: 1 = *less than high school*; 2 = *high school degree, GED, or equivalent*; 3 = *some college, associate degree, or trade school*; 4 = *bachelor's degree*; and 5 = *graduate degree (master's, doctorate, or professional)*. NIH = National Institutes of Health; Min = minimum; Max = maximum; GED = general educational development. All correlations are significant ($p < .001$).

Figure 2

Latent Change Score Model for Overall Neurocognitive Function Using the Total Cognition Composite From the NIH Toolbox



Note. The orange paths examine our hypotheses. Differences between younger children (green) and older children (blue) were found in the effect of changes in maternal education on neurocognitive scores. All other regression paths were constrained to be equal across groups (Black). This model had adequate fit (CFI = 0.99, TLI = 0.93, RMSEA = 0.05; SRMR = 0.02). Coefficients represent unstandardized coefficients because variances were allowed to vary between groups. NIH = National Institutes of Health; CFI = comparative fit index; TLI = Tucker–Lewis index; RMSEA = root-mean-square error of approximation; SRMR = standardized root-mean-square residual. * indicates statistical significance. See the online article for the color version of this figure.

described when examining age-related differences. Results of these multigroup models revealed no significant sex differences in the effects of maternal education on overall neurocognitive function, $\Delta\chi^2(2) = 0.22$, $p = .895$, or language and executive function, $\Delta\chi^2(4) = 1.33$, $p = .856$.

Sensitivity Analyses

To examine the robustness of our results to several methodological decisions, we conducted the following sensitivity analyses. First, although we did not include a measure of income in our main analyses because it was only available in early childhood and in a subset of participants ($n = 751$), analyses that included this early measure of income during pregnancy and infancy revealed the same pattern of results with similar effect sizes (Table S1 in the online supplemental materials). Household income during the perinatal period significantly predicted the overall ($\beta = .14$, $p = .001$) and language ($\beta = .24$, $p < .001$) composites, but it did not predict the executive function composite ($\beta = .04$, $p = .433$). Importantly, the relations with perinatal maternal education and changes in maternal education remained unchanged when including early income in the models. This included a significant interaction between changes in maternal education and age predicting overall neurocognitive function. In the same way, controlling for maternal age at the time of the child's birth or removing race and ethnicity as covariates produced the same pattern of results. Similarly, conducting the analyses with uncorrected neurocognitive scores, rather than age-corrected scores, yielded a similar pattern of results—albeit the effect sizes were smaller

Table 3

Regression Paths From the Latent Change Score Models Examining the Effects of Perinatal Maternal Education and Changes in Maternal Education on Overall Cognition (Model 1) and Language and Executive Function (Model 2)

Predictor/outcome	β	*b*	*p*	CI lower	CI upper
Model 1					
Overall cognition					
Sex	**.05**	**1.82**	**.005**	**0.552**	**3.086**
Ethnicity	.00	0.16	.860	−1.628	1.949
Child race (Black)	**−.16**	**−7.08**	**.000**	**−8.845**	**−5.320**
Child race (Mix)	.01	0.58	.576	−1.454	2.615
Child race (Other)	−.01	−0.41	.759	−3.023	2.204
Perinatal maternal education	**.32**	**4.51**	**.000**	**3.873**	**5.154**
Δ in maternal education	−.01	−0.37	.635	−1.900	1.158
Model 2					
Language					
Sex	.01	0.41	.560	−0.957	1.767
Ethnicity	**−.09**	**−4.07**	**.000**	**−6.085**	**−2.048**
Child race (Black)	**−.17**	**−7.52**	**.000**	**−9.357**	**−5.691**
Child race (Mix)	−.01	−0.67	.554	−2.893	1.551
Child race (Other)	−.03	−2.14	.284	−6.054	1.777
Perinatal maternal education	**.38**	**5.13**	**.000**	**4.441**	**5.815**
Δ in maternal education	**.08**	**2.24**	**.004**	**0.715**	**3.764**
Executive function					
Sex	**.05**	**2.01**	**.009**	**0.494**	**3.527**
Ethnicity	−.03	−1.67	.161	−4.013	0.666
Child race (Black)	**−.14**	**−6.41**	**.000**	**−8.432**	**−4.390**
Child race (Mix)	−.01	−0.45	.739	−3.066	2.175
Child race (Other)	−.01	−0.57	.781	−4.608	3.465
Perinatal maternal education	**.27**	**3.86**	**.000**	**3.089**	**4.624**
Δ in maternal education	.04	1.06	.216	−0.620	2.744

Note. Sex was coded as 1 = *female* and 0 = *male*; ethnicity was coded as 0 = *non-Hispanic*; 1 = *Hispanic/Latinx*. Race (White, Black, Mix, and Other) was dummy-coded with White as the reference group. Bolded estimates and *p* values meet statistical significance. β = standardized regression coefficient; *b* = unstandardized regression coefficient; Δ in maternal education = changes in maternal education; CI lower = lower limit of the 95% confidence interval; CI upper = upper limit of the 95% confidence interval.

(Table S2 in the online supplemental materials). However, the interaction between changes in maternal education and age predicting overall neurocognitive function was not significant for this model.

To examine the potential effects of the different cohorts, we conducted our analyses with the five cohorts (out of 21 cohorts) that contributed the most participants (>200 participants/cohort; $n = 1,509$). As shown in Table S3 in the online supplemental materials, this analysis produced the same pattern of results with similar effect sizes as the ones reported in the main analyses. This included a significant interaction between changes in maternal education and age predicting overall neurocognitive function. To further examine the effects of nesting within cohorts, we conducted a similar model using MLMs rather than SEMs. These models included change in maternal education as a simple difference score rather than a latent change score. Moreover, these MLMs allowed us to model cohort-level random effects for the intercept as well as the effects of perinatal maternal education and changes in maternal education. As shown in Table S4 in the online supplemental materials, the results and estimates are similar to the ones presented in the main analyses. One exception was that the interaction between changes in maternal education and age predicting overall neurocognitive function

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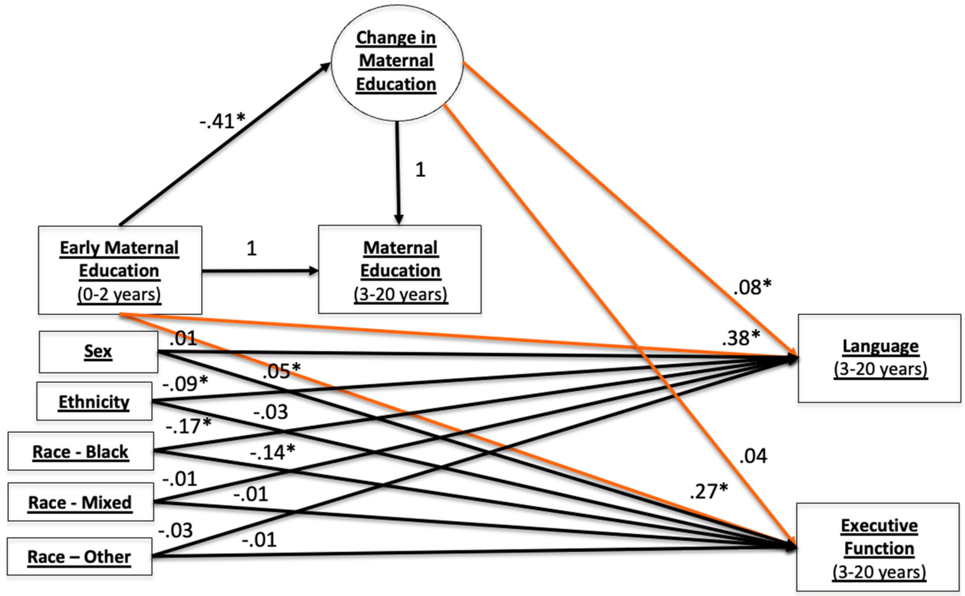
Figure 3

Latent Change Score Model for Language and Executive Function Using the Crystallized and Fluid Cognition Composites From the NIH Toolbox



Note. The orange paths examine our hypotheses. No differences in the regression paths of interest were found between younger and older children. Coefficients represent standardized coefficients. NIH = National Institutes of Health. * indicates statistical significance. See the online article for the color version of this figure.

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was not significant for this model—albeit it was in the same direction, such that increases in maternal education were related to higher overall neurocognitive scores for older children (b = 2.07, $p = .054$), but not for younger children ($b = -1.27$, $p = .488$). The MLMs handle missing data with listwise deletion of the predictors, suggesting that our results remained mostly unchanged with different ways of handling missing data. In a further test of the effects of different ways of handling missing data, we tested the main SEM models using listwise deletion rather than FIML (n = 1,298 for the overall model and n = 915 for the language and executive function model). This analysis also yielded a similar pattern of results and effect sizes (Table S5 in the online supplemental materials), including a significant interaction between changes in maternal education and age predicting overall neurocognitive function. In a final test to examine the impacts of missing data, we conducted the same analyses using only the participants who completed the entire NIH Toolbox Cognition Battery (n = 2,063). This analysis produced a comparable pattern of findings and magnitudes of effects (Table S6 in the online supplemental materials). Although the interaction between changes in maternal education and age predicting overall neurocognitive function was a not significant trend for this model likely due to the reduction in power ($p = .061$), it was in the same direction, such that increases in maternal education were related to higher overall neurocognitive scores for older children ($\beta = .10$, $p = .010$), but not for younger children ($\beta = -.02$, $p = .683$).

As a sensitivity analysis to the latent change score model, we also conducted an analysis regressing neurocognitive outcomes on maternal education at the second timepoint controlling for perinatal maternal education (first timepoint). We found a similar pattern of results and effect sizes, such that the relations with perinatal maternal education were significant for all outcomes: overall, language, and executive function. Moreover, the later measure of maternal education, when neurocognitive function was assessed, was only significant for language, and it was not significant for overall and executive function—after controlling for perinatal maternal education. Moreover, when examining the interaction with age, we also found that the regression paths involving maternal education were significantly different between age groups. When probing the interactions, we observed that the later measure of maternal education was related to higher overall neurocognitive scores for older participants (>10 years), but not for younger participants (≤10 years). These sensitivity analyses generally support our main findings with the latent change score models.

Finally, to analyze in greater detail the interaction with age, we conducted two additional sensitivity analyses. First, we utilized a more fine-grained age group analysis using the following age bins: 3–6, 7–10, 11–15, and 16–20 years. Utilizing these age groups did not reveal a significant interaction, $\Delta\chi^2(6) = 7.52$, $p = .276$. However, examining effects for each group showed a pattern of results in line with the results reported in the main article (see the online supplemental materials). Second, we extracted scores for the latent change variable to use it as an observed variable and modeled linear changes with continuous age. This analysis also revealed a nonsignificant interaction with age (see the online supplemental materials). The fact that neither of these sensitivity analyses is significant indicates that the interaction with age is not a robust finding.

Because these sensitivity analyses produced similar results leading to the same conclusions, we believe that our main, noninteractive

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results are largely robust based on these methodological decisions. The only exception was the interaction between changes in maternal education and age to predict overall neurocognitive scores; thus, we interpret the interaction findings with additional caution and do not consider the findings regarding the interaction as one of the main results/conclusions from this article.

Discussion

Despite a wealth of research suggesting that SES is related to child neurocognitive functions, such as executive functions and language, relatively few studies have examined this link longitudinally across childhood, tested the differential relations between dimensions of neurocognitive function, or considered changes in SES across childhood. Here, by utilizing a large multicohort sample, we investigated the longitudinal associations between perinatal maternal education and changes in maternal education with overall neurocognitive function as well as executive function and language across development (ages 3–20 years) using an accelerated longitudinal design.

We first examined associations between perinatal maternal education and changes in maternal education with overall neurocognitive performance across childhood. Consistent with our hypothesis, higher levels of perinatal maternal education were longitudinally related to higher neurocognitive functioning scores across childhood. This finding is consistent with the existing literature suggesting that SES is related to neurocognitive performance (e.g., Lawson et al., 2018; Pace et al., 2017). Moreover, when testing the longitudinal relations between perinatal maternal education and distinct neurocognitive dimensions, we found that perinatal maternal education predicted both executive function and language performance. However, the relation was significantly stronger for language than for executive functioning performance. This pattern of results suggests that although perinatal maternal education is important and has moderate effect sizes for both forms of neurocognitive functioning, differences in perinatal maternal education may be especially evident for language performance. Interestingly, in supplemental analyses, we observed the same pattern of results for income during the perinatal period.

Additionally, our results align with a common taxonomy based on theoretical and psychometric characteristics that groups neurocognitive functions into crystallized and fluid dimensions (Cattell, 1987; Horn, 1968; S.-C. Li et al., 2004). Fluid cognitive functions involve the ability to rapidly process and integrate information for problem-solving and goal-directed behavior, such as executive functions (Akshoomoff et al., 2013). Historically, fluid abilities have been proposed to be especially dependent on biologically based individual factors and less influenced by previous experiences (Horn, 1968). In contrast, crystallized abilities are proposed to represent verbal skills and accrued knowledge, such as vocabulary (Cattell, 1987); thus, they are thought to be more strongly shaped by previous experiences, such as educational or enriching home environments than fluid performance (Akshoomoff et al., 2013; Anum, 2022; Hackman et al., 2021; Horn, 1968; Rindermann & Ceci, 2018; Rindermann et al., 2010).

Moreover, findings from our robustness checks provide evidence for the independent relations between maternal education and neurocognitive skills, over and above the effects of other indicators of SES, such as income. Although this should be considered preliminary evidence because of the amount of missing data in our income measure, the relations between perinatal maternal education and neurocognitive performance remained significant while controlling for income. This corresponds with the literature suggesting that the associations of SES with neurocognitive and academic outcomes may be especially true for the relation between maternal education and those outcomes over other indicators of SES, such as income or occupational prestige (Dickinson & Adelson, 2014; Hackman et al., 2014; Magnuson et al., 2009; Muñez et al., 2021; Romeo et al., 2018).

When examining if the relations between perinatal maternal education and child neurocognitive skills changed with age, we did not find significant differences between younger and older participants. This implies that perinatal maternal education may have a pervasive effect that does not increase with age. At the same time, it also suggests that this effect does not get smaller as age increases, as we did not observe significant recovery as other developmental processes take place (e.g., schooling). This is consistent with studies examining longitudinal relations with SES, finding that the association between SES and executive function remains consistent across age and that early SES is associated with the initial levels, but not the rate of development, of neurocognitive functions (Hackman et al., 2014, 2015; Hughes et al., 2009; Last et al., 2018; Lawson et al., 2018; Romeo et al., 2022). Together, this evidence suggests that the association between SES and neurocognitive development emerges in early childhood and remains relatively stable. Moreover, these findings may highlight the importance of SES during early development (e.g., pregnancy and infancy) in which brain development is changing most rapidly and neurocognitive systems may be most sensitive to environmental influences.

To more directly test the relations between maternal education and neurocognitive performance, we examined relations with changes in maternal education over time. We found mixed support for our hypotheses that increasing maternal education during childhood may be related to higher neurocognitive scores likely due to only observing modest increases in maternal education in our sample. Although we did not observe an association of changes in maternal education with overall neurocognitive performance or executive function, we found a significant association with language in the expected direction—increases in maternal education were associated with higher levels of children's language performance. This finding provides a more direct link between maternal education and language and further supports the existing literature, suggesting that increases in maternal education predict higher scores on language and academic outcomes (Magnuson, 2003, 2007; Magnuson et al., 2009; Rosenzweig & Wolpin, 1994). Moreover, when examining changes between younger and older participants, we found that the relation of changes in maternal education with overall neurocognitive performance was only significant for older participants ($>$10 years). This is likely because changes in maternal education were higher for older participants (Table S7 in the online supplemental materials) as there was more time for mothers to increase their education. An important caveat to this finding is that this interaction did not remain significant in all the sensitivity analyses, including models examining age as a continuous variable, and additional caution should be taken when interpreting this finding.

In contrast, we did not observe a relation between changes in maternal education and executive function. This is contrary to evidence showing that increases in income are associated with increases in

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several executive functions (Hackman et al., 2015). Although the estimates did not significantly differ, this is generally in line with our longitudinal findings and previous discussion that executive functioning performance is less affected by SES than language performance. Another possibility is that although we observed significant increases in maternal education, the changes in maternal education were likely not large enough or experienced by enough participants to result in significant effects on executive function. Similarly, previous studies examining associations with changes in maternal education have consistently found relations with language, but less consistently on academic outcomes and math achievement (Magnuson, 2007; Magnuson et al., 2009); thus, it is possible that maternal education is particularly related with language outcomes.

Together, our results highlight the importance of early maternal education for children's neurocognitive development. Although we found mixed evidence for the role of changes in maternal education on neurocognitive functions, the results we obtained for language and overall neurocognitive functions predominantly support the existing literature on the beneficial relations with maternal education. These findings suggest that increasing maternal education may lead to higher neurocognitive performance in children later in development, especially with regard to children's language performance. This could be achieved through enhanced access to high-quality education programs. However, previous interventions aimed at increasing maternal education have not been successful (Quint et al., 1997), highlighting the need for more targeted approaches. As such, additional research is needed to better understand the mechanisms involved in the associations linking early maternal education and changes in maternal education to children's neurocognitive outcomes to design more effective intervention programs. Although not the focus of this article, previous studies have found that the associations between maternal education and language or executive function are partially mediated by the quality of the home environment or maternal sensitivity (Hackman et al., 2015; Magnuson et al., 2009). For example, family-based interventions targeting parent–child interactions have found improvements in both language and executive function outcomes in young children (e.g., Neville et al., 2013). This suggests that maternal education affects multiple facets of the child's environment that could serve as targets for intervention (e.g., parent-centered educational interventions) or structural changes in public policies that would facilitate the ability for mothers to gain additional education.

Limitations

Although our study has several notable strengths, such as longitudinal maternal education data and a large and diverse sample brought together by combining several cohorts, our current findings should be interpreted while considering several notable limitations. The main limitation is that this was a correlational study. Despite our use of changes in maternal education to examine a more direct link, we were unable to provide causal interpretations of the effects of maternal education on neurocognitive outcomes. Moreover, there are several unmeasured variables that could bias our results (Duncan et al., 2004), such as other family characteristics (e.g., maternal neurocognitive function), the home environment, and children's educational experiences. We also only examined changes in maternal education and did not assess changes in children's neurocognitive function due to a lack of sufficient longitudinal data. It is also worth noting that the changes in maternal education were modest and only 24.1% ($n = 321$ with complete data) of mothers increased their education; thus, our effects may more clearly highlight the effects of perinatal maternal education and likely underestimate the effects of changes in maternal education. In addition, there were significant missing data in our measure of perinatal maternal education. Although we utilized analytic approaches that maximized the available data and have shown to mitigate potential bias due to missingness (Enders & Bandalos, 2001), this is an important limitation of the current study. Moreover, we did not test for potential mediators of the observed associations. We encourage future studies to examine more proximal factors that explain the links between maternal education and neurocognitive development, such as changes in the home environment, maternal sensitivity, and parenting practices (Hackman et al., 2015; Magnuson et al., 2009). We also did not examine possible effect modifiers that may have amplified the association between maternal education and increases in maternal education over time on children's neurocognitive outcomes for a subset of children. Finally, we were not able to examine changes in family income due to missing data. Previous studies have examined changes in maternal education and family income separately, but to the best of our knowledge, no studies have investigated changes in both of these SES components or their interaction. We encourage future studies to examine the independent and interactive effects of changes in different indices of SES, which could inform future interventions and policies.

Conclusion

The current study provides evidence that early maternal education during the perinatal period is significantly associated with their children's later neurocognitive function. Moreover, when examining differential relations between perinatal maternal education and dimensions of neurocognitive function, we found a larger longitudinal relation with language than executive function. Furthermore, changes in maternal education, above and beyond the effects of perinatal maternal education, were related to improved language performance but were not associated with executive functioning performance. Our findings highlight that perinatal maternal education is an important predictor of later neurocognitive outcomes. Moreover, our results suggest that examining how maternal education changes across development can provide important insights that can help inform policies and interventions to foster neurocognitive development.

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