Maternal diet quality during pregnancy and child cognition and behavior in a US cohort

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ABSTRACT

Background: Maternal intake of several nutrients during pregnancy is linked to offspring cognition. The relation between maternal dietary patterns and offspring cognition is less established.

Objectives: We aimed to examine associations of maternal diet quality during pregnancy with child cognition and behavior.

Methods: Among 1580 mother–child pairs in Project Viva, a prospective prebirth cohort, we assessed maternal diet during pregnancy using FFQs and evaluated diet quality using versions modified for pregnancy of the Mediterranean Diet Score (MDS-P) and Alternate Healthy Eating Index (AHEI-P). Child cognitive and behavioral outcomes were assessed using standardized tests and questionnaires at infancy and in early and mid-childhood. We conducted multivariable linear regression analyses.

Results: Mothers were predominantly white, college-educated, and nonsmokers. After adjustment for child age and sex and maternal sociodemographic and lifestyle characteristics, maternal high (6–9) compared with low (0–3) MDS-P during pregnancy was associated with higher child Kaufman Brief Intelligence Test (KBIT-II) nonverbal (mean difference for first trimester: 4.54; 95% CI: 1.53, 7.56) and verbal scores (3.78; 95% CI: 1.37, 6.19) and lower Behavioral Rating Inventory of Executive Function (BRIEF) Metacognition Index (−1.76; 95% CI: −3.25, −0.27), indicating better intelligence and fewer metacognition problems in mid-childhood. Maternal Q4 compared with Q1 AHEI-P during pregnancy was associated with higher Wide Range Assessment of Visual Motor Abilities matching scores in early childhood (mean difference for first trimester: 2.79; 95% CI: 0.55, 5.04) and higher KBIT-II verbal scores (2.59; 95% CI: 0.13, 5.04) and lower BRIEF Global Executive Composite scores in mid-childhood (−1.61; 95% CI: −3.20, −0.01), indicating better visual spatial skills, verbal intelligence, and executive function.

Conclusions: Maternal intake of a better-quality diet during pregnancy was associated with better visual spatial skills in the offspring at early childhood and with better intelligence and executive function in the offspring at mid-childhood. *Am J Clin Nutr* 2022;115:128–141.

Keywords: birth cohort, maternal diet during pregnancy, early-life nutrition, prenatal nutrition, Mediterranean diet, Alternate Healthy Eating Index, childhood cognition, cognitive development, early development, programming

Introduction

The human brain is dependent on a sufficient supply of nutrients to support its morphological development, neurochemistry, and neurophysiology (1–5). Adequate nutrition is important especially during pregnancy and the first few years of life, because it is during the prenatal and early postnatal period that the brain grows most rapidly and the foundation is set for the development of cognitive, motor, and socioemotional skills (1).

Most studies on associations of nutrition during pregnancy with subsequent cognitive development have examined the intake of individual micro- or macronutrients or foods, such as vitamin A, vitamin B-12, folate, choline, iron, zinc, iodine, omega-3 fatty acids, protein, and fish (2–5). Although this single-nutrient/food approach is important to investigate biological relations between dietary components and health outcomes, it does not fully capture the complex interactions among nutrients and foods. To complement these studies, we must also consider the impact of the overall diet quality, ideally using dietary pattern analysis, to evaluate combined effects of all foods consumed in actual diets and to account for nutrient synergies and for the variability in food sources of nutrients (6, 7). Despite emphasis of recent dietary recommendations on healthy dietary patterns, there are currently few studies on the associations between maternal dietary patterns during pregnancy and neurodevelopmental outcomes in their offspring (8). Apparently unhealthy maternal dietary patterns during pregnancy have been reported to be associated with lower intelligence scores (9, 10), higher emotional-behavioral dysregulation (11), increased risk of externalizing problems (12, 13), and likelihood of hyperactivity-inattention symptoms (14)

 Am J Clin Nutr 2022;115:128–141. Printed in USA.

in the offspring. However, these studies evaluated limited aspects of cognition during childhood and assessed maternal diet quality using empirically derived, data-driven methods to identify dietary patterns. In addition, most have limited their diet assessment to only 1 time point during pregnancy, although brain development evolves over the course of gestation (1, 5).

Previous studies in children and older adults have examined cross-sectional and longitudinal associations between dietary patterns and cognition and have generally shown that intake of healthier dietary patterns—characterized by intake of foods such as fruits, vegetables, and fish—was associated with better cognitive outcomes (15–23). These findings underline the importance of diet quality throughout the life span on cognition and raise a question on the extent to which maternal diet quality during pregnancy, arguably the most sensitive period for brain development, may play a role in neurodevelopment.

The purpose of this study was to investigate the associations between maternal diet quality during pregnancy assessed by 2 healthy dietary patterns modified for pregnancy, the Mediterranean Diet Score (MDS-P) and the Alternate Healthy Eating Index (AHEI-P), and cognitive outcomes among offspring in infancy and in early and mid-childhood as well as behavior and social-emotional functioning in mid-childhood.

Methods

Study population

We studied mother–child pairs from Project Viva, an ongoing prospective prebirth cohort study investigating pre- and perinatal factors in relation to child health outcomes (24). Pregnant women were recruited between 1999 and 2002 at their first prenatal care visit from 8 offices of Atrius Harvard Vanguard Medical Associates, a multispecialty group practice in eastern Massachusetts. Exclusion criteria included multiple gestation, inability to answer questions in English, gestational age >22 wk at the time of the initial prenatal visit, and plans to move out of the area before delivery. Women who agreed to participate in the study (64% of those eligible) completed the first study visit after their obstetric appointment. We completed in-person visits with mothers during pregnancy in the late first (median: 9.9 weeks of gestation; range: 5.6–22.0 weeks of gestation) and second (median: 28.0 weeks of gestation; range: 22.3–39.7 weeks of gestation) trimesters. Detailed recruitment procedures were described previously (24). The institutional review boards of participating institutions authorized the study protocols. At each visit, mothers provided written informed consent and, beginning in mid-childhood, children provided verbal assent.

The Project Viva cohort consists of 2128 liveborn singleton infants and their mothers. For this analysis, we included 1580 mother–child pairs whose children completed ≥1 cognitive/behavioral assessment at infancy, early childhood, or mid-childhood, and whose mothers completed the early- and/or mid-pregnancy study visits (**Figure 1**).

Measurements

Exposures: maternal diet quality during pregnancy.

Maternal diet during pregnancy was assessed using a self-administered validated 166-item semiquantitative FFQ modified and calibrated for use in pregnancy (25–27). The first FFQ was administered at enrollment during the early-pregnancy visit (range: 5.6–29.7 weeks of gestation; median: 11.1 weeks of gestation) and the reference period considered to fill out the FFQ was the time since the last menstrual period to reflect intakes during the first trimester of pregnancy. The second FFQ was administered during the mid-pregnancy visit (range: 20.6–40.1 weeks of gestation; median: 28.9 weeks of gestation) and the reference period considered to fill out the FFQ was the previous 3 mo, roughly reflecting intake in the second trimester. We did not administer a full dietary assessment covering the third trimester because it was deemed too burdensome for mothers after delivery. Nutrient content of foods was derived from the Harvard nutrient composition database, which is based on USDA publications and is supplemented by other sources (28). To address potential measurement error in the FFQ assessments, and to provide nutrient estimates independent of energy intake, we adjusted nutrient estimates for total energy intake using the nutrient residual method (29). To assess overall diet quality during pregnancy, we used 2 predefined dietary pattern scores, modified for pregnancy.

We computed a version of the Mediterranean diet score (MDS) modified for pregnancy (MDS-P) as follows (30). We calculated the median intakes of food groups associated with a traditional Mediterranean diet in our study population, then assigned a value of 0 or 1 to each of the score components. Mothers received a point if their consumption of fruits, vegetables, legumes, whole grains, fish, dairy, and nuts, and their monounsaturated-to-saturated fat ratio, were at or above the median, and if their intake of red and processed meat was below the median (**Supplemental Table 1**). Although alcohol consumption was collected as part of the FFQ, we excluded the alcohol component from the original MDS because alcohol consumption is not recommended for pregnant women and our participants had very low alcohol consumption during pregnancy. Thus, MDS-P ranged

Supported by Kemin Foods, L.C. (to HAM, EJJ, and PFJ) and USDA Agricultural Research Service agreement no. 58-1950-4-003 (to PFJ). Project Viva is funded by US NIH grants R01 HD034568 and UH3 OD023286 (to KMS, SLR-S, and EO). Neither Project Viva nor any Project Viva investigators nor any investigators other than those indicated on the title page received funding from Kemin Foods. The funder (Kemin Foods) was not involved in the study design; the collection, analysis, and interpretation of data; writing the manuscript; or the decision to submit the manuscript for publication. The views expressed in this article are those of the authors and do not necessarily represent the views of the funding organizations.

Supplemental Tables 1–7 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/ajcn/.

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Abbreviations used: AHEI, Alternate Healthy Eating Index; AHEI-P, Alternate Healthy Eating Index modified for pregnancy; BRIEF, Behavioral Rating Inventory of Executive Function; GEC, Global Executive Composite; HOME-SF, Home Observation Measurement of the Environment-Short Form; KBIT-II, Kaufman Brief Intelligence Test, Second Edition; MDS, Mediterranean diet score; MDS-P, Mediterranean diet score modified for pregnancy; MI, Metacognition Index; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; SDQ, Strengths and Difficulties Questionnaire; VRM, visual recognition memory; WRAML, Wide Range Assessment of Memory and Learning, Second Edition; WRAVMA, Wide Range Assessment of Visual Motor Abilities.

Received January 5, 2021. Accepted for publication September 22, 2021.

First published online November 8, 2021; doi: https://doi.org/10.1093/ajcn/nqab325.

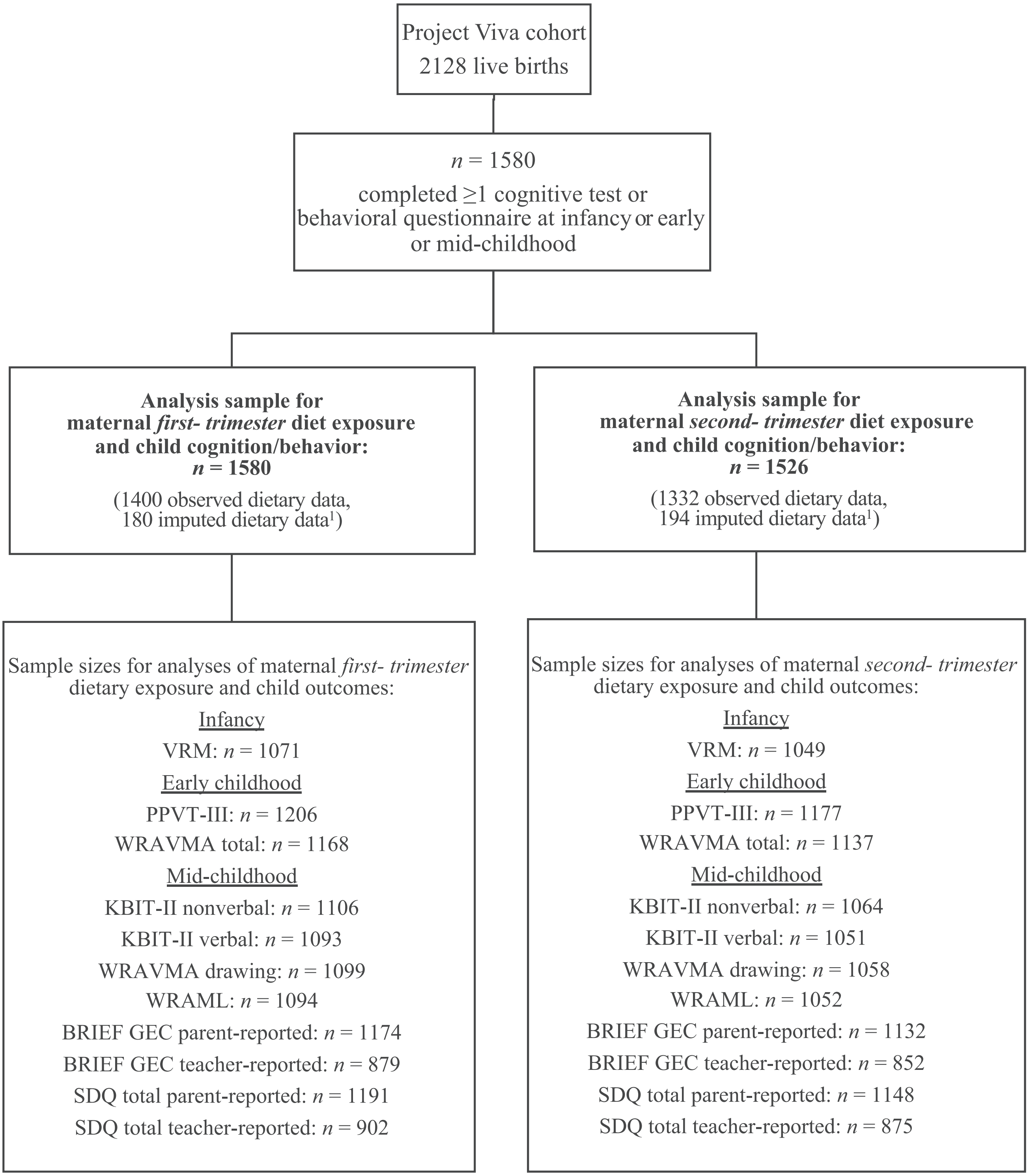

FIGURE 1 Flow diagram for inclusion in the study population. [1]Exposure data were imputed for participants who had missing data but were eligible to complete the questionnaire (i.e., who completed the study visit but did not complete an FFQ). BRIEF GEC, Behavioral Rating Inventory of Executive Function Global Executive Composite; KBIT-II, Kaufman Brief Intelligence Test, Second Edition; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; SDQ, Strengths and Difficulties Questionnaire; VRM, visual recognition memory; WRAML, Wide Range Assessment of Memory and Learning, Second Edition; WRAVMA, Wide Range Assessment of Visual Motor Abilities.

from 0 to 9, with higher scores indicating better adherence to a Mediterranean-type diet.

We computed a modified version of the Alternate Healthy Eating Index (AHEI) used in adults to incorporate nutrition recommendations for pregnancy (AHEI-P) (31, 32). Each of the following 9 components contributes a minimum of 0 and a maximum of 10 possible points: vegetables, fruit, ratio of white to red meat, fiber, *trans* fat (% energy), ratio of PUFA to SFAs, and folate, calcium, and iron from foods. We excluded the alcohol component from the original AHEI. We excluded the nuts and soy protein component because during the time of study enrollment women in our cohort may have avoided nuts during pregnancy out of concern for offspring allergy sensitization, and we preferred not to use only half of the component from the original AHEI. Instead, we included tofu or soybeans in the vegetable component. We also added 3 components, not considered in the original AHEI, to reflect intake of nutrients especially important during pregnancy: folate, iron, and calcium. We limited these nutrient components to intakes from foods only, not including supplements. We defined white meat as poultry or fish, and red meat as beef, pork, or lamb and processed meats. We calculated the ratio of white to red meat using gram sums. We defined the *trans*-fat component by its nutrient density (% of energy from *trans*-fat), to be consistent with the original AHEI scoring system. Each component contributed 0–10 points to the total AHEI-P score, such that a score of 10 indicates that the participant met the recommendation fully, whereas a score of 0 indicates minimum adherence to the recommendation (**Supplemental Table 2**). We scored intermediate intakes proportionately between 0 and 10 by multiplying the number of daily servings consumed by 10, then dividing by the criterion value for a maximum score. For each participant, we assigned individual scores to each component and then summed all component scores to obtain a total AHEI-P ranging from 0 (worst diet quality score) to 90 (best diet quality score).

Brain development is a complex process, with different parts and functions developing and maturing at different times and rates (1, 5). It is possible that maternal dietary quality at different time points in pregnancy may have variable associations with the cognitive development of the offspring. Therefore, we examined maternal diet quality scores in the first and second trimesters separately for all analyses.

Outcomes: child cognition and behavior.

Child cognition was assessed using various standardized tests or questionnaires at each of the infancy, early childhood, and mid-childhood study visits.

At the infancy visit (median age: 6.4 mo; range: 5.2–10.0 mo), cognitive testing was performed using the visual recognition memory (VRM) paradigm (33). In the familiarization trial, trained test administrators repeatedly presented the infant with 2 identical photographs until the infant became habituated to the stimulus. In the testing trial, the infant was simultaneously presented with 2 photos, one being the previously seen photo and the second being a novel photo. Test administrators tracked the amount of time that the infant looked at each stimulus and calculated a percentage novelty preference as the percentage of the total test time that the infant spent looking at the novel stimulus rather than the familiar stimulus. The VRM paradigm consists of 9 sets of trials. Each set includes 1 familiarization trial and 2 test trials, and the final score is determined as the mean of the 2 test trials. The VRM score is calculated as the average of the 9 sets of trials and this mean is used as the VRM outcome in the analyses. The VRM test reflects the infant's ability to encode a stimulus into memory, to recognize that stimulus, and to look preferentially at a novel stimulus; scores in infancy correlate with measures of cognitive abilities (including IQ, language, and memory) later in childhood (34–37). Higher percentage novelty preference scores indicate better VRM.

At the early childhood visit (median age: 3.2 y; range: 2.8–6.2 y), research staff administered the Peabody Picture Vocabulary Test—Third Edition (PPVT-III), a test of receptive language correlated with intelligence tests (38), and the Wide Range Assessment of Visual Motor Abilities (WRAVMA) including the pegboard, matching, and drawing subtests to assess fine motor, visual spatial, and visual motor abilities, respectively (39). WRAVMA subtest scores were combined to generate a visual motor total composite score. The PPVT-III and WRAVMA are each scaled to a mean score of 100 (SD = 15) and higher scores indicate greater verbal ability and visual motor ability, respectively.

At the mid-childhood visit (median age: 7.7 y; range: 6.6–10.9 y), research staff administered the Kaufman Brief Intelligence Test, second edition (KBIT-II), to assess verbal and nonverbal global intelligence, and the WRAVMA drawing subtest, a measure of visual-motor integration (40). The KBIT-II and WRAVMA are each scaled to a mean score of 100 (SD = 15). Memory and learning were also assessed using the Wide Range Assessment of Memory and Learning (WRAML) design memory and picture memory subtests (41). The 2 WRAML subtests are scaled to a mean of 10 (SD = 3) and were summed to yield a total visual memory score. For all cognitive tests, we excluded results for which the administrator did not have confidence in the test performance (<1%). Higher scores on the KBIT reflect better verbal and nonverbal intelligence, whereas higher scores on the WRAML reflect better memory and learning.

In addition, parents and teachers completed the Behavioral Rating Inventory of Executive Function (BRIEF) for children in mid-childhood, a validated 86-item questionnaire devised to assess executive function behaviors in home and school environments (42, 43). The BRIEF includes the following subscales: inhibit, shift, emotional control, initiate, working memory, plan/organize, organization of materials, and monitor. The subscales form 2 indexes: *1*) the Behavioral Regulation Index (BRIEF BRI), which reflects the ability of the child "to shift cognitive set and modulate emotions and behavior via appropriate inhibitory control," and *2*) the Metacognition Index (BRIEF MI), which indicates the child's ability to "initiate, plan, organize, and sustain future-oriented problem-solving in working memory." The BRIEF indexes are each scaled to a mean of 50 (SD = 10). The BRIEF Global Executive Composite (GEC) represents a summary measure of executive function by combining the 2 indexes. Higher BRIEF scores indicate worse executive function.

Parents and teachers also completed the Strengths and Difficulties Questionnaire (SDQ) for children in mid-childhood, a validated 23-item questionnaire designed to assess social, emotional, and behavioral functioning (44). The SDQ is used extensively in clinical and research settings (45) and includes 5 subscales (prosocial behavior, hyperactivity/inattention, emotional symptoms, conduct problems, and peer relationship problems). Possible scores range from 0 to 40 points. Higher scores represent greater difficulties on all except the prosocial subscale, on which a higher score is more favorable. Normative data for the SDQ stem from a representative sample of US children (46).

Covariates.

Using a combination of self-administered questionnaires and interviews in pregnancy and shortly after delivery, Project Viva collected information on maternal age, race/ethnicity, education, household income, marital status, prepregnancy weight and height (to calculate BMI), parity, smoking history, and breastfeeding duration (24). We derived maternal intake of total energy from the FFQs administered at the early- and mid-pregnancy visits. The child's sex, birth weight, and date of birth were obtained from hospital medical records. We calculated gestational age from the date of the last menstrual period or from the second-trimester ultrasound if the 2 differed by >10 d. We calculated sex-specific birth-weight-for-gestational-age z score using a US national reference (47). Maternal cognition was evaluated using the PPVT-III at the early childhood visit and the KBIT-II at the mid-childhood visit. At the mid-childhood visits, mothers completed the Home Observation Measurement of the Environment-Short Form (HOME-SF), a validated measure of cognitive stimulation and emotional support in the child's home (48).

Statistical analysis

Before initiating analyses, we calculated statistical power to detect a 10% difference in cognitive test score between the highest quartile and lowest quartile of maternal first-trimester AHEI-P at the 0.05 α level for the available sample size for each cognitive test. The use of a 10% difference was based on a previous study in the same Project Viva cohort that showed a mean difference of 6% in WRAVMA scores in children whose mothers consumed >2 servings of fish per week compared with those whose mothers never consumed fish (49). We demonstrated ≥98% power for all but the parent-reported and teacher-reported SDQ total, which had power of 0.44 and 0.21, respectively (**Supplemental Table 3**).

All cognitive outcomes were age-standardized except for the VRM, based on external scoring guidelines/reference data for each cognitive test, and all were analyzed as continuous variables. Because we saw evidence of possible nonlinear relations between the maternal diet quality scores and some child cognitive outcomes, we characterized the MDS-P into the commonly used 3 categories (low, 0–3; middle, 4–5; and high, 6–9) and AHEI-P into quartile categories [median (range) for Q1: 48.960 (30.767–53.614); for Q2: 57.173 (53.616–60.242); for Q3: 63.847 (60.248–67.412); and for Q4: 72.773 (67.414–88.232)]. The use of the categorical maternal MDS-P and AHEI-P allowed a common analytical approach for all associations. Using multivariable linear regression, we modeled the associations between the categorical MDS-P and AHEI-P and each of the child cognitive and behavioral outcomes, and present effect estimates as the adjusted differences in mean scores between the higher diet score categories and the lowest.

To identify covariates to include in the multivariable model, we first performed bivariate analyses of maternal and child characteristics with child cognitive/behavioral outcomes and maternal diet scores (as continuous variables). We selected covariates that we considered a priori to be important confounders and that were associated ($P < 0.1$) with ≥1 child cognitive/behavioral outcome and maternal diet scores in either the first or second trimester of pregnancy. These variables included maternal age, race/ethnicity, marital status, parity, education, income, smoking history, prepregnancy BMI, and trimester-specific intake of total energy. We also considered adjustment for breastfeeding, but ultimately decided not to include this variable in our models because it may be in the causal pathway between maternal diet quality and child cognition. We present results from multiple models to show the extent to which the addition of covariates changes effect estimates. Model 1 adjusted for child sex and age at cognitive/behavioral assessment, whereas model 2 in addition adjusted for maternal sociodemographic and lifestyle characteristics.

As part of our secondary analyses, we adjusted in addition for maternal cognition in model 3, such that early childhood models were adjusted for maternal PPVT, and mid-childhood models were adjusted for maternal KBIT. Although maternal cognition was assessed temporally after the maternal exposure, at the early and mid-childhood visits, it reflects a stable construct and likely represents maternal cognition before/during pregnancy and can act as a confounder. But because previous evidence suggests that diet quality is associated with cognitive health (20–23), we were concerned that maternal diet quality would simultaneously affect maternal and child cognition. In addition, much of the variance in maternal cognition may be captured by maternal education and household income, which we already adjusted for in model 2.

As part of our secondary analyses, for the mid-childhood cognitive outcomes, we adjusted in addition for the child's home environment assessed by the HOME-SF score in model 4. The home environment is a possible confounder in the maternal diet and child cognition associations, but it was only assessed at the mid-childhood visit (median age: 7.7 y), which may not accurately reflect the home environment several years prior during pregnancy. Model 5 included all covariates in Model 2 in addition to both maternal cognition and the HOME-SF score.

Because of the number of cognitive tests with subtests, our primary analyses included only composite scores. The results of subtest analyses are presented in the supplementary data.

We used multiple imputation to account for missing data. We generated 50 imputed data sets using chained imputation, and combined estimates using Rubin's rules (50, 51). All 2128 participants were used in generating the imputed data set, but analysis included only mother–child pairs in which children completed ≥1 cognitive/behavioral assessment at infancy, early childhood, or mid-childhood and mothers completed a study visit (i.e., were eligible for a diet assessment) in the first ($n = 1580$) and/or second trimester ($n = 1526$) of pregnancy. We did not use imputed values for missing child outcome data. When maternal dietary data were missing, we used imputed data only for mothers who attended a study visit. We used imputed covariate data for all eligible pairs. Our analytic sample included participants with imputed exposure and covariate data, and only observed cognitive outcome data, so the sample sizes vary by cognitive/behavioral outcome and trimester of exposure. All analyses were performed using both original and imputed data, and results were similar. Therefore, we present results only from the imputed analysis throughout the article. We used SAS software, version 9.4 (SAS Institute) for all analyses.

Results

Included compared with excluded mother–child pairs

Mean maternal MDS-P scores during the first and second trimesters of pregnancy were slightly higher among included participants ($n = 1580$) than among excluded participants ($n = 548$) (MDS-P: 4.9 compared with 4.5, $P < 0.001$ in the first trimester, and 4.8 compared with 4.6, $P < 0.05$ in the second trimester). Mean maternal AHEI-P did not differ between the included and excluded participants. Compared with participants not included in our analysis, included mothers were older in age (32 compared with 31 y, $P < 0.001$), more likely to be college graduates (68% compared with 55%, $P < 0.001$), more likely to be white (69% compared with 60%, $P < 0.001$), more likely to have a household income >$70,000 (59% compared with 54%, $P = 0.02$), more likely to be exclusively breastfeeding at 6 mo (26% compared with 19%, $P < 0.001$), and had higher scores on the PPVT-III and the KBIT-II ($P < 0.001$). We did not observe differences between included and excluded participants for marital status, prepregnancy BMI, parity, smoking history, HOME-SF score, or child sex, gestational age at birth, or birth-weight-for-gestational-age *z* score.

Participant characteristics

Table 1 presents characteristics of the included 1580 mother–child pairs. Women in our eligible sample had a mean ± SD MDS-P of 4.9 ± 1.6 in the first trimester and 4.8 ± 2.0 in the second trimester of pregnancy. Mean ± SD maternal AHEI-P was 60.6 ± 9.9 in the first trimester and 60.3 ± 10.6 in the second trimester of pregnancy; neither of these differences were statistically significant. Women in our sample were predominantly white (69%), married or living with a partner (92%), college educated (68%), had a normal prepregnancy BMI (60%), and never smoked (69%). **Table 2** presents child cognitive and behavioral outcomes according to maternal first-trimester MDS-P and AHEI-P. (Maternal and child characteristics, and child cognitive and behavioral outcomes, according to maternal second-trimester MDS-P and AHEI-P are presented in **Supplemental Tables 4** and **5**, respectively.)

Associations of maternal diet quality with child cognition in infancy

We did not observe associations between maternal MDS-P or AHEI-P and child VRM scores, after adjustment for child age and sex, maternal sociodemographic and lifestyle characteristics, and maternal cognition (**Tables 3** and **4**).

Associations of maternal diet quality with offspring cognition in early childhood

In models adjusted for child age and sex and maternal sociodemographic and lifestyle characteristics, we did not observe associations of maternal MDS-P or AHEI-P with child PPVT-III and WRAVMA total scores (Tables 3 and 4). After accounting for maternal characteristics, the secondary analyses showed no associations between the WRAVMA subtest scores and maternal MDS-P (**Supplemental Table 6**), but children with mothers in the highest quartile category of AHEI-P in the first trimester had WRAVMA matching scores 2.79 (95% CI: 0.55, 5.04) points higher than children with mothers in the lowest AHEI-P quartile category, indicating better visual spatial skills after adjustment for maternal characteristics (**Supplemental Table 7**). This association remained significant, although slightly attenuated, after additional adjustment for maternal cognition (model 3).

Associations of maternal diet quality with offspring cognition in mid-childhood

In models adjusted for child age and sex and maternal sociodemographic and lifestyle characteristics, children of mothers with high MDS-P (6–9) in the first and second trimesters of pregnancy had KBIT-II nonverbal scores 4.54 (95% CI: 1.53, 7.56) and 3.30 (95% CI: 0.23, 6.36) points higher than children of mothers with low MDS-P (0–3), respectively. Children of mothers with high MDS-P during pregnancy also had higher KBIT-II verbal scores than children of mothers with low MDS-P [first-trimester high–low mean difference: 3.78 (95% CI: 1.37, 6.19); and second trimester: 3.80 (95% CI: 1.40, 6.20)] (Table 3). This association between maternal first-trimester MDS-P and child KBIT-II verbal was attenuated but remained statistically significant after additional adjustment for maternal cognition and HOME-SF score (model 5).

In models adjusting for child age and sex and maternal sociodemographic and lifestyle characteristics, children of mothers with the highest AHEI-P in the first and second trimesters of pregnancy had KBIT verbal scores 2.59 points (95% CI: 0.13, 5.04 points) and 2.89 points (95% CI: 0.38, 5.40 points) higher than children of mothers with the lowest AHEI-P (Table 4), respectively. These associations were attenuated and became nonsignificant after additional adjustment for maternal cognition and HOME-SF score (model 5).

We did not observe any associations between maternal MDS-P or AHEI-P during pregnancy and child WRAVMA drawing or WRAML.

Associations of maternal diet quality with offspring executive function, behavior, and social-emotional development in mid-childhood

When analyzing subscales of BRIEF in secondary analyses, we found that children of mothers with high MDS-P in the first trimester had parent-reported BRIEF MI scores 1.76 points (95% CI: −3.25, −0.27 points) lower than children of mothers with low MDS-P, and that this association was attenuated and became nonsignificant after additional adjustment for maternal cognition and HOME-SF score, indicating fewer metacognition problems (Supplemental Table 6). We observed a difference in mean teacher-reported BRIEF GEC scores among children of mothers who had a moderate MDS-P compared with those who had a low MDS-P, but no difference was found in mean scores between children of mothers who had a high MDS-P and those with a low MDS-P (Table 3).

In models adjusted for child age and sex and maternal sociodemographic and lifestyle characteristics, children with

TABLE 1 Selected maternal and child characteristics of included Project Viva mother–child pairs according to maternal first-trimester MDS-P and AHEI-P[1]

		Maternal MDS-P		Maternal AHEI-P[2]	
	Overall	Low (0–3) (n = 423)	High (6–9) (n = 585)	Q1 (n = 395)	Q4 (n = 395)
MDS-P	4.9 ± 1.6	2.4 ± 0.8	6.8 ± 0.9	3.1 ± 1.5	6.5 ± 1.5
AHEI-P	60.6 ± 9.9	52.3 ± 8.1	68.0 ± 8.3	48.0 ± 4.5	73.6 ± 4.7
Age, y	32.1 ± 5.2	30.7 ± 5.9	33.1 ± 4.9	30.9 ± 5.9	33.1 ± 4.8
Race/ethnicity					
White	1087 (68.8)	276 (65.3)	436 (74.5)	244 (61.9)	289 (73.4)
Black	238 (15.1)	71 (16.7)	70 (12.0)	70 (17.8)	47 (11.9)
Asian	83 (5.3)	16 (3.7)	29 (4.9)	16 (4.2)	22 (5.7)
Hispanic	106 (6.7)	41 (9.7)	33 (5.7)	38 (9.5)	25 (6.3)
Other	66 (4.2)	19 (4.6)	17 (2.9)	26 (6.7)	11 (2.7)
Education					
Less than college degree	506 (32.0)	186 (44.0)	130 (22.3)	176 (44.5)	72 (18.2)
4-y college or more	1074 (68.0)	237 (56.0)	455 (77.7)	220 (55.5)	323 (81.8)
Annual household income, $					
≤70,000	640 (40.5)	208 (49.3)	203 (34.8)	195 (49.3)	136 (34.3)
>70,000	940 (59.5)	214 (50.7)	382 (65.2)	200 (50.7)	259 (65.7)
Married or cohabitating					
Yes	1455 (92.1)	369 (87.4)	555 (94.8)	342 (86.6)	383 (97.2)
No	125 (7.9)	53 (12.6)	31 (5.2)	53 (13.4)	11 (2.8)
Prepregnancy BMI, kg/m^2					
<18.5 (underweight)	49 (3.1)	6 (1.5)	23 (4.0)	9 (2.3)	14 (3.5)
18.5–24.9 (normal)	953 (60.3)	239 (56.6)	389 (66.4)	220 (55.6)	267 (67.7)
25.0–29.9 (overweight)	344 (21.8)	102 (24.2)	110 (18.9)	96 (24.4)	76 (19.4)
≥30 (obese)	234 (14.8)	75 (17.8)	63 (10.8)	70 (17.7)	37 (9.4)
Parity					
Nulliparous	755 (47.8)	185 (43.9)	304 (51.9)	170 (42.9)	215 (54.4)
≥1	825 (52.2)	237 (56.1)	281 (48.1)	226 (57.1)	180 (45.6)
Smoking status					
Never	1090 (69.0)	277 (65.5)	417 (71.3)	245 (62.1)	293 (74.1)
Former	312 (19.8)	77 (18.3)	136 (23.3)	75 (18.9)	82 (20.7)
During pregnancy	178 (11.3)	69 (16.2)	32 (5.4)	75 (18.9)	20 (5.1)
Total energy intake	2061 ± 693	1740 ± 563	2375 ± 710	1901 ± 640	2243 ± 668
PPVT-III	104.6 ± 15.5	101.8 ± 15.7	107.7 ± 15.7	101.8 ± 15.5	107.1 ± 16.3
KBIT-II	106.2 ± 15.1	102.6 ± 16.6	109.5 ± 17.1	103.2 ± 16.6	109.0 ± 16.9
HOME-SF score	18.3 ± 2.4	17.8 ± 2.7	18.8 ± 2.5	17.8 ± 2.8	18.8 ± 2.4
Child sex					
Male	810 (51.3)	216 (51.1)	289 (49.4)	194 (49.1)	193 (48.8)
Female	770 (48.7)	207 (48.9)	296 (50.6)	201 (50.9)	202 (51.2)
Gestational age, wk	39.5 ± 2.0	39.4 ± 1.9	39.6 ± 1.8	39.4 ± 1.8	39.5 ± 1.9
Birth-weight-for-gestational-age z score	0.19 ± 0.79	0.24 ± 1.03	0.17 ± 0.99	0.20 ± 1.05	0.11 ± 0.94
Breastfeeding at 6 mo					
Formula only, never breastfed	173 (10.9)	74 (17.4)	29 (5.0)	72 (18.2)	22 (5.5)
Formula only, weaned	591 (37.4)	200 (47.4)	172 (29.4)	175 (44.3)	126 (31.8)
Mixed formula and breast milk	402 (25.5)	77 (18.3)	171 (29.3)	84 (21.3)	108 (27.3)
Breast milk only, no formula	414 (26.2)	71 (16.9)	212 (36.3)	64 (16.2)	140 (35.5)

[1]n = 1580. Values are n (%) or mean ± SD. AHEI-P, Alternate Healthy Eating Index modified for pregnancy; HOME-SF, Home Observation Measurement of the Environment-Short Form; KBIT-II, Kaufman Brief Intelligence Test, Second Edition; MDS-P, Mediterranean diet score modified for pregnancy; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; Q, quartile.

[2]Median (range) maternal AHEI-P, for each quartile: Q1 = 48.960 (30.767–53.614), Q2 = 57.173 (53.616–60.242), Q3 = 63.847 (60.248–67.412), and Q4 = 72.773 (67.414–88.232).

mothers in the highest quartile category of AHEI-P had lower parent-reported BRIEF GEC scores than children with mothers in the lowest quartile category (first-trimester Q4–Q1 mean difference: −1.61; 95% CI: −3.20, −0.01 and second-trimester: −1.73; 95% CI: −3.40, −0.07), indicating better executive function (Table 4). The association remained and was slightly attenuated after additional adjustment for maternal cognition (model 3) and was not statistically significant after additional adjustment for HOME-SF score (model 5). When considering teacher-reported scores, although children with mothers in the second quartile category of second-trimester AHEI-P had lower teacher-reported BRIEF GEC than children with mothers in the lowest quartile category, no difference was found in mean BRIEF GEC scores among children of mothers in the third and fourth

TABLE 2 Child cognitive and behavioral outcomes according to maternal first-trimester MDS-P and AHEI-P[1]

Time of cognitive/behavioral test administration	Overall	Maternal MDS-P		Maternal AHEI-P[2]	
		Low (0–3)	High (6–9)	Q1	Q4
Infancy (median age: 6.4 mo)					
VRM, % novelty preference (n = 1071)	63.8 ± 16.3	64.1 ± 17.8	64.0 ± 16.2	65.1 ± 16.7	63.7 ± 16.4
Early childhood (median age: 3.2 y)					
PPVT-III (n = 1206)	104 ± 14.4	102 ± 15.0	106 ± 14.1	101 ± 15.2	106 ± 14.3
WRAVMA total (n = 1168)	102 ± 11.3	101 ± 10.8	103 ± 12.1	101 ± 11.1	103 ± 12.0
Mid-childhood (median age: 7.7 y)					
KBIT-II verbal (n = 1093)	112 ± 15.0	108 ± 16.2	115 ± 15.4	108 ± 15.9	115 ± 15.2
KBIT-II nonverbal (n = 1106)	106 ± 16.8	103 ± 17.5	109 ± 18.8	104 ± 17.8	108 ± 18.5
WRAVMA drawing (n = 1099)	92.1 ± 16.6	91.8 ± 18.3	91.9 ± 16.5	91.7 ± 17.8	91.9 ± 16.7
WRAML summary score (n = 1094)	16.9 ± 4.4	16.6 ± 4.9	17.0 ± 4.5	16.8 ± 4.8	17.1 ± 4.5
BRIEF GEC parent-reported (n = 1174)	48.7 ± 9.1	48.8 ± 9.6	48.6 ± 9.3	49.6 ± 9.2	48.4 ± 9.1
BRIEF GEC teacher-reported (n = 879)	51.1 ± 10.5	52.3 ± 12.2	50.1 ± 10.7	52.5 ± 12.1	50.2 ± 10.1
SDQ total parent-reported (n = 1191)	6.6 ± 4.8	7.1 ± 5.2	6.2 ± 4.8	7.3 ± 4.9	6.1 ± 4.8
SDQ total teacher-reported (n = 902)	6.4 ± 5.8	6.8 ± 6.4	5.8 ± 6.0	6.9 ± 6.3	6.3 ± 6.0

[1] n = 1580. AHEI-P, Alternate Healthy Eating Index modified for pregnancy; BRIEF GEC, Behavioral Rating Inventory of Executive Function Global Executive Composite; KBIT-II, Kaufman Brief Intelligence Test, Second Edition; MDS-P, Mediterranean diet score modified for pregnancy; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; Q, quartile; SDQ, Strengths and Difficulties Questionnaire; VRM, visual recognition memory; WRAML, Wide Range Assessment of Memory and Learning, Second Edition; WRAVMA, Wide Range Assessment of Visual Motor Abilities.

[2] Median (range) maternal AHEI-P, for each quartile: Q1 = 48.960 (30.767–53.614), Q2 = 57.173 (53.616–60.242), Q3 = 63.847 (60.248–67.412), and Q4 = 72.773 (67.414–88.232).

quartile categories of AHEI-P compared with those in the lowest AHEI-P category.

Although we found evidence of an association between maternal moderate MDS-P in the second trimester and child teacher-reported SDQ total scores, the trend did not persist into the high MDS-P category (Table 3).

We found evidence of an inverse association between maternal first-trimester AHEI-P and child parent-reported SDQ total scores (Q3–Q1 mean difference: −0.87; 95% CI: −1.67, −0.07), indicating fewer child behavioral difficulties with higher maternal AHEI-P. This association remained but was attenuated after additional adjustment for maternal cognition (model 3) and became nonsignificant after adjustment for HOME-SF score (model 5) (Table 4).

Discussion

In this prospective cohort study, higher maternal MDS-P scores during pregnancy were associated with better verbal and nonverbal intelligence and fewer metacognition problems (a subscale of executive function) in mid-childhood. Higher maternal AHEI-P scores during pregnancy were associated with better visual spatial skills in early childhood and with better verbal intelligence and executive function in mid-childhood.

Studies in adults have shown that greater adherence to healthy dietary patterns is associated with better cognitive health (20, 52). But research on the relation between maternal diet quality during pregnancy and child cognition is limited to a few published studies that used data-driven methods to characterize dietary patterns. Data from the Avon Longitudinal Study of Parents and Children showed that a prenatal "unhealthy" dietary pattern, characterized by intake of processed food and confectionary, was associated with poorer child cognitive function at age 8 y (9) and higher levels of child emotional-behavioral dysregulation up to age 7 y (11), and that pregnant women who were classified in the "fruits and vegetables" cluster had children with higher mean IQ at age 8 y than children of mothers classified in the "meat and potatoes" and "white bread and coffee" clusters (10). The Norwegian Mother and Child Cohort Study demonstrated that intake of an "unhealthy" dietary pattern during pregnancy—characterized by high intake of processed meat products, refined cereals, sweet drinks, and salty snacks—predicted externalizing problems among children 1.5–5 y of age (12). The Generation R Study found that both low adherence to a Mediterranean-type diet pattern and high adherence to a traditionally Dutch diet pattern (characterized by high intakes of fresh and processed meat and potatoes and by very low intake of soy and diet products) during pregnancy were associated with increased risk of externalizing problems among offspring ≤6 y of age (13). Results of a French mother–child cohort showed that maternal "Low Healthy" and "High Western" dietary patterns were positively related to children's hyperactivity-inattention symptoms at ages 3–8 y (14). To our knowledge, our study is the first to evaluate maternal diet quality during pregnancy using predefined a priori diet scores in relation to comprehensive measures of cognition and behavior in the offspring. Our findings of a positive association of a healthier overall diet during pregnancy with child visual spatial skills, intelligence, and executive function are consistent with those previously reported, even though all previous studies were conducted in Northern European populations, used some different tests of cognition and behavior, and adjusted for different sets of confounders.

We observed associations of maternal AHEI-P and MDS-P in both the first and second trimesters of pregnancy with measures of child cognition and behavior, suggesting that maternal diet quality may play a role throughout the period of pregnancy. Cognitive domains mature at different times and rates, and nutrition at various stages of pregnancy is likely to affect the specific function developing at that time (1, 5). Moreover, our

TABLE 3 Associations of maternal MDS-P with child cognitive and behavioral outcomes[1]

Age at assessment, outcome model[2]	Difference in means (95% CI) from low MDS-P (0–3)			
	First-trimester MDS-P		Second-trimester MDS-P	
	Moderate (4–5)	High (6–9)	Moderate (4–5)	High (6–9)
Infancy				
VRM, % novelty preference	$n = 1071$		$n = 1049$	
1	− 0.81 (−3.49, 1.87)	− 0.20 (−2.78, 2.38)	− 0.13 (−2.80, 2.55)	0.31 (−2.34, 2.97)
2	− 0.42 (−3.17, 2.34)	0.41 (−2.54, 3.35)	0.59 (−2.20, 3.38)	1.27 (−1.80, 4.34)
3	− 0.43 (−3.18, 2.33)	0.36 (−2.60, 3.32)	0.57 (−2.24, 3.37)	1.23 (−1.87, 4.33)
Early childhood				
PPVT-III	$n = 1206$		$n = 1177$	
1	0.72 (−1.43, 2.88)	3.37 (1.25, 5.49)[3]	1.83 (−0.36, 4.02)	4.02 (1.87, 6.17)[3]
2	− 0.06 (−2.05, 1.94)	1.51 (−0.64, 3.66)	0.37 (−1.62, 2.37)	1.18 (−1.00, 3.37)
3	− 0.12 (−2.08, 1.84)	1.04 (−1.07, 3.16)	− 0.22 (−2.20, 1.76)	0.53 (−1.65, 2.70)
WRAVMA total	$n = 1168$		$n = 1137$	
1	0.82 (−0.86, 2.51)	1.33 (−0.33, 2.99)	0.71 (−1.04, 2.45)	1.47 (−0.24, 3.17)
2	0.71 (−0.99, 2.40)	1.21 (−0.63, 3.05)	0.31 (−1.41, 2.04)	1.02 (−0.89, 2.93)
3	0.69 (−1.00, 2.38)	1.02 (−0.82, 2.86)	0.08 (−1.65, 1.81)	0.75 (−1.16, 2.66)
Mid-childhood				
KBIT-II nonverbal	$n = 1106$		$n = 1064$	
1	3.17 (0.46, 5.89)[3]	5.59 (2.85, 8.33)[3]	3.03 (0.26, 5.80)[3]	5.19 (2.45, 7.93)[3]
2	2.74 (0.00, 5.48)	4.54 (1.53, 7.56)[3]	1.90 (−0.92, 4.71)	3.30 (0.23, 6.36)[3]
3	2.41 (−0.30, 5.12)	3.73 (0.73, 6.72)[3]	1.20 (−1.62, 4.01)	2.35 (−0.72, 5.42)
4	2.65 (−0.10, 5.40)	4.37 (1.34, 7.41)[3]	1.81 (−1.02, 4.63)	3.18 (0.09, 6.26)[3]
5	2.33 (−0.39, 5.05)	3.58 (0.56, 6.59)[3]	1.12 (−1.71, 3.94)	2.25 (−0.84, 5.34)
KBIT-II verbal	$n = 1093$		$n = 1051$	
1	2.71 (0.25, 5.17)[3]	6.80 (4.37, 9.24)[3]	4.35 (1.92, 6.79)[3]	8.11 (5.76, 10.46)[3]
2	1.33 (−0.88, 3.55)	3.78 (1.37, 6.19)[3]	2.52 (0.29, 4.75)[3]	3.80 (1.40, 6.20)[3]
3	0.91 (−1.25, 3.07)	2.77 (0.42, 5.13)[3]	1.68 (−0.51, 3.87)	2.68 (0.33, 5.04)[3]
4	1.14 (−1.08, 3.35)	3.40 (0.99, 5.81)[3]	2.26 (0.04, 4.48)[3]	3.45 (1.05, 5.85)[3]
5	0.72 (−1.44, 2.88)	2.42 (0.06, 4.77)[3]	1.43 (−0.75, 3.61)	2.35 (0.00, 4.70)
WRAVMA drawing	$n = 1099$		$n = 1058$	
1	0.55 (−2.22, 3.32)	− 0.03 (−2.69, 2.63)	2.39 (−0.33, 5.11)	2.12 (−0.55, 4.80)
2	− 0.15 (−3.01, 2.71)	− 1.41 (−4.44, 1.62)	2.04 (−0.77, 4.85)	1.68 (−1.41, 4.77)
3	− 0.31 (−3.17, 2.55)	− 1.79 (−4.84, 1.26)	1.75 (−1.07, 4.57)	1.28 (−1.83, 4.39)
4	− 0.33 (−3.20, 2.53)	− 1.73 (−4.78, 1.32)	1.80 (−1.01, 4.61)	1.34 (−1.76, 4.45)
5	− 0.48 (−3.34, 2.38)	− 2.09 (−5.16, 0.98)	1.52 (−1.31, 4.34)	0.96 (−2.16, 4.08)
WRAML summary	$n = 1094$		$n = 1052$	
1	0.46 (−0.27, 1.20)	0.42 (−0.30, 1.14)	0.18 (−0.56, 0.92)	0.34 (−0.37, 1.05)
2	0.35 (−0.40, 1.10)	0.11 (−0.70, 0.92)	− 0.05 (−0.80, 0.71)	− 0.05 (−0.86, 0.76)
3	0.31 (−0.44, 1.06)	0.02 (−0.80, 0.83)	− 0.12 (−0.88, 0.63)	− 0.16 (−0.98, 0.66)
4	0.33 (−0.42, 1.09)	0.08 (−0.73, 0.90)	− 0.06 (−0.82, 0.70)	− 0.07 (−0.89, 0.74)
5	0.30 (−0.45, 1.05)	− 0.01 (−0.82, 0.81)	− 0.14 (−0.90, 0.62)	− 0.17 (−1.00, 0.65)

(*Continued*)

TABLE 3 (*Continued*)

Age at assessment, outcome model[2]	Difference in means (95% CI) from low MDS-P (0–3)			
	First-trimester MDS-P		Second-trimester MDS-P	
	Moderate (4–5)	High (6–9)	Moderate (4–5)	High (6–9)
BRIEF GEC parent-reported	$n = 1174$		$n = 1132$	
1	− 0.12 (−1.55, 1.31)	− 0.32 (−1.71, 1.08)	− 0.85 (−2.32, 0.61)	− 0.28 (−1.69, 1.13)
2	− 0.46 (−1.90, 0.97)	− 1.41 (−2.96, 0.13)	− 1.00 (−2.49, 0.50)	− 0.71 (−2.33, 0.91)
3	− 0.50 (−1.93, 0.94)	− 1.52 (−3.07, 0.04)	− 1.07 (−2.57, 0.42)	− 0.82 (−2.45, 0.81)
4	− 0.05 (−1.45, 1.35)	− 0.72 (−2.23, 0.79)	− 0.58 (−2.04, 0.88)	− 0.18 (−1.76, 1.41)
5	− 0.09 (−1.50, 1.31)	− 0.84 (−2.36, 0.69)	− 0.67 (−2.13, 0.80)	− 0.31 (−1.90, 1.29)
BRIEF GEC teacher-reported	$n = 879$		$n = 852$	
1	− 0.84 (−2.71, 1.03)	− 1.63 (−3.45, 0.19)	− 2.72 (−4.59, −0.85)[3]	− 1.64 (−3.49, 0.21)
2	− 0.34 (−2.15, 1.48)	− 0.86 (−2.77, 1.05)	− 2.16 (−4.04, −0.28)[3]	− 0.28 (−2.32, 1.76)
3	− 0.31 (−2.13, 1.51)	− 0.79 (−2.71, 1.14)	− 2.09 (−3.98, −0.20)[3]	− 0.18 (−2.24, 1.89)
4	− 0.12 (−1.92, 1.68)	− 0.50 (−2.41, 1.40)	− 1.91 (−3.78, −0.04)[3]	0.07 (−1.98, 2.11)
5	− 0.10 (−1.90, 1.71)	− 0.44 (−2.36, 1.48)	− 1.84 (−3.72, 0.04)	0.16 (−1.90, 2.22)
SDQ total parent-reported	$n = 1191$		$n = 1148$	
1	− 0.40 (−1.17, 0.37)	− 0.81 (−1.56, −0.07)[3]	− 0.60 (−1.34, 0.15)	− 0.65 (−1.39, 0.08)
2	− 0.23 (−0.99, 0.52)	− 0.69 (−1.49, 0.10)	− 0.33 (−1.08, 0.42)	− 0.15 (−0.97, 0.67)
3	− 0.23 (−0.98, 0.53)	− 0.67 (−1.47, 0.13)	− 0.31 (−1.06, 0.45)	− 0.12 (−0.94, 0.71)
4	− 0.04 (−0.78, 0.70)	− 0.37 (−1.15, 0.41)	− 0.13 (−0.86, 0.60)	0.11 (−0.69, 0.92)
5	− 0.04 (−0.78, 0.71)	− 0.36 (−1.14, 0.43)	− 0.12 (−0.85, 0.62)	0.13 (−0.68, 0.94)
SDQ total teacher-reported	$n = 902$		$n = 875$	
1	− 0.17 (−1.22, 0.87)	− 0.86 (−1.87, 0.14)	− 1.64 (−2.68, −0.60)[3]	− 1.05 (−2.08, −0.02)[3]
2	0.13 (−0.91, 1.16)	− 0.52 (−1.61, 0.57)	− 1.26 (−2.31, −0.20)[3]	− 0.27 (−1.43, 0.89)
3	0.16 (−0.88, 1.19)	− 0.44 (−1.54, 0.65)	− 1.20 (−2.26, −0.14)[3]	− 0.19 (−1.36, 0.98)
4	0.27 (−0.76, 1.30)	− 0.29 (−1.38, 0.79)	− 1.09 (−2.14, −0.05)[3]	− 0.04 (−1.21, 1.12)
5	0.29 (−0.74, 1.32)	− 0.23 (−1.32, 0.87)	− 1.04 (−2.10, 0.01)	0.03 (−1.14, 1.20)

[1]Values are mean differences (95% CIs) in cognitive/behavioral scores compared with the lowest category of maternal MDS-P (reference) based on multivariable linear regression. BRIEF GEC, Behavioral Rating Inventory of Executive Function Global Executive Composite; HOME-SF, Home Observation Measurement of the Environment-Short Form; KBIT-II, Kaufman Brief Intelligence Test, 2nd Edition; MDS-P, Mediterranean Diet Score modified for pregnancy; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; SDQ, Strengths and Difficulties Questionnaire; VRM, visual recognition memory; WRAML, Wide Range Assessment of Memory and Learning, 2nd Edition; WRAVMA, Wide Range Assessment of Visual Motor Abilities.

[2]Model 1: adjusted for child sex and age at outcome; Model 2: Model 1 + maternal age, race/ethnicity, marital status, parity, education, pregnancy smoking status, prepregnancy BMI category, trimester-specific total energy intake, and household income; Model 3: Model 2 + maternal cognition (PPVT-III for infancy and early-childhood outcomes or KBIT-II for mid-childhood outcomes); Model 4: Model 2 + HOME-SF score; Model 5: Model 2 + maternal cognition + HOME-SF score.

[3]95% CI for the difference in cognitive/behavioral scores relative to low maternal MDS-P excludes 0.

TABLE 4 Associations of maternal AHEI-P with child cognitive and behavioral outcomes[1]

	Difference in means (95% CI) from AHEI-P Q1[2]					
	First-trimester AHEI-P			Second-trimester AHEI-P		
Age at assessment, outcome model[3]	Q2	Q3	Q4	Q2	Q3	Q4
Infancy						
VRM, % novelty preference		*n* = 1071			*n* = 1049	
1	− 1.21 (−4.19, 1.76)	− 2.75 (−5.62, 0.11)	− 1.41 (−4.30, 1.48)	− 2.33 (−5.33, 0.67)	− 0.76 (−3.68, 2.17)	− 0.54 (−3.51, 2.43)
2	− 0.97 (−3.97, 2.04)	− 2.24 (−5.16, 0.68)	− 0.88 (−3.96, 2.20)	− 1.53 (−4.65, 1.60)	− 0.12 (−3.19, 2.95)	0.31 (−2.94, 3.56)
3	− 0.99 (−3.99, 2.02)	− 2.25 (−5.18, 0.67)	− 0.90 (−3.98, 2.18)	− 1.56 (−4.69, 1.57)	− 0.17 (−3.25, 2.92)	0.26 (−3.00, 3.53)
Early childhood						
PPVT-III		*n* = 1206			*n* = 1177	
1	1.99 (−0.42, 4.40)	3.73 (1.36, 6.10)[4]	4.17 (1.84, 6.49)[4]	1.63 (−0.79, 4.05)	3.82 (1.41, 6.24)[4]	4.39 (2.06, 6.71)[4]
2	0.15 (−2.01, 2.32)	1.42 (−0.74, 3.58)	1.09 (−1.10, 3.28)	− 0.86 (−3.06, 1.33)	1.08 (−1.14, 3.30)	1.11 (−1.12, 3.34)
3	0.03 (−2.10, 2.16)	1.27 (−0.85, 3.40)	0.86 (−1.29, 3.01)	− 0.99 (−3.15, 1.17)	0.69 (−1.50, 2.88)	0.87 (−1.33, 3.07)
WRAVMA total		*n* = 1168			*n* = 1137	
1	1.09 (−0.76, 2.95)	1.58 (−0.27, 3.43)	2.10 (0.29, 3.92)[4]	− 0.37 (−2.31, 1.57)	1.73 (−0.20, 3.66)	1.11 (−0.74, 2.96)
2	0.72 (−1.12, 2.55)	0.76 (−1.07, 2.60)	1.33 (−0.54, 3.21)	− 1.26 (−3.19, 0.66)	0.60 (−1.34, 2.54)	− 0.05 (−1.99, 1.90)
3	0.66 (−1.16, 2.49)	0.70 (−1.13, 2.53)	1.23 (−0.64, 3.10)	− 1.33 (−3.25, 0.58)	0.46 (−1.47, 2.40)	− 0.16 (−2.10, 1.79)
Mid-childhood						
KBIT-II nonverbal		*n* = 1106			*n* = 1064	
1	1.61 (−1.47, 4.69)	3.66 (0.63, 6.69)[4]	4.62 (1.64, 7.61)[4]	2.58 (−0.59, 5.75)	3.45 (0.37, 6.54)[4]	3.47 (0.46, 6.49)[4]
2	0.88 (−2.17, 3.93)	2.01 (−1.02, 5.04)	2.27 (−0.83, 5.36)	0.79 (−2.35, 3.94)	1.08 (−2.03, 4.19)	0.74 (−2.42, 3.90)
3	0.62 (−2.39, 3.63)	1.88 (−1.11, 4.86)	1.90 (−1.16, 4.96)	0.49 (−2.61, 3.59)	0.60 (−2.46, 3.66)	0.30 (−2.82, 3.42)
4	0.80 (−2.26, 3.85)	1.86 (−1.18, 4.90)	2.06 (−1.07, 5.18)	0.71 (−2.44, 3.87)	0.93 (−2.20, 4.06)	0.54 (−2.65, 3.73)
5	0.55 (−2.47, 3.56)	1.75 (−1.25, 4.74)	1.72 (−1.36, 4.80)	0.42 (−2.69, 3.52)	0.47 (−2.61, 3.55)	0.13 (−3.03, 3.28)
KBIT-II verbal		*n* = 1093			*n* = 1051	
1	3.19 (0.49, 5.90)[4]	5.56 (2.91, 8.22)[4]	6.70 (4.09, 9.31)[4]	4.04 (1.22, 6.87)[4]	5.54 (2.81, 8.27)[4]	7.32 (4.68, 9.96)[4]
2	1.65 (−0.74, 4.05)	2.64 (0.24, 5.05)[4]	2.59 (0.13, 5.04)[4]	1.07 (−1.44, 3.57)	1.70 (−0.80, 4.21)	2.89 (0.38, 5.40)[4]
3	1.28 (−1.03, 3.60)	2.44 (0.11, 4.77)[4]	2.14 (−0.25, 4.53)	0.71 (−1.74, 3.16)	1.12 (−1.31, 3.56)	2.40 (−0.03, 4.84)
4	1.48 (−0.90, 3.87)	2.33 (−0.07, 4.74)	2.17 (−0.29, 4.64)	0.86 (−1.65, 3.36)	1.32 (−1.19, 3.83)	2.41 (−0.11, 4.92)
5	1.13 (−1.18, 3.44)	2.15 (−0.18, 4.48)	1.76 (−0.64, 4.16)	0.51 (−1.94, 2.96)	0.76 (−1.68, 3.19)	1.94 (−0.50, 4.38)
WRAVMA drawing		*n* = 1099			*n* = 1058	
1	1.17 (−1.79, 4.13)	0.68 (−2.27, 3.62)	0.26 (−2.61, 3.14)	3.72 (0.60, 6.83)[4]	1.38 (−1.67, 4.42)	1.64 (−1.29, 4.56)
2	0.59 (−2.42, 3.60)	− 0.43 (−3.47, 2.61)	− 1.24 (−4.33, 1.84)	3.13 (−0.07, 6.33)	0.53 (−2.65, 3.70)	0.51 (−2.67, 3.69)
3	0.47 (−2.54, 3.47)	− 0.49 (−3.52, 2.55)	− 1.41 (−4.49, 1.67)	3.01 (−0.18, 6.20)	0.34 (−2.83, 3.51)	0.33 (−2.85, 3.50)
4	0.45 (−2.56, 3.46)	− 0.68 (−3.73, 2.37)	− 1.58 (−4.68, 1.52)	2.93 (−0.28, 6.14)	0.16 (−3.04, 3.35)	0.02 (−3.19, 3.23)
5	0.34 (−2.68, 3.35)	− 0.73 (−3.77, 2.32)	− 1.73 (−4.83, 1.36)	2.82 (−0.38, 6.02)	− 0.02 (−3.21, 3.17)	− 0.15 (−3.35, 3.06)
WRAML summary		*n* = 1094			*n* = 1052	
1	0.08 (−0.73, 0.88)	0.15 (−0.63, 0.94)	0.27 (−0.50, 1.04)	0.14 (−0.67, 0.95)	0.47 (−0.34, 1.28)	0.23 (−0.55, 1.01)
2	− 0.04 (−0.86, 0.77)	− 0.09 (−0.90, 0.72)	− 0.07 (−0.88, 0.75)	− 0.08 (−0.90, 0.75)	0.19 (−0.65, 1.03)	− 0.09 (−0.93, 0.75)
3	− 0.07 (−0.89, 0.74)	− 0.10 (−0.91, 0.70)	− 0.11 (−0.92, 0.71)	− 0.11 (−0.93, 0.72)	0.14 (−0.70, 0.98)	− 0.14 (−0.98, 0.71)
4	− 0.06 (−0.87, 0.76)	− 0.11 (−0.92, 0.70)	− 0.10 (−0.92, 0.72)	− 0.09 (−0.92, 0.74)	0.17 (−0.67, 1.02)	− 0.12 (−0.96, 0.73)
5	− 0.08 (−0.90, 0.73)	− 0.12 (−0.93, 0.69)	− 0.13 (−0.95, 0.69)	− 0.12 (−0.95, 0.71)	0.12 (−0.72, 0.97)	− 0.16 (−1.01, 0.69)

(*Continued*)

TABLE 4 (*Continued*)

Age at assessment, outcome model[3]	Difference in means (95% CI) from AHEI-P Q1[2]					
	First-trimester AHEI-P			Second-trimester AHEI-P		
	Q2	Q3	Q4	Q2	Q3	Q4
BRIEF GEC parent-reported		$n = 1174$			$n = 1132$	
1	− 0.39 (−1.99, 1.22)	− 2.00 (−3.56, −0.44)[4]	− 1.29 (−2.83, 0.24)	− 0.32 (−1.96, 1.32)	− 0.69 (−2.25, 0.86)	− 1.65 (−3.22, −0.08)[4]
2	− 0.58 (−2.17, 1.00)	− 2.00 (−3.56, −0.43)[4]	− 1.61 (−3.20, −0.01)[4]	− 0.33 (−1.99, 1.33)	− 0.66 (−2.26, 0.95)	− 1.73 (−3.40, −0.07)[4]
3	− 0.60 (−2.19, 0.98)	− 2.02 (−3.58, −0.45)[4]	− 1.65 (−3.25, −0.05)[4]	− 0.36 (−2.02, 1.30)	− 0.71 (−2.31, 0.90)	− 1.78 (−3.45, −0.12)[4]
4	− 0.42 (−1.97, 1.13)	− 1.53 (−3.06, 0.00)	− 0.98 (−2.54, 0.58)	− 0.03 (−1.67, 1.60)	− 0.17 (−1.74, 1.41)	− 0.96 (−2.60, 0.67)
5	− 0.45 (−2.00, 1.10)	− 1.55 (−3.08, −0.02)[4]	− 1.04 (−2.60, 0.53)	− 0.07 (−1.71, 1.57)	− 0.23 (−1.81, 1.35)	− 1.02 (−2.66, 0.62)
BRIEF GEC teacher-reported		$n = 879$			$n = 852$	
1	− 0.48 (−2.61, 1.65)	− 2.10 (−4.16, −0.05)[4]	− 1.63 (−3.63, 0.36)	− 3.70 (−5.78, −1.61)[4]	− 1.55 (−3.57, 0.46)	− 2.85 (−4.80, −0.91)[4]
2	0.26 (−1.78, 2.30)	− 0.97 (−2.99, 1.05)	− 0.31 (−2.33, 1.71)	− 2.79 (−4.86, −0.72)[4]	− 0.27 (−2.28, 1.74)	− 1.64 (−3.68, 0.40)
3	0.27 (−1.77, 2.31)	− 0.96 (−2.98, 1.07)	− 0.28 (−2.30, 1.75)	− 2.75 (−4.82, −0.68)[4]	− 0.21 (−2.23, 1.81)	− 1.58 (−3.63, 0.46)
4	0.38 (−1.64, 2.40)	− 0.72 (−2.74, 1.29)	0.02 (−2.00, 2.03)	− 2.63 (−4.69, −0.57)[4]	0.04 (−1.97, 2.05)	− 1.21 (−3.25, 0.83)
5	0.39 (−1.63, 2.41)	− 0.71 (−2.73, 1.30)	0.04 (−1.97, 2.06)	− 2.59 (−4.65, −0.53)[4]	0.09 (−1.93, 2.10)	− 1.16 (−3.21, 0.88)
SDQ total parent-reported		$n = 1191$			$n = 1148$	
1	− 0.46 (−1.28, 0.36)	− 1.24 (−2.05, −0.43)[4]	− 1.17 (−1.97, −0.37)[4]	− 0.90 (−1.75, −0.05)[4]	− 0.83 (−1.66, −0.01)[4]	− 1.04 (−1.85, −0.23)[4]
2	− 0.30 (−1.10, 0.51)	− 0.87 (−1.67, −0.07)[4]	− 0.78 (−1.59, 0.04)	− 0.58 (−1.42, 0.27)	− 0.41 (−1.24, 0.42)	− 0.57 (−1.42, 0.27)
3	− 0.29 (−1.10, 0.52)	− 0.86 (−1.66, −0.07)[4]	− 0.77 (−1.58, 0.05)	− 0.57 (−1.42, 0.27)	− 0.40 (−1.23, 0.44)	− 0.56 (−1.41, 0.28)
4	− 0.21 (−0.99, 0.58)	− 0.65 (−1.43, 0.13)	− 0.48 (−1.28, 0.32)	− 0.45 (−1.28, 0.38)	− 0.19 (−1.01, 0.63)	− 0.21 (−1.04, 0.61)
5	− 0.20 (−0.99, 0.58)	− 0.64 (−1.42, 0.14)	− 0.47 (−1.27, 0.33)	− 0.44 (−1.28, 0.39)	− 0.18 (−1.01, 0.64)	− 0.21 (−1.03, 0.62)
SDQ total teacher-reported		$n = 902$			$n = 875$	
1	− 0.42 (−1.57, 0.73)	− 1.34 (−2.50, −0.18)[4]	− 0.71 (−1.81, 0.40)	− 1.91 (−3.09, −0.74)[4]	− 0.90 (−2.04, 0.23)	− 1.51 (−2.61, −0.41)[4]
2	− 0.05 (−1.17, 1.08)	− 0.82 (−1.97, 0.34)	− 0.04 (−1.18, 1.10)	− 1.44 (−2.62, −0.26)[4]	− 0.28 (−1.44, 0.88)	− 0.87 (−2.04, 0.30)
3	− 0.03 (−1.15, 1.10)	− 0.80 (−1.95, 0.36)	− 0.01 (−1.15, 1.14)	− 1.40 (−2.59, −0.21)[4]	− 0.23 (−1.39, 0.94)	− 0.82 (−1.99, 0.35)
4	0.04 (−1.07, 1.16)	− 0.66 (−1.80, 0.49)	0.16 (−0.97, 1.29)	− 1.33 (−2.50, −0.15)[4]	− 0.07 (−1.23, 1.09)	− 0.58 (−1.75, 0.59)
5	0.06 (−1.05, 1.18)	− 0.64 (−1.79, 0.51)	0.19 (−0.94, 1.32)	− 1.29 (−2.47, −0.12)[4]	− 0.02 (−1.19, 1.14)	− 0.54 (−1.71, 0.64)

[1]Values are mean differences (95% CIs) in cognitive/behavioral scores compared with the lowest category of maternal AHEI-P (reference) based on multivariable linear regression. AHEI-P, Alternate Healthy Eating Index modified for pregnancy; BRIEF GEC, Behavioral Rating Inventory of Executive Function Global Executive Composite; HOME-SF, Home Observation Measurement of the Environment-Short Form; KBIT-II, Kaufman Brief Intelligence Test, 2nd Edition; PPVT-III, Peabody Picture Vocabulary Test, Third Edition; Q, quartile; SDQ, Strengths and Difficulties Questionnaire; VRM, visual recognition memory; WRAML, Wide Range Assessment of Memory and Learning, 2nd Edition; WRAVMA, Wide Range Assessment of Visual Motor Abilities.

[2]Median (range) maternal AHEI-P for each quartile: first trimester ($n = 1580$): Q1 = 48.960 (30.767–53.614), Q2 = 57.173 (53.616–60.242), Q3 = 63.847 (60.248–67.412), and Q4 = 72.773 (67.414–88.232); second trimester ($n = 1526$): Q1 = 48.234 (29.888–53.015), Q2 = 56.503 (53.016–60.329), Q3 = 63.573 (60.333–67.619), and Q4 = 72.536 (67.622–90.000).

[3]Model 1: adjusted for child sex and age at outcome; Model 2: Model 1 + maternal age, race/ethnicity, marital status, parity, education, pregnancy smoking status, prepregnancy BMI category, trimester-specific total energy intake, and household income; Model 3: Model 2 + maternal cognition (PPVT-III for infancy and early-childhood outcomes or KBIT-II for mid-childhood outcomes); Model 4: Model 2 + HOME-SF score; Model 5: Model 2 + maternal cognition + HOME-SF score.

[4]95% CI for the difference in cognitive/behavioral scores relative to low maternal AHEI-P excludes 0.

findings suggest that maternal diet during pregnancy may have persistent effects on cognition throughout childhood, because we found evidence of associations between maternal diet quality scores during pregnancy and measures of cognition in early and mid-childhood but not in infancy. The latter may be a consequence of using a single, simple cognitive test in infancy. However, major structural and functional developments occur in the brain throughout childhood and effects of diet may not manifest until later in childhood as more advanced cognitive domains develop. For example, executive function, one of the last cognitive domains to develop, would not be measurable in infancy or early childhood.

Our study has several strengths. Project Viva is a prospective cohort, and maternal diet quality was assessed at 2 time points in pregnancy and using 2 predefined diet quality scores. We assessed cognitive outcomes using a comprehensive set of age-appropriate validated tests at 3 different stages of child development, to give an overall picture of cognitive function in childhood. We adjusted for various important confounders.

Nevertheless, our study had several limitations. First, measurement errors in dietary assessment are always a concern. However, the FFQs used were previously validated, and calibrated for use in pregnancy. In addition, random error in the diet exposure would likely have attenuated our effect estimates, which makes our findings conservative. Second, dietary data were not available for the third trimester. We used the MDS-P as a marker of diet quality and not adherence to the traditional Mediterranean diet because its scoring is based on cohort-specific medians and our study population does not consume a traditional Mediterranean diet (30, 53). A higher MDS-P score reflected a more plant-based diet, with higher intake of fish, lower intake of red meat, and higher intake of MUFAs than saturated fats. The AHEI-P, on the other hand, included fewer plant-based components, and emphasized type of meats without a limit on quantity, PUFAs instead of MUFAs, and individual nutrients. Despite these differences between the diet scores, they were both similarly associated with verbal intelligence and executive function. Third, there is possibility for measurement error in the cognitive test scores. However, the tests were administered by trained research assistants, we excluded results for which the administrator did not have confidence in the test performance, and errors in the dependent variable would have reduced the precision of our effect estimates, rendering our results conservative. Fourth, although many confounders were considered, we cannot rule out the possibility of residual confounding. For instance, the age range in which the cognitive outcomes were administered in mid-childhood (2.8–6.2 y) was large, but we used age-standardized test scores and adjusted for age in the multivariable models. No measure of home environment was assessed in early childhood, but this was partly accounted for by adjusting for maternal socioeconomic status. Fifth, we were unable to measure a mother's commitment to her and her offspring's health, which might have been another reason for the observed associations. Sixth, multiple outcomes were assessed over time and numerous exposure groups and the number of associations considered may have resulted in spurious associations. However, the use of multiple outcomes was inevitable because they are scores from tests assessing different cognitive domains, and the use of 2 diet quality scores at early and mid-pregnancy allowed us to assess the possible associations with maternal dietary exposures during 2 stages of prenatal brain development. Also, spurious findings are less likely for outcomes that were associated with both diet quality scores. Lastly, the generalizability of our results may be limited because participants resided in eastern Massachusetts, received health care, and most were college-educated.

Our findings are still valuable because they showed that, even in women who are apparently well-nourished and socioeconomically advantaged, small differences in maternal overall dietary pattern at the critical period of pregnancy may have implications for child cognition. The lack of detected associations with many of the child cognitive outcomes and modest effect sizes could be due in part to our sample being at low risk of nutrient deficiencies or the fact that suboptimal dietary conditions during pregnancy could be compensated over time (e.g., by the maternal diet during breastfeeding, child diet, or cognitive stimulation) and may not result in detectable consequences on cognitive function during childhood.

In summary, our findings suggest that maternal diet quality during pregnancy was associated with child visual spatial skills in early childhood and with intelligence and executive function in mid-childhood. Diet quality is one of many factors associated with cognitive and behavioral development in early life. Because maternal diet is modifiable, the association between maternal diet quality and child cognition deserves further investigation.

The authors' responsibilities were as follows—HAM, KMS, TMS, EJJ, and PFJ: designed the research; KMS, SLR-S, and EO: oversaw data collection and provided access to the Project Viva data set; SLR-S: provided guidance on the statistical analysis; HAM: analyzed the data and wrote the paper; HAM and PFJ: had primary responsibility for the final content; and all authors: read and approved the final manuscript. The authors report no conflicts of interest.

Data Availability

Data described in the article and the associated code book and analytic code are available from Project Viva upon request, pending application and approval.

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