Original Research Communications

Maternal pregnancy diet, postnatal home environment and executive function and behavior in 3- to 4-y-olds

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ABSTRACT

Background: Optimal maternal nutrition during pregnancy has been linked to better cognitive and behavioral development in children. However, its influence on the effects of suboptimal postnatal exposures like reduced stimulation and support in the home is not known.

Objectives: To examine the effect of maternal pregnancy diet on executive function and/or behavioral development in children raised in suboptimal home environments.

Methods: Data were provided by 808 mother–infant dyads from the Canadian Maternal-Infant Research on Environmental Chemicals–Child Development study. Maternal pregnancy diet was self-reported using the Healthy Eating Index 2010 questionnaire. Stimulation and support in the home was assessed using the Home Observation for Measurement of the Environment (HOME) when children were 3–4 y old. Child executive function was reported by mothers at this age using the Behavior Rating Inventory of Executive Functioning–Preschool Edition, and child behavior was assessed using the Behavior Assessment System for Children–2nd Edition. We examined the interaction of maternal pregnancy diet and postnatal HOME scores on child executive function and behavior using linear regression adjusted for maternal education, postpartum depression, prepregnancy BMI, and smoking.

Results: Maternal pregnancy diet was associated with an increasingly positive association with child working memory (β: 0.21; 95% CI: 0.82, 3.41; P = 0.001), planning (β: 0.17; 95% CI: 0.38, 2.84; P = 0.007), and adaptability (β: –0.13; 95% CI: –1.72, –0.08; P = 0.032) as levels of postnatal stimulation decreased.

Conclusions: The positive association of maternal pregnancy diet quality and executive function and adaptability in 3- to 4-y-olds appeared to increase with decreasing levels of postnatal stimulation and support. These results suggest that overall maternal pregnancy diet could be linked to better child neurodevelopment in families experiencing barriers to providing stimulation and support to children in their home. *Am J Clin Nutr* 2021;00:1–10.

Keywords: maternal pregnancy diet, home environment, executive function, cognitive development, behavioral development

Introduction

Difficulties in cognition and behavior affect 1 in 5 children globally (1). Executive function (EF), the processes involved in goal-targeted and purposeful behavior (2), can be an important contributor to these problems. Understanding the factors influencing EF in children is important given its role in academic functioning (3), interpersonal relations (4), and psychopathology across the life span (5, 6). Observable aspects of EF emerge in the preschool years (7) when children have to regulate emotions and attend to others (8) and are the building blocks for problem solving and decision making (9).

Adverse prenatal exposures, such as maternal infection and suboptimal nutrition, can negatively affect neurodevelopment (10, 11), whereas more favorable intrauterine conditions like good nutrition (12) and exercise (13–15) can improve these processes. Although individual nutrients (i.e., iron, zinc, folate) are important, overall high-quality diet is key to cognitive and behavioral development (16).

More than 60% of women of childbearing age in North America consume an unhealthy "Western diet" (17, 18) consisting of an excess of foods that are high in fats and sugar and low in

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Data described in the manuscript, code book, and analytic code will be made available upon request pending the approval of the MIREC Study Team.

Supplemental Figures 1 and 2 and Supplemental Table 1 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: BASC-2, Behavior Assessment System for Children–2nd Edition; BRIEF-P, Behavior Rating Inventory of Executive Functioning–Preschool Edition; CES-D-10, 10-item version of the Center for Epidemiological Studies–Depression; EF, executive function; GDM, gestational diabetes mellitus; HEI, Healthy Eating Index; HOME, Home Observation for Measurement of the Environment; MIREC-CD Plus, Maternal-Infant Research on Environmental Chemicals–Child Development; PFC, prefrontal cortex; VIF, variance inflation factor.

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nutrients (17). Consumption of this type of diet during pregnancy can adversely alter the fetal brain (19), including development of the hippocampus (20), a structure critical to cognitive functioning and behavioral regulation (21). Because maternal pregnancy diet is modifiable (22), improving maternal gestational diet quality could be capable of optimizing brain development and function (22).

One of the most powerful postnatal factors affecting cognitive and behavioral development is the rearing environment in the home (23–29). Stimulation and support at home provide the basis for cognitive and behavioral functioning (30) and the foundation that later environments (e.g., school) build upon (31). Home environments lacking these features can adversely affect brain regions core to healthy cognitive and behavioral functioning (23), including the prefrontal cortex (PFC) and its associated connections with the hippocampus (32). Positive and supportive experiences in the home can enable optimal EF and behavioral development and functioning (33).

Maternal diet quality during pregnancy may be one modifiable way to mitigate the adverse effects of suboptimal postnatal home environments. Proper dietary intake during pregnancy can ensure that synaptogenesis and neuronal and glial cell proliferation occur optimally during gestation (34), promote healthy neurodevelopment, and reduce the impact of postnatal adversities like deprived home environments (35). It is therefore important to examine associations between maternal diet during pregnancy and offspring cognition and behavior in home environments marked by less stimulation and support.

To our knowledge, no studies have examined how maternal pregnancy diet quality and postnatal adversity interact to influence offspring EF and behavior. As a result, it remains unclear if maternal diet quality can benefit EF and behavioral development in children who experience postnatal adversity.

Methods

Sample

Participants in this study were initially enrolled in the Canadian Maternal-Infant Research on Environmental Chemicals (MIREC) cohort, a longitudinal pregnancy cohort that recruited 2001 women from across Canada (Vancouver, Edmonton, Winnipeg, Sudbury, Toronto, Hamilton, Kingston, Ottawa, Montreal, and Halifax) before 14 wk of gestation and between 2008 and 2011. The current study used data from the MIREC–Child Development (CD Plus) cohort (a substudy of the original MIREC cohort) to assess the neurodevelopment of 808 children aged 3–4 y and who were selected to complete the Behavior Rating Inventory of Executive Functioning–Preschool Edition (BRIEF-P; a measure of child executive functioning) and the Behavior Assessment System for Children–2nd Edition (BASC-2; an assessment of emotions and behavior) (please refer to **Supplemental Figure 1** for the participant flowchart). To improve efficiency and reduce costs, the MIREC-CD Plus study was restricted to the 6 recruitment sites of MIREC that had the most births: Vancouver, Toronto, Hamilton, Montreal, Kingston, and Halifax.

Mothers of singleton children aged 3–4 y, born at a gestational age >28 wk, and without major congenital anomalies or a history of convulsions or major neurologic disorders during the data collection period were invited to take part in the children's neurobehavioral assessment phase of the study.

This research was approved by Health Canada's Research Ethics Board and by ethics committees of each participating hospital. Each participant signed an informed consent form at recruitment and before the follow-up for cognitive and behavioral assessment of children.

Predictors

Maternal diet quality during pregnancy

Maternal pregnancy diet quality was defined using 2 measures. At 16–21 wk of gestation, mothers completed an FFQ (36). This semiquantitative measure assessed the frequency (daily, weekly, or monthly) and portion size (small, average, or large) intake of 46 foods across 8 subgroups (fruit, vegetables, poultry, meat, fish and alternatives, grains, dairy, and commonly consumed composite foods, i.e., desserts, pasta, pizza) (36). This FFQ was developed to obtain information about nutrients critical to a healthy pregnancy consumed in the prior month. Serving sizes for each of the 46 items were converted to servings per day. A 33% inflation factor was used for large servings and a 33% reduction factor for small servings. Serving size, gram weights, and nutrient amounts were obtained for each food item using the 2010 Canadian Nutrient File [national nutrition database supported by Health Canada (37)]. For composite foods (e.g., "pizza"), the Canadian Community Health Survey, Cycle 2.2 [a nationally representative Canadian survey on the nutrition of pregnant and nonpregnant women (38)] was used to rank the popularity and the weighted average of amounts of nutrients per serving of foods.

The validity of the FFQ was examined by administering a second FFQ to a subset of 115 participants 2 wk following administration of the first, and 24-h dietary recalls were also used. Results from Pearson product-moment correlations and Spearman rank-order correlations indicated that the FFQ was valid in assessing absolute amounts of foods (in grams) and absolute intake of nutrients (all correlations were statistically significant). Other short-form versions of the FFQ have been shown to be useful in assessing average food group intake (39), as well as an acceptable tool for assessing nutrition in large epidemiologic studies (40).

The Healthy Eating Index (HEI) 2010 used data from this FFQ to provide an estimate of overall prenatal maternal diet quality. It converted dietary intake information from the FFQ into a single score capturing overall maternal diet quality during pregnancy. The following 3 steps were carried out to convert FFQ data to HEI 2010 scores. First, for each FFQ item, a composite score was created based on the frequency and serving sizes of each food item for each participant. Second, each FFQ item was matched to the corresponding food within the Food Patterns Equivalents Database (41). Information on sodium and fatty acids was obtained from a USDA food compositions data set. Composite FFQ scores were multiplied by each food's nutrient components to obtain food pattern scores for each participant based on the amount of each food item they consumed. Finally, this information was inputted into the HEI 2010 macros to obtain estimates of total diet quality. These macros are freely available from the Epidemiology and Genetics Research Program (42). The

HEI has been found to be a reliable and valid measure of diet quality for pregnant women (43) and provides a valid means by which short-form FFQs can be converted to a single diet quality score (44).

The HEI generates 9 dietary "adequacy" components (total fruit, whole fruit, total vegetables, greens and beans, whole grains, dairy, total protein, seafood and plant proteins, and fatty acids). Higher scores for each of these components is consistent with better diet quality. The HEI also consists of 3 "moderation" dietary components (refined grains, sodium, and empty calories from fats and sugars), things that are best consumed in moderation. These moderation items are reverse scored, so that higher scores in these dietary components indicate poorer diet quality (43). The sum of the adequacy and moderation dietary components results in a single HEI score up to 100, with higher scores indicating better diet quality. This HEI total score was used to determine overall diet quality in this study. HEI scores were also categorized so that HEI scores >80 were considered "good," HEI scores <50 were considered "poor," and HEI scores between 50 and 80 were considered "needing improvement" (45).

Quality of home environment

The quality of the child's home environment was assessed when children were aged 3–4 y using the observer-rated Home Observation for Measurement of the Environment (HOME) scale. The HOME scale is the most commonly used assessment of the home environment in developmental research and is used to assess the quality of stimulation and support provided to the child in a naturalistic environment (46). It has been shown to be reliable and valid (47) and was administered by trained research staff.

Its scoring involves both observation of the home environment as well as a semistructured interview with the mother. During the observational component of this measure, interviewers used a binary (yes/no) scale to observe *1*) the presence of stimulating resources such as books, toys, and games in the home; *2*) maternal–child interactive behaviors; and *3*) the absence of harmful aspects such as hazards. During the semistructured interview, mothers were asked to focus on a specific day of the week and recall their child's experience at home. The HOME scale consists of 45 items and took ∼1 h to administer. Total HOME scores were calculated (maximum of 55 points), with lower scores indicating less optimal home environments (48).

Child Outcomes

Child executive function (BRIEF-P)

The BRIEF-P provides a measure of EF using parental reports in children (7) and yields an internally consistent ($r = 0.80$–0.90), valid, and temporally stable score ($r = 0.90+$) for assessing EF (49, 50). The scale consists of 63 items comprising 5 subscales that are standardized across children aged 2–5 y to assess working memory (difficulties retaining information needed to complete a task), planning/organizing (difficulties preparing for future events), inhibition (difficulties with controlling impulses), shift (difficulties moving from one situation/activity to another), and emotional control (difficulties with modifying emotions) (51). Mothers were then asked to respond to each item as "never" (0), "sometimes" (1), or "often" (2). *Higher* scores on the BRIEF-P indicate *more problems* with executive functioning (50). Given the multiple objectives and wide-ranging data collection procedures in the MIREC-CD Plus study, mothers were asked to complete only items for the BRIEF-P working memory and planning/organizing scales.

Child behavior (BASC-2)

The BASC-2 is based on a multidimensional system used to understand the behaviors and emotions of children from the perspectives of parents, teachers, and the self (52). The parent-reported preschool form of the BASC-2 was used in this study. It is a comprehensive, psychometrically sound 134- to 160-item scale that is standardized to assess child behavior at 2–5 y of age (53).

In the present study, mothers were asked to respond to each item based on a 4-point Likert scale (0 = never to 3 = almost always). The BASC-2 generates 16 scales (hyperactivity, aggression, conduct problems, anxiety, learning problems, depression, somatization, atypicality, withdrawal, attention problems, study skills, adaptability, social skills, leadership, activities of daily living, and functional communication) and 5 composite scales including adaptive skills (ability to adapt to surroundings), externalizing problems (impulsive and uncontrolled behaviors), internalizing problems (sadness and withdrawal behaviors), behavioral symptoms index (overall level of behavioral problems), and school problems (areas of attention problems and learning problems) (54), with higher scores indicating greater levels of adaptability (55).

In keeping with most previous research, T scores for each of the composite scales were used in this analysis (55). T scores indicate the distance of scores from the norm-group mean (mean ± SD: 50 ± 10) (56). Because they capture the broadest aspects of child behavior at 3–4 y of age, we examined internalizing, externalizing, and adaptability outcomes in the present study.

Both early executive functioning and behavioral development are critical to adaptive functioning across the life span. Therefore, our primary outcome variables included both working memory and planning scales of the BRIEF-P, as well as the adaptability, internalizing, and externalizing scales of the BASC-2. Given the exploratory nature of the study, we did not adjust for multiple comparisons.

Covariates

To examine the interaction of maternal pregnancy diet quality and postnatal home environment on EF and behavior in 3- to 4-y-old children, and in order to attempt to isolate the association of these predictors individually and jointly on our outcomes, we adjusted for covariates. Our covariates were selected a priori based on previous evidence reporting consistent associations of our covariates with our predictors (home environment and prenatal diet) and offspring cognitive and behavioral outcome variables (57–60).

Maternal educational attainment

Research has shown a strong link between maternal education and the development of EF and adaptive behavioral functioning in children (61, 62). Mothers who have completed a higher level of education tend to interact more with their child (63), as well as provide more stimulating resources in the home environment (64). In addition, women with more education tend to have better dietary patterns (65). Therefore, in this study, we adjusted for self-reported maternal education (high school or less compared with postsecondary education or greater) in our statistical analyses.

Maternal postpartum depression

Studies have consistently reported that mothers who have depressive symptoms are more likely to struggle with parenting (66) and be less warm, sensitive, and supportive toward their children (67). Such exposures have been linked to poor EF development and an early onset of behavioral problems (68). Therefore, maternal depressive symptoms were adjusted for statistically in this study. It was assessed at 6 mo postpartum using the 10-item version of the Center for Epidemiological Studies–Depression (CES-D-10) scale. The CES-D-10 has been shown to be both reliable and valid (68). Mothers were asked to rate any depressive symptoms experienced the previous week on a 4-point scale (1 = rarely to 4 = all of the time). A score of 10 or higher on the scale indicates a possible presence of major depressive disorder symptoms (69).

Maternal prepregnancy BMI

Maternal prepregnancy BMI can affect fetal neurodevelopment (70), as well as the behavioral and neurocognitive development of the fetus (71–73), and has been linked to poorer pregnancy diet quality (74). Maternal prepregnancy BMI (normal: BMI 18.5 to <25 compared with overweight/obese: BMI >25) was obtained by dividing self-reported prepregnancy weight (kg) by height (m^2) measured at the first-trimester study visit.

Maternal smoking during pregnancy

Extensive research also supports links between maternal prenatal smoking and altered child neurocognitive and neurobehavioral development (75), and maternal prenatal smoking has been linked to maternal pregnancy diet (76) and home environment (60). Self-reported maternal prenatal smoking patterns were obtained at the third prenatal visit by asking mothers if they "never smoked," "formerly smoked" (quit smoking before knowledge of pregnancy), or "quit during pregnancy" (smoked during part of pregnancy but quit smoking at some point during pregnancy).

Statistical analyses

The characteristics of the study sample were described using means and SDs for continuous variables and frequencies for categorical variables. Multiple linear regression models were used to assess the relation between our 2 predictors and 5 child outcomes. We did not observe any evidence of violations to the assumptions of multiple linear regression models [i.e., all data were visually inspected for normality, and we statistically tested for this using the Shapiro–Wilk test ($P > 0.05$), data were independent, there was no evidence of heteroscedasticity, and so we assumed and examined linear relations]. These models were then adjusted for our covariates (maternal educational attainment, maternal depression at 6 mo, maternal prepregnancy BMI, and maternal prenatal smoking). The presence of multicollinearity was examined in our adjusted models using variance inflation factors (VIFs). All VIF values were <10; therefore, no multicollinearity was observed. Standardized βs were reported and show how many SDs the outcome variable changes per SD increase in a predictor.

Diet and home variables were centered at the mean prior to the creation of our interaction variable (mean-centered diet quality score was multiplied by mean-centered HOME scale scores). Also, to better illustrate the impact of maternal pregnancy diet quality in home environments marked by less or more stimulation and/or support, we dichotomized HOME scores at the median for the current sample.

Listwise deletion was used to account for any missing data. A missing values analysis was conducted on predictor, outcome, and covariate variables and revealed that the Little test of missing completely at random was not significant ($\chi^2 = 134.9$, $df = 123$, $P = 0.218$), suggesting data are missing completely at random. All analyses were performed using SPSS statistics 23 (SPSS, Inc.) and were 2-tailed with significance levels set at $P < 0.05$.

Results

The characteristics of the MIREC-CD Plus sample involved in the present study are presented in **Table 1**. The mean ± SD age of mothers was 32.8 ± 4.8 y at enrollment, and 57.4% had a BMI in the normal range at the first pregnancy study visit. Most mothers had completed college or above (89.3%). The majority of women were married/common law (96%) and born in Canada (81.7%). Maternal characteristics from our sample were comparable to maternal characteristics from other large, representative Canadian pregnancy cohorts (77). HOME total scale scores ranged from 27 to 55. The mean ± SD total HEI score was 72.2 ± 7.9 (minimum: 40.7; maximum: 92.7), with the majority of women consuming diets that need improvement (79%), 7% of women consuming poor diets, and 14% of women consuming good diets. HEI data from our sample are comparable to HEI data in other Canadian samples of pregnant women (78). However, the total HEI score in our study was moderately higher than mean HEI scores among current nonpregnant Canadian adults (mean: 50.9) (79), but this may be due to the fact that pregnant women consume healthier overall diets compared with nonpregnant women (80). Infants were born at a mean ± SD of 38.9 ± 1.7 wk of gestation and provided EF and behavioral data at 3.4 ± 0.31 y. Most infants were breastfed for 6 mo or less (83.3%). Most of the mothers in our sample used a multivitamin supplement during pregnancy (86%). Women participating in the MIREC-CD Plus subsample differed from the women participating in the original MIREC study on maternal age, total HEI score, gestational age of child (weeks), birthweight of child (g), education level, and pregnancy smoking status.

A statistically significant interaction was observed between maternal diet quality during pregnancy and HOME scale scores on the working memory (β: 0.13; 95% CI: 0.52, 2.32; $P < 0.001$) and planning (β: 0.11; 95% CI: 0.27, 2.00; $P = 0.006$) scales of the BRIEF-P (**Table 2**). There was also a statistically significant interaction between maternal diet quality and HOME scores on the child adaptability composite of the BASC-2 (β: –0.14;

TABLE 1 Child and maternal characteristics of MIREC-CD Plus sample ($n = 808$) compared with original MIREC cohort ($n = 1983$)[1]

Characteristic	MIREC-CD Plus ($n = 808$)[2]	Original MIREC ($n = 1983$)[3]	P value[4]
Children			
Birthweight, g	3442.1 ± 529.9	3384.9 ± 649.10	0.03
Gestational age, wk	38.9 ± 1.7	38.0 ± 4.62	<0.01
Mothers			
Maternal age, y	32.8 ± 4.8	31.8 ± 5.24	<0.01
Maternal depression (CES-D-10 score)	5.8 ± 3.7	[5]	
HOME total score	47.3 ± 4.3	[5]	
HEI total score	72.2 ± 7.9	71.4 ± 8.82	0.01
Maternal education			<0.01
Less than high school	8 (1)	39 (3.3)	
High school graduate	75 (9.2)	158 (13.4)	
College or trade school graduate	172 (21.2)	295 (25.1)	
University graduate or above	551 (68.1)	683 (58.1)	
Marital status			0.62
Married/common law	777 (96)	1120 (95.3)	
Divorced/separated/single	30 (3.7)	54 (4.6)	
Country of birth			0.64
Canada	661 (81.7)	951 (80.9)	
Outside of Canada	147 (18.2)	224 (19.1)	
Maternal BMI			0.34
Normal	464 (57.4)	642 (54.6)	
Overweight	153 (18.9)	251 (21.4)	
Obese	120 (14.8)	97 (8.3)	
Maternal pregnancy smoking			<0.01
Never	529 (65.4)	673 (57.3)	
Former	212 (26.2)	332 (28.3)	
Quit during pregnancy	67 (8.3)	170 (14.5)	
Maternal HEI score (diet quality)			0.07
Poor	58 (7)	107 (10.3)	
Needs improvement	622 (79)	780 (75.1)	
High	111 (14)	151 (14.6)	
Maternal multivitamin usage			0.15
Yes	694 (86)	1037 (88.3)	
No	113 (14)	138 (11.7)	
Duration of breastfeeding			
6 mo or less	457 (83.3)	[5]	
More than 6 mo	91 (16.7)	[5]	

[1]Values are presented as number (%) or mean ± SD unless otherwise indicated. CES-D-10, 10-item version of the Center for Epidemiological Studies–Depression; HEI, Healthy Eating Index; HOME, Home Observation for the Measurement of the Environment; MIREC, Maternal-Infant Research on Environmental Chemicals; MIREC-CD Plus, Maternal-Infant Research on Environmental Chemicals–Child Development.

[2]For the MIREC-CD Plus sample, maternal education is only reported for 806 women, marital status is reported for 807 women, BMI is reported for 737 women, maternal HEI score is reported for 791 women, multivitamin usage is reported for 807 women, and breastfeeding duration is reported for 548 women.

[3]For the Original MIREC sample, maternal education is only reported for 1175 women, marital status is reported for 1174 women, country of birth is reported for 1175 women, BMI is reported for 990 women, maternal smoking is reported for 1175 women, maternal HEI score is reported for 1038 women, and multivitamin usage is reported for 1175 women.

[4]Differences between categorical variables between each cohort were examined using χ^2 tests. Differences in continuous variables were tested using independent samples t tests. The MIREC-CD Plus subsample is independent of the original MIREC cohort.

[5]CES-D, HOME score, and duration of breastfeeding measures were not obtained as part of the original MIREC sample.

95% CI: –1.38, –0.13; $P < 0.001$) but not for internalizing or externalizing problems (Table 2). After adjusting for maternal BMI, education, depression, and smoking, statistically significant interactions remained between overall maternal diet quality during pregnancy and HOME scale scores on child working memory (β: 0.21; 95% CI: 0.82, 3.41; $P < 0.001$) and planning (β: 0.17; 95% CI: 0.38, 2.84; $P = 0.007$) of the BRIEF-P, as well as adaptability (β: –0.13; 95% CI: –1.72, –0.08; $P = 0.032$) on the BASC-2. These results are summarized in **Table 3**. The covariates that accounted for significant variance in the adjusted model were

TABLE 2 Unadjusted associations between maternal pregnancy diet, HOME scores, EF (BRIEF-P), and behavior (BASC-2) outcomes in children at 3–4 y of age[1]

Characteristic	R^2	Standardized β	95% CI	P value
BRIEF-P ($n = 698$)				
Working memory	0.08			
Total HOME score		–0.23	(–0.71, –0.31)	<0.001
Total diet quality score (HEI)		0.01	(–0.11, 0.12)	0.829
Diet × Home		0.13	(0.52, 2.32)	<0.001
Planning ($n = 699$)	0.06			
Total HOME score		–0.21	(–0.64, –0.24)	<0.001
Total diet quality score (HEI)		–0.01	(–0.12, 0.09)	0.944
Diet × Home		0.11	(0.27, 2.00)	0.006
BASC-2				
Internalizing ($n = 693$)	0.01			
Total HOME score		–0.06	(–0.29, 0.04)	0.145
Total diet quality score (HEI)		0.07	(–0.01, 0.16)	0.100
Diet × Home		–0.05	(–1.15, 0.29)	0.242
Externalizing ($n = 699$)	0.06			
Total HOME score		–0.24	(–0.60, –0.29)	<0.001
Total diet quality score (HEI)		0.03	(–0.06, 0.11)	0.539
Diet × Home		0.07	(–0.13, 1.23)	0.115
Adaptability ($n = 700$)	0.03			
Total HOME score		0.07	(0.26, 0.54)	0.088
Total diet quality score (HEI)		0.01	(–0.02, 0.13)	0.757
Diet × Home		–0.14	(–1.38, –0.13)	<0.001

[1]Linear regression model was used to analyze the data. BASC-2, Behavior Assessment System for Children–2nd Edition; BRIEF-P, Behavior Rating Inventory of Executive Functioning–Preschool Edition; EF, executive function; HEI, Healthy Eating Index; HOME, Home Observation Measurement of the Environment.

maternal postpartum depression (statistically significant for all 3 outcomes) and maternal smoking during pregnancy (statistically significant for the BASC-2 adaptability outcome) (**Supplemental Table 1**).

To better understand the impact of maternal pregnancy diet quality in home environments marked by less or more stimulation and/or support, we dichotomized HOME scores at the median for the current sample. For each of the statistically significant interactions noted, associations between prenatal maternal diet quality and child EF and behavior scores were examined in less (below median split) or more (above median split) stimulating/supportive home environments (**Supplemental Figure 2**).

These analyses suggest that increased prenatal maternal diet quality in our sample was associated with better working memory (β: –0.17; 95% CI: –0.57, –0.10; $P = 0.007$), planning (β: –0.09;

TABLE 3 Adjusted associations between maternal pregnancy diet quality, HOME scores, EF (BRIEF-P), and behavior (BASC-2) outcomes in children at 3–4 y of age[1]

Characteristic	R^2	Standardized β	95% CI	P value
BRIEF-P ($n = 698$)				
Working memory scale	0.12			
Total HOME score		–0.18	(–0.77, –0.04)	0.006
Total diet quality score (HEI)		0.12	(–0.02, 0.34)	0.064
Diet × Home		0.21	(0.82, 3.41)	0.001
Planning scale ($n = 699$)	0.10			
Total HOME score		–0.16	(–0.68, –0.38)	0.015
Total diet quality score (HEI)		0.12	(–0.02, 0.32)	0.060
Diet × Home		0.17	(0.38, 2.84)	0.007
BASC-2				
Adaptability composite ($n = 700$)	0.10			
Total HOME score		0.17	(0.08, 0.51)	0.008
Total diet quality score (HEI)		0.07	(–0.05, 0.18)	0.277
Diet × Home		–0.13	(–1.72, –0.08)	0.032

[1]Multiple linear regression models are adjusted for maternal BMI, years of education, depression at 6 mo, and prenatal smoking. BASC-2, Behavior Assessment System for Children–2nd Edition; BRIEF-P, Behavior Rating Inventory of Executive Functioning–Preschool Edition; EF, executive function; HEI, Healthy Eating Index; HOME, Home Observation Measurement of the Environment.

95% CI: –0.48, –0.08; $P = 0.006$), and adaptability (β: 0.18; 95% CI: 0.01, 0.35; $P = 0.044$) in less stimulating home environments. In more stimulating home environments, associations between pregnancy diet quality in mothers and working memory (β: 0.06; 95% CI: –0.07, 0.28; $P = 0.173$), planning (β: 0.02; 95% CI: –0.13, 0.24; $P = 0.452$), or adaptability (β: –0.06; 95% CI: –0.19, 0.07; $P = 0.345$) were not statistically significant.

Although not as consistently linked to our predictors and outcomes in the literature as our a priori covariates, we did conduct a series of post hoc sensitivity analyses to examine potential associations with other variables of interest. Maternal multivitamin usage, exclusive breastfeeding duration, maternal age, marital status, gestational age, and birthweight were added individually to our adjusted models to avoid overfitting our data. However, the results of our interactions were unchanged when these variables were examined. Finally, we also examined if diet quality moderated the links between home environment and our outcomes in children, as well as links between home environment and each of our outcomes in children at both high and low levels of diet quality (assessed by a median split of the data set). Home environment was statistically significantly associated with each of our outcome variables at both high and low levels of diet quality (Supplemental Figure 2).

6 Discussion

This study used data from a large Canadian birth cohort to investigate whether maternal pregnancy diet quality moderated the association between postnatal caregiving environment and offspring executive function and behavior in 3- to 4-y-old children. Our findings suggest that associations between better overall diet quality during pregnancy and offspring working memory, planning, and adaptability are stronger as stimulation in the home decreases. These findings raise the possibility that interventions aimed at optimizing pregnancy diet could be associated with improved offspring executive function and behavior in those at higher risk (i.e., less optimal home environments), in developed countries at least.

Previous studies have examined the joint effects of prenatal exposures and postnatal adversity on child neurodevelopment [e.g., Nomura et al. (81) and Ezpeleta et al. (82)], but these studies have generally reported cumulative risk effects. Indeed, Nomura et al. (81) reported that in 212 preschool children, the joint effect of maternal prenatal gestational diabetes mellitus (GDM) and low socioeconomic status postnatally on child attention-deficit/hyperactivity disorder at 6 y of age was greater than in those with GDM and less socioeconomic disadvantage. However, the findings presented here show not only that an absence of gestational adversity (poorer diet) is ideal but that the presence of better diet may actually be associated with more benefit in increasingly poor conditions. To our knowledge, this is the first study to show the positive associations between a prenatal exposure in the presence of increased postnatal adversity, suggesting that healthier prenatal diet quality could have the potential to benefit children from suboptimal home environments, one of the best validated predictors of poor school and behavioral performance in children.

Working memory and planning are the aspects of executive functioning that require the ability to hold onto information during a task and the prediction of future tasks/events, respectively (82). Adaptability, on the other hand, is a behavioral regulatory skill that requires the ability to adapt to changing environmental and socioemotional conditions (83). Despite different definitions, these skills share common neural underpinnings and rely largely on optimal functioning within the PFC, as well as its connections to subcortical areas such as the hippocampus (84, 85). It has been established that the hippocampal-PFC circuit is involved in working memory (86), planning (87), and adaptability/flexibility skills (88). This circuit supports cognition and behavior by allowing information to be relayed bidirectionally between these coactivated brain regions (85, 89). Therefore, optimal development of the foundations for this circuit during the prenatal period could be one mechanism by which optimal pregnancy diet can buffer associations between less stimulating postnatal home environments and child executive function and behavior.

Prenatal maternal diet quality is important for fetal neurodevelopment, and evidence suggests that it can adversely affect the development of the hippocampus and its associated connections (90). The hippocampus is a region that is sensitive to nutritional insults and undergoes rapid development prenatally (91, 92). Poorer prenatal nutrition has been linked to modified gene expression of genes critical for hippocampal development, function, and volume (93). Furthermore, synapses in the hippocampus of individuals exposed to poorer prenatal diets exhibit weaker connectivity with the PFC postnatally (94). Thomas et al. (95) have reported that provision of a combination of choline and DHA to female rats during gestation resulted in pups with significantly higher numbers of neurons in the hippocampus compared with a control group who did not receive the nutritional supplement or who received only a single nutrient supplement. Therefore, optimal prenatal development of the PFC-hippocampal circuit may depend on the synergistic effect of exposure to multiple nutrients (as might be present in good overall diet). As a result, good prenatal diet may play a role in altering hippocampal-PFC circuitry, which could result in improvements in cognitive and behavioral deficits, including working memory, cognitive flexibility, adaptability, emotion regulation, and planning (96).

Regardless, it is important that our results suggest that better pregnancy diet quality may be associated with beneficial effects in families and children who may be more vulnerable to problems with cognition and behavior be replicated given the massive potential public health potential of these findings. We should also note that we did not observe associations between maternal diet quality and behavior (internalizing and externalizing) problems in offspring at ages 3–4 y. This may be explained by a lower sensitivity to behavioral vulnerabilities in offspring at this age. The BASC-2 could also lack the sensitivity needed to detect these interactions. However, reassessment of behavioral outcomes later in life may demonstrate a different finding. Finally, because children exposed to poorer home environments appear to exhibit problems with executive function, this may increase the risk of emotional and behavioral outcomes later in life.

However, it is important to view the results of this work with the following limitations in mind. First, only the home environment was used as a marker of postnatal adversity in this study. Although there are other forms of adversity, we chose home environment because it is one of the best understood factors affecting child EF and behavioral development (97). However, given its correlation with other forms of adversity (91), it may be a reasonable proxy for this construct as a whole. Another limitation is that we did not have a measure of children's postnatal nutrition, which can affect brain development postnatally. However, other groups [e.g., Jacka et al. (98)] have reported that maternal gestational diet can predict behavioral and emotional problems in offspring independent of postnatal child diet. Third, the study used a short-form (46-item) version of the FFQ to estimate overall dietary intake, which may have limited the extent of our dietary assessment. Although other short-form versions of the FFQ (i.e., 52-item) are validated measures of dietary intake (39), future studies could use more comprehensive versions of the FFQ or other measures of pregnancy diet. Fourth, although we did adjust for maternal education, this is not likely to be able to completely control for the impact of maternal EF. Fifth, given that this was an exploratory study, future studies that include more diverse samples of mother–child dyads are needed. Sixth, although our study adjusted for variables with associations between each of our covariates and our child outcome variables, future studies could examine additional covariates that may influence the results. Last, our findings require replication before informing public health efforts because our (Canadian) sample appeared well educated and potentially well supported. For context, we compared our demographics to data reported by Statistics Canada (99) on mother and childbirth outcomes in 2019. The average age of mothers at birth was 30.7 years, 62% of mothers were married, 35% of mothers had a university degree, average birthweight of infants was 3315 g, and 91% of infants were born at gestational ages 37–41 wk. As a result, the present results may only be generalizable to similar groups, namely those in Western nations, and mothers who may be relatively less socioeconomically disadvantaged. Confirmation of these findings in more diverse areas and samples is required to assess the full potential for pregnancy diet to improve executive function and behavior, particularly in more vulnerable families.

In this study, we used data from a large Canadian cohort to show that better maternal pregnancy diet quality may be associated with better working memory, planning, and adaptability in children, an association that was stronger with decreasing levels of stimulation and support present in the home. Because pregnancy diet is potentially modifiable, public health has the mandate and capacity to introduce broad and targeted interventions, and given that women are more motivated to make healthy changes during pregnancy than at any other time in their lives, improving maternal diet quality during pregnancy could represent an important potential future means by which public health units in Western countries could positively affect child neurodevelopment, particularly for families that face challenges to providing optimally stimulating home environments for their children.

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