




Association of Gestational Diabetes Mellitus and Perinatal Maternal Depression with Early Childhood Behavioral Problems: An Environmental Influences on Child Health Outcomes (ECHO) Study

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Abstract

This study examined the association of gestational diabetes mellitus (GDM), prenatal, and postnatal maternal depressive symptoms with externalizing, internalizing, and autism spectrum problems on the Preschool Child Behavior Checklist in 2379 children aged 4.12±0.60 (48% female; 47% White, 32% Black,

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15% Mixed Race, 4% Asian, <2% American Indian/Alaskan Native, <2% Native Hawaiian; 23% Hispanic). Data were collected from the NIH Environmental influences on Child Health Outcomes (ECHO) Program from 2009–2021. GDM, prenatal, and postnatal maternal depressive symptoms were each associated with increased child externalizing and internalizing problems. GDM was associated with increased autism behaviors only among children exposed to perinatal maternal depressive symptoms above the median level. Stratified analyses revealed a relation between GDM and child outcomes in males only.

A robust literature under the Developmental Origins of Health and Disease (DOHaD) framework has demonstrated the role of environmental exposures in shaping offspring life course neurodevelopmental outcomes through fetal programming mechanisms. Gestational diabetes mellitus (GDM), defined as diabetes that was not clearly present prior to pregnancy, but develops during gestation (American Diabetes Association, 2021), has been linked to both adverse perinatal maternal mental health and child neurodevelopmental outcomes (Cai et al., 2016; Chen et al., 2021; Delanerolle et al., 2021; Rowland & Wilson, 2021; Wilson et al., 2020). Prior research suggests an association between GDM with perinatal maternal depression (Delanerolle et al., 2021; Wilson et al., 2020). GDM and prenatal depression affect approximately 10% and 13% of women in the United States, respectively. Each diagnosis is associated with an increased risk for neurodevelopmental sequelae in offspring mediated through independent or overlapping fetal programming mechanisms (Burlina et al., 2019; Fraser & Lawlor, 2014; Shuffrey & Fifer, 2020). Additionally, maternal postpartum depression (PPD) is associated with behavioral dysregulation in offspring through postnatal maternal stress or caregiving-related pathways (Chen et al., 2021; Goodman, 2019; Rowland & Wilson, 2021). Despite the public health relevance, the impact of comorbid GDM and prenatal maternal depression or the potentially moderating role of postnatal maternal depression on child neurobehavioral outcomes has not been examined in a unified framework nor using a prospective cohort design.

Several large maternal cohort studies and subsequent meta-analyses have identified associations between in utero exposure to GDM and an increased risk for neurodevelopmental disorders (NDDs) in children. For example, GDM exposure has been associated with child autism spectrum disorder (ASD), with a pooled odds ratio (OR) of 1.42 (95% CI 1.22, 1.65) across 18 studies (Rowland & Wilson, 2021). However, results have been mixed when examining associations between GDM exposure and the prevalence of attention-deficit/hyperactivity disorder (ADHD) (Chen et al., 2021; Rowland & Wilson, 2021). In addition to specific NDDs, GDM exposure has been associated with variation in several other neurodevelopmental outcomes, including deficits or delays in auditory attention (Cai et al., 2016), explicit

and recognition memory (DeBoer et al., 2005; Nelson et al., 2000, 2003; Riggins et al., 2009), sensorimotor systems (Ghassabian et al., 2016; Ornoy et al., 2001), and social processes (Krzczykowski et al., 2019). Research focused on identifying biological pathways between GDM and neurodevelopmental sequelae in offspring has suggested epigenetic changes, altered maternal immune or hypothalamic–pituitary–adrenal (HPA) axis function, placental dysregulation, hormonal changes, or pathologic levels of glucose, lipids, or amino acids as possible fetal programming mechanisms (Edalat et al., 2013; Kong et al., 2020; Money et al., 2018; Pantham et al., 2015; Richardson & Carpenter, 2007).

GDM is also a risk factor for perinatal maternal depression, which can affect child neurobehavioral development through independent or overlapping fetal programming mechanisms in utero and altered caregiving behaviors in the postpartum. A recent meta-analysis reported that GDM was associated with increased depressive symptoms around the time of a GDM diagnosis (OR 2.08; 95% CI 1.42, 3.05), following a GDM diagnosis (OR 1.41; 95% CI 0.88, 2.25), and in the postpartum period (OR 1.59; 95% CI 1.26, 2.00) (Wilson et al., 2020). Other large, diverse cohort studies in the United States have identified comorbid GDM and prenatal maternal depression are associated with increased risk for postpartum depression (Shuffrey et al., 2022). Prenatal maternal depression is also associated with an increased risk for child ASD, ADHD (Chen et al., 2020; Rai et al., 2013; Wiggins et al., 2019), deficits in social processes (Leis et al., 2014; Madigan et al., 2018), and psychopathology (O'Donnell et al., 2014). Similar to GDM, studies examining potential biological pathways underlying the associations between prenatal maternal depression and child neurobehavioral outcomes have demonstrated epigenetic changes, altered maternal immune system function, and altered HPA axis function as possible fetal programming mechanisms (Christian et al., 2009; Coussons-Read et al., 2007; Edalat et al., 2013; Money et al., 2018; Pantham et al., 2015; Richardson & Carpenter, 2007; Rogers et al., 2020). In the postpartum period, maternal depression can potentiate the effects of in utero exposure to GDM and depression through altered maternal parenting behaviors, impaired maternal–infant bonding, or other postnatal pathways, potentially

acting as an effect modifier (Goodman, 2019). For example, maternal major depressive disorder in the first year postpartum is associated with increased child behavior problems between 1.5 and 12 years of age (Bagner et al., 2010).

GDM and perinatal maternal depression are frequently co-morbid, yet prior studies have not examined the interactive effects of these exposures on child neurobehavioral outcomes. Externalizing and internalizing behaviors are cross-cutting dimensions of several neurodevelopmental disorders. Externalizing behaviors are characterized by disruptive conduct, aggression, hyperactivity, and attentional problems whereas internalizing behaviors are characterized by depressive and anxiety symptoms, social withdrawal, and somatic complaints (Achenbach et al., 2016). One prior study has examined the role of GDM and postnatal maternal depression on child externalizing and internalizing outcomes. A study of 815 mother–child dyads examined the association between maternal metabolic disorders (GDM $n=60$, overweight/obese $n=342$) and externalizing and internalizing behaviors at 2 years of age operationalized by the parent-report preschool child behavior checklist (CBCL 1½-5) (Krzeczkowski et al., 2019). GDM and higher pre-pregnancy body mass index (BMI) were associated with increased externalizing and internalizing problems (Krzeczkowski et al., 2019). After adjusting for maternal PPD and socioeconomic status (SES), only gestational diet, though not maternal PPD, was associated with externalizing and internalizing problems. This suggests maternal PPD may be a mediator on the causal pathway between GDM, prenatal depression, and behavioral outcomes or a postnatal effect modifier (Krzeczkowski et al., 2019). However, this study did not include measurements of prenatal maternal depressive symptoms.

Together, this evidence underscores a gap in knowledge surrounding the possible joint roles of GDM and prenatal maternal depressive symptoms in shaping early childhood behavioral development through potentially interactive fetal programming mechanisms. Additionally, postnatal maternal depressive symptoms may moderate the effects of adverse in utero exposures. The objective of this analysis was to examine the independent and joint effects of in utero exposure to GDM and prenatal maternal depressive symptoms on behavioral problems during early childhood as measured by the Preschool CBCL (internalizing, externalizing, and autism spectrum problems). We hypothesized that in utero exposure to comorbid GDM and higher levels of prenatal maternal depressive symptoms would be associated with increased child externalizing and autism spectrum problems. We also hypothesized that increased postnatal maternal depressive symptoms would moderate the association between GDM, increased prenatal maternal depressive symptoms, and increased child externalizing and autism spectrum

problems. Although not the primary focus of the current analyses, we additionally hypothesized that prenatal and postnatal maternal depressive symptoms would be associated with increased internalizing problems. Finally, although several sex differences have been noted in developmental programming models (Aiken & Ozanne, 2013), few studies have systematically investigated these differences. Leveraging the relatively large sample size, we explored potential sexually dimorphic effects in all models.

METHOD

Study design and participants

Data for this analysis were collected through the National Institutes of Health's (NIH) Environmental influences on Child Health Outcomes (ECHO) Program, which consists of longitudinal birth cohort studies across the United States and Puerto Rico. The goal of the ECHO Program is to investigate how early-life environmental exposures affect child health and development across five primary domains: pre-, peri-, and postnatal outcomes; upper and lower airway conditions; obesity; neurodevelopment; and positive health (Blaisdell et al., 2021; Forrest et al., 2018; Gillman & Blaisdell, 2018). The ECHO-wide protocol can be found at: <https://echochildren.org/echo-program-protocol/>. ECHO-wide analyses are pre-registered through the ECHO program via a two-step analysis proposal process. Access to ECHO-wide de-identified data is not granted until after an analysis proposal is approved.

Current study: Participants in the current analysis included children enrolled in an ECHO cohort between 2 and <6 years of age with available data on the CBCL 1½-5 which was collected between 2009 and 2021. Additional inclusion criteria included information regarding prenatal maternal GDM status, a minimum of one self-reported prenatal maternal depressive symptom assessment, and a minimum of one self-reported postnatal maternal depressive symptom assessment collected during the first postpartum year ($n=2500$). Exclusion criteria included participants in an ECHO cohort contributing fewer than 25 participants to the analysis or contributing to less than 1% of the total sample size ($n=30$ participants from several cohorts) or missing information regarding the enrollment ECHO cohort ($n=91$, 3.6%). After exclusions, a total of 2379 child participants across five ECHO cohorts enrolled from five U.S. states (Colorado, Massachusetts, New York, Pennsylvania, and Tennessee) met the inclusion criteria and were included in the current analysis. All participants consented to participate in their local ECHO cohort and share their information with the ECHO consortia. Both a central and cohort-specific



Institutional Review Board monitored human subject activities at each cohort site and the centralized ECHO Data Analysis Center. Written informed consent and parent's/guardian's permission were obtained along with child assent as appropriate, for ECHO-wide Cohort Data Collection Protocol participation. Reporting followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for reporting observational studies.

Gestational Diabetes mellitus

Information regarding GDM was harmonized across ECHO cohorts based on either the mother's gestational diabetes diagnosis from self-report using ECHO case report forms or maternal medical record abstraction.

NIH patient-reported outcomes measurement information system depression scale (PROMIS®-D)

The PROMIS-D scale (Cella et al., 2010) was utilized by the NIH ECHO Program to harmonize different self-report depression symptom instruments used by individual ECHO cohorts into one common scale. This enables researchers interested in aggregating data across studies that use the Edinburgh Prenatal/Postnatal Depression Scale (EPDS), the Adult Self-Report (ASR) Achenbach System Depression Problems Syndrome Scale, the Brief Symptom Inventory-18 item (BSI-18), the Center for Epidemiological Studies Depression Scale (CES-D), the Patient Health Questionnaire-9 (PHQ-9), Beck Depression Inventory, the SF-36 Health Survey Mental Health Summary, or the Kessler 6 Mental Health Scale. By placing all scores on the same PROMIS-D T-score metric, scores can be compared and used in combined analyses that span multiple studies. Since PROMIS-D allows for a comparison of depressive symptoms across ECHO cohorts, data from the original depression instruments were not available for this analysis. PROMIS-D T-scores are referenced to a mean of 50 and standard deviation of 10 with respect to the general adult U.S. population, such that individuals with T-scores of 50 have depressive symptom severity equal to the mean in the general adult U.S. population. In the current analysis, prenatal maternal depressive symptoms were originally measured using the Brief Symptom Inventory-18 item (BSI-18) (40%), the Edinburgh Prenatal/Postnatal Depression Scale (EPDS) (30%), and the Patient Health Questionnaire-9 (PHQ-9) (30%) assessments prior to being harmonized to the PROMIS-D. All participants were administered the EPDS (100%) for assessment of postnatal depressive symptoms up to 1 year postpartum. Both prenatal and postnatal maternal depressive symptoms were harmonized from the original assessment

scales described above to PROMIS-D T scores by the ECHO Data Analysis Center (DAC).

Preschool child behavior checklist 1½-5 (CBCL 1½-5)

The CBCL is one of the most widely used parental report measures of child social, emotional, and behavioral concerns. The Preschool CBCL consists of 100 items that describe children's behaviors such as “*doesn't get along well with other children*” where parents are asked to describe their child's behavior now or within the past 2 months on a Likert scale where 0=Not True (as far as you know), 1=Somewhat or Sometimes True, and 3=Very True or Often True. The original factor analysis of the CBCL revealed 7 first-order factors (emotionally reactive, anxious/depressed, somatic complaints, withdrawn, sleep problems, attention problems, and aggressive behaviors) and 2 second-order factors (externalizing problems and internalizing problems) (Achenbach & Rescorla, 2000). The CBCL also includes Diagnostic and Statistical Manual of Mental Disorders (DSM)-oriented scales that map on to diagnostic constructs, including the autism spectrum problems subscale (Achenbach et al., 2003). A study examining the utility of the autism spectrum problems subscale as an ASD screening tool demonstrated that a receiver operating characteristic analyses (ROC) with a cut point of a T-score ≥ 60 yielded a sensitivity of 77% and a specificity of 97%–99% in predicting ASD in a cohort of children with and without familial risk for ASD (Rescorla, Winder-Patel, et al., 2019). A separate study demonstrated that the autism spectrum problems subscale indicated good measurement invariance for configural and metric invariance through confirmatory factor analysis in a sample of 20,000 participants across multiple societies (Rescorla et al., 2020) and that items from the autism spectrum problems subscale were stable over time (Rescorla, Ghassabian, et al., 2019).

Maternal and child sociodemographic and medical history

Maternal race, ethnicity, pre-pregnancy weight, age at delivery, delivery mode, child sex assigned at birth, gestational age, and age at CBCL administration were harmonized across ECHO cohorts. Sociodemographic and medical history data were assessed via maternal self-report using ECHO case report forms or through maternal–infant medical record abstraction.

Statistical analyses

All statistical analyses were conducted in R version 4.1.0 in a secure virtual private network platform hosted by the Research Triangle Institute (RTI) using de-identified data.

Sociodemographic characteristics of mothers with and without GDM and their children with and without exposure to GDM were compared using one-way analyses of variance (ANOVAs), the chi-squared test, or Fisher's exact test. Primary analyses consisted of a series of linear regression models to estimate the interaction terms (two-way and three-way) and simple main effects and of maternal GDM (binary), prenatal maternal depressive symptoms (continuous PROMIS T-score), and postnatal maternal depressive symptoms (continuous PROMIS T-score) in the same model with each of the following CBCL 1½-5 domains (separately): externalizing problems T-score, internalizing problems T-score, and autism spectrum problems T-score. Unadjusted models were restricted to GDM, prenatal maternal depressive symptoms, and postnatal maternal

depressive symptoms as predictors with the original depression instrument (BSI-18, EPDS, or PHQ-9) coded as a nominal covariate. Adjusted models additionally included maternal race, ethnicity, age at delivery, pre-pregnancy BMI category (underweight or normal weight vs. overweight or obese), child-assigned sex at birth, gestational age category (preterm vs. term), and age at CBCL 1½-5 assessment. Missing covariate data are reported in Table 1. Missing data were handled using the missing-indicator method. Significant main effects and interactions were probed through secondary stratified analyses. We observed a main effect of child-assigned sex at birth in our planned analyses, therefore post hoc analyses consisted of repeating linear regression models stratified by child-assigned sex at birth. For all models, we report the regression coefficients

TABLE 1 Participant demographic information.

	GDM (<i>n</i> =216)	Non-GDM (<i>n</i> =2163)	Overall (<i>n</i> =2379)
Maternal race			
American Indian or Alaskan Native	<5 (<1%) ^a	<10 (<1%) ^a	<15 (<2%) ^a
Asian	18 (8.3%)	82 (3.8%)	100 (4.2%)
Black	37 (17.1%)	719 (33.2%)	756 (31.8%)
Mixed Race	46 (21.3%)	308 (14.2%)	354 (14.9%)
Native Hawaiian or Other Pacific Islander	<5 (<3%) ^a	<15 (<1%) ^a	<20 (<2%) ^a
White	110 (50.9%)	1003 (46.4%)	1113 (46.8%)
Missing	<5 (<1%) ^a	<35 (<2%) ^a	<35 (<2%) ^a
Maternal ethnicity			
Hispanic or Latino	78 (36.1%)	465 (21.5%)	543 (22.8%)
Non-Hispanic or Latino	138 (63.9%)	1692 (78.2%)	1830 (76.9%)
Missing	<5 (<1%) ^a	<5 (<1%) ^a	<5 (<5%) ^a
Maternal age at delivery			
Mean (SD)	32.6 (5.66)	29.3 (5.89)	29.6 (5.95)
Median (min, max)	33.0 (18.0, 49.0)	29.0 (16.0, 50.0)	30.0 (16.0, 50.0)
Maternal pre-pregnancy BMI			
Underweight or normal weight	63 (29.2%)	990 (45.8%)	1053 (44.3%)
Overweight or obese	125 (57.9%)	1032 (47.7%)	1157 (48.6%)
Missing	28 (13.0%)	141 (6.5%)	169 (7.1%)
Birth mode			
Cesarean	81 (37.5%)	643 (29.7%)	724 (30.4%)
Vaginal	130 (60.2%)	1477 (68.3%)	1607 (67.5%)
Missing	<8 (<3%) ^a	<45 (<3%) ^a	<50 (<2.5%) ^a
Gestational age category			
Preterm	22 (10.2%)	135 (6.2%)	157 (6.6%)
Term	194 (89.8%)	2028 (93.8%)	2222 (93.4%)
Child's biological sex at birth			
Male	126 (58.3%)	1102 (50.9%)	1228 (51.6%)
Female	90 (41.7%)	1061 (49.1%)	1151 (48.4%)
Child's age at CBCL assessment			
Mean (SD)	4.21 (0.582)	4.11 (0.606)	4.12 (0.604)
Median (min, max)	4.08 (2.00, 5.83)	4.00 (2.00, 5.92)	4.00 (2.00, 5.92)

Abbreviations: BMI, body mass index; CBCL, child behavior checklist; GDM, gestational diabetes mellitus; SD, standard deviation.

^aThe ECHO Program requires masking of cells with sample sizes <5.



(β) and the standard error of estimates for each main effect and the significant interaction term. Finally, secondary analyses consisted of logistic regression analyses to estimate the interaction terms and simple main effects of in utero exposure to GDM and prenatal and postnatal maternal depressive symptoms with clinically relevant scores on the CBCL: externalizing problems (T -score ≥ 64), internalizing problems (T -score ≥ 64), and autism spectrum problems (T -score ≥ 70). Logistic regression analyses were estimated for both univariate models (e.g., GDM only, prenatal maternal depressive symptoms only, and postnatal maternal depressive symptoms only) and adjusted models. We report unadjusted and adjusted odds ratios (ORs) and the 95% confidence intervals (CIs) of the ORs.

RESULTS

Sample characteristics

The final sample consisted of 2379 children, with 216 exposed to GDM and 2163 not exposed (Table 1). Compared with the non-GDM group, a greater proportion of mothers with GDM self-identified as Asian ($\chi^2=8.97, p=.0028$), Black ($\chi^2=22.78, p<.0001$), mixed race ($\chi^2=7.17, p=.0074$), or Hispanic/Latina ($\chi^2=22.99, p<.0001$). No significant differences were observed in the proportion of mothers who self-identified as White between the GDM and non-GDM groups. We were unable to examine demographic differences in the proportion of mothers who self-identified as American Indian or Alaskan Native and Native Hawaiian or Other Pacific Islander between the GDM and non-GDM groups due to small cell sizes. Women with GDM were more likely to be overweight or obese prior to pregnancy compared with women without GDM ($X^2=27.88, p<.0001$). Women with GDM had increased prenatal maternal depressive symptoms, as measured by PROMIS-D T -scores, compared with women without GDM ($F(1, 2377)=7.66, p=.006$). No significant differences were observed in postnatal maternal depressive symptoms between women with and without GDM ($p>0.05$). In addition, no significant differences were detected in the birth mode between children with and without exposure to GDM. Children with in utero exposure to GDM were more likely to be born preterm (<37 weeks' gestation) ($\chi^2=4.34, p<.05$) and were older at the CBCL assessment ($F(1, 1420)=41.79, p<.0001$). Child sex did not differ by in utero exposure to GDM.

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child externalizing problems

Linear regression models showed no significant two or three-way interaction effect of GDM and prenatal

and postnatal maternal depressive symptoms on child externalizing problems. Simple main effects of GDM and prenatal and postnatal maternal depressive symptoms on child externalizing problems were observed in the adjusted model ($F(15, 2363)=16.99, p<.0001, \text{adj. } R^2=0.09$). GDM ($\beta=1.86\pm 0.69$), prenatal maternal depressive symptoms ($\beta=0.19\pm 0.03$), and postnatal maternal depressive symptoms ($\beta=0.21\pm 0.03$) were each independently associated with increased child externalizing problems (Figure 1a). Significant covariates in the adjusted models included child age at CBCL assessment ($\beta=-0.86\pm 0.33$) and female sex ($\beta=-1.64\pm 0.39$). Due to the significant effect of child-assigned sex at birth on externalizing problems, *post-hoc* analyses were conducted.

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child externalizing problems stratified by sex

Post-hoc analyses stratified by child sex revealed an association between in utero exposure to GDM and externalizing problems in male children ($\beta=2.29\pm 0.94$), but not in female children ($\beta=0.59\pm 1.07$) (Figure 1b). Prenatal and postnatal maternal depressive symptoms remained predictors of externalizing problems in both male and female children.

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child internalizing problems

Linear regression models showed no two or three-way interaction effect of GDM and prenatal and postnatal maternal depressive symptoms on child internalizing problems. The main effects of GDM and prenatal and postnatal maternal depressive symptoms on child internalizing problems were observed in the adjusted model ($F(15, 2363)=27.48, p<.0001, \text{adj. } R^2=0.14$). GDM ($\beta=1.50\pm 0.71$), prenatal maternal depressive symptoms ($\beta=0.22\pm 0.03$), and postnatal maternal depressive symptoms ($\beta=0.22\pm 0.03$) were each independently associated with increased child internalizing problems (Figure 1a). Significant covariates in the adjusted models included child age at CBCL assessment ($\beta=0.67\pm 0.33$) and maternal age at delivery ($\beta=-0.71\pm 0.38$). Child-assigned sex at birth was not a significant predictor of internalizing problems. However, due to analyses revealing an effect of GDM on externalizing problems in male children only, *post-hoc* analyses stratified by child-assigned sex at birth were conducted to understand the potential role of sex in the association between GDM and child internalizing problems.

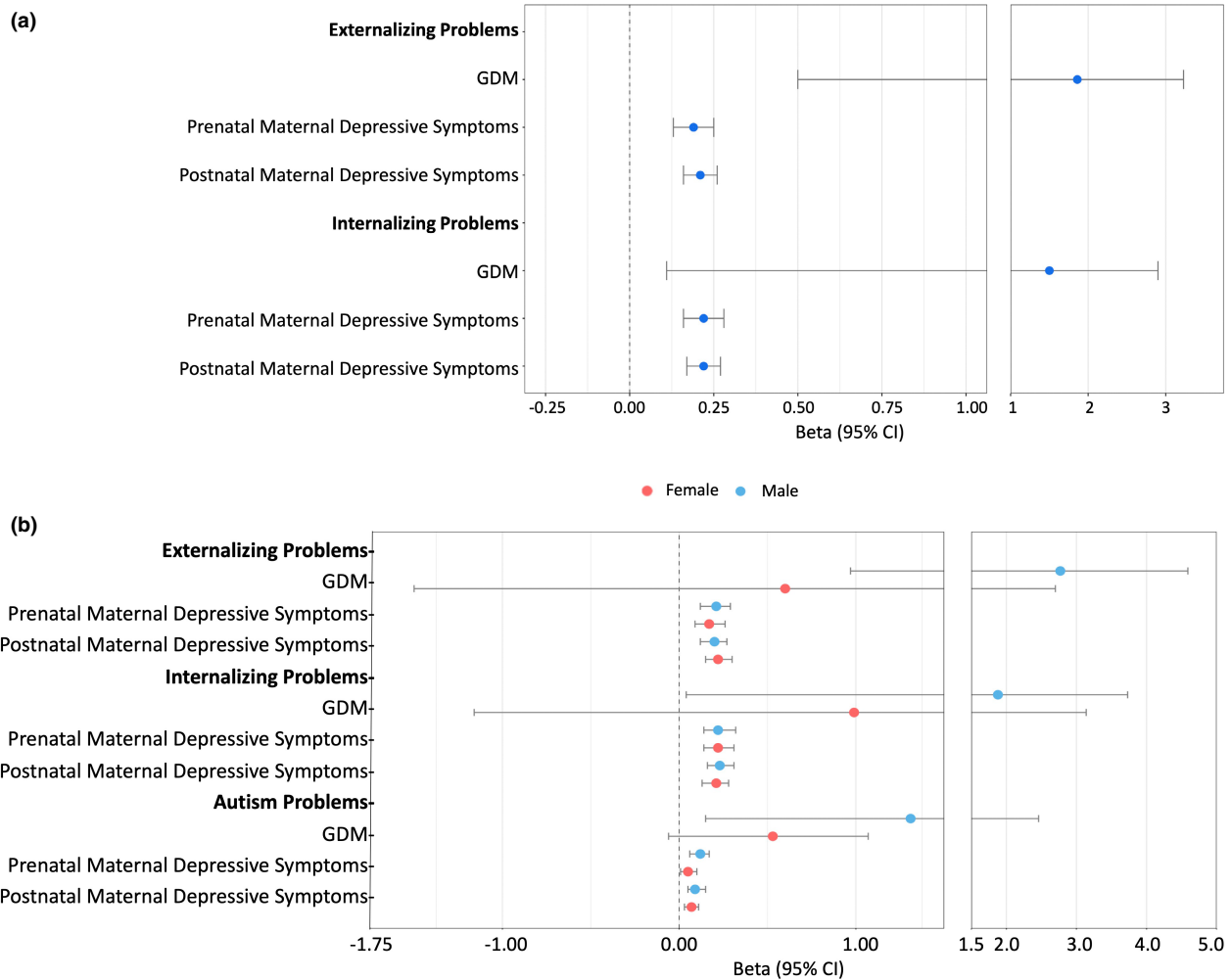


FIGURE 1 Association between gestational diabetes mellitus (GDM) and prenatal and postnatal maternal depressive symptoms (y-axis) (a) with behavioral outcomes on the child behavior checklist (CBCL) (x-axis), (b) stratified by child's biological sex with behavioral outcomes on the Child Behavior Checklist (CBCL) (x-axis). Error bars reflect fully adjusted β coefficients with 95% confidence intervals (CIs).

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child internalizing problems stratified by sex

Post-hoc analyses stratified by child sex revealed an association between in utero exposure to GDM and internalizing problems in male children ($\beta=1.89\pm 0.94$), but not in female children ($\beta=0.99\pm 1.10$) (Figure 1b). Prenatal and postnatal maternal depressive symptoms remained predictors of internalizing problems in both male and female children.

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child autism spectrum problems

Linear regression models showed a three-way interaction effect of GDM and prenatal and postnatal maternal depressive symptoms on child autism spectrum problems in the adjusted model ($F(19, 2359)=12.21, p<.0001$,

adj. $R^2=0.08$). To better interpret the three-way interaction effect of GDM and prenatal and postnatal maternal depressive symptoms on child autism spectrum problems, we stratified by maternal postnatal depressive symptoms.

Association of GDM and prenatal maternal depressive symptoms with child autism spectrum problems stratified by postnatal maternal depressive symptoms. We were not adequately powered to run stratified analyses based on a clinically relevant cutoff for maternal postnatal depressive symptoms, therefore we examined the two-way interaction effect and main effects of GDM and prenatal maternal depressive symptoms at lower levels of postnatal depressive symptoms and higher levels of postnatal depressive symptoms based on a median split (Median = 43.7). Stratified analyses within the lower postnatal maternal depressive symptoms group ($N=1007$) revealed no significant two-way interaction effect of GDM and prenatal maternal depression on child autism spectrum problems. Within the lower postnatal maternal depressive symptoms group, there was a main effect of

prenatal maternal depressive symptoms ($\beta=0.09\pm 0.02$), but not GDM status ($\beta=0.58\pm 0.62$), on child autism spectrum problems ($F(13, 993)=5.35, p<.0001, \text{adj. } R^2=0.05$). Similarly, stratified analyses within the higher postnatal maternal depressive symptoms group ($N=1372$) revealed no significant two-way interaction effect of GDM and prenatal maternal depression on child autism spectrum problems. However, within the higher postnatal maternal depressive symptoms group there was a main effect of both GDM status ($\beta=1.21\pm 0.57$) and prenatal maternal depressive symptoms ($\beta=0.11\pm 0.03$) on child autism spectrum problems ($F(13, 1358)=10.43, p<.0001, \text{adj. } R^2=0.08$) (Figure 2a).

Association of GDM and postnatal maternal depressive symptoms with child autism spectrum problems stratified by prenatal maternal depressive symptoms. We conducted a sensitivity analysis to determine if the association between GDM and autism problems was similarly moderated by prenatal maternal depressive symptoms. We examined the two-way interaction effect and main effects of GDM and postnatal maternal depressive symptoms at

lower levels of prenatal depressive symptoms and higher levels of prenatal depressive symptoms based on a median split (Median=45.9). Stratified analyses within the lower prenatal maternal depressive symptoms group ($N=1167$) revealed no significant two-way interaction effect of GDM and postnatal maternal depression on child autism spectrum problems. Within the lower prenatal maternal depressive symptoms group, there was a main effect of postnatal maternal depressive symptoms ($\beta=0.12\pm 0.02$), but not GDM status ($\beta=-0.30\pm 0.02$), on child autism spectrum problems ($F(11, 1155)=5.19, p<.0001, \text{adj. } R^2=0.04$). Similarly, stratified analyses within the higher prenatal maternal depressive symptoms group ($N=1212$) revealed no significant two-way interaction effect of GDM and postnatal maternal depression on child autism spectrum problems. However, within the higher prenatal maternal depressive symptoms group there was a main effect of both GDM status ($\beta=1.38\pm 0.58$) and postnatal maternal depressive symptoms ($\beta=0.08\pm 0.02$) on child autism spectrum problems ($F(11, 1200)=8.68, p<.0001, \text{adj. } R^2=0.06$) (Figure 2b).

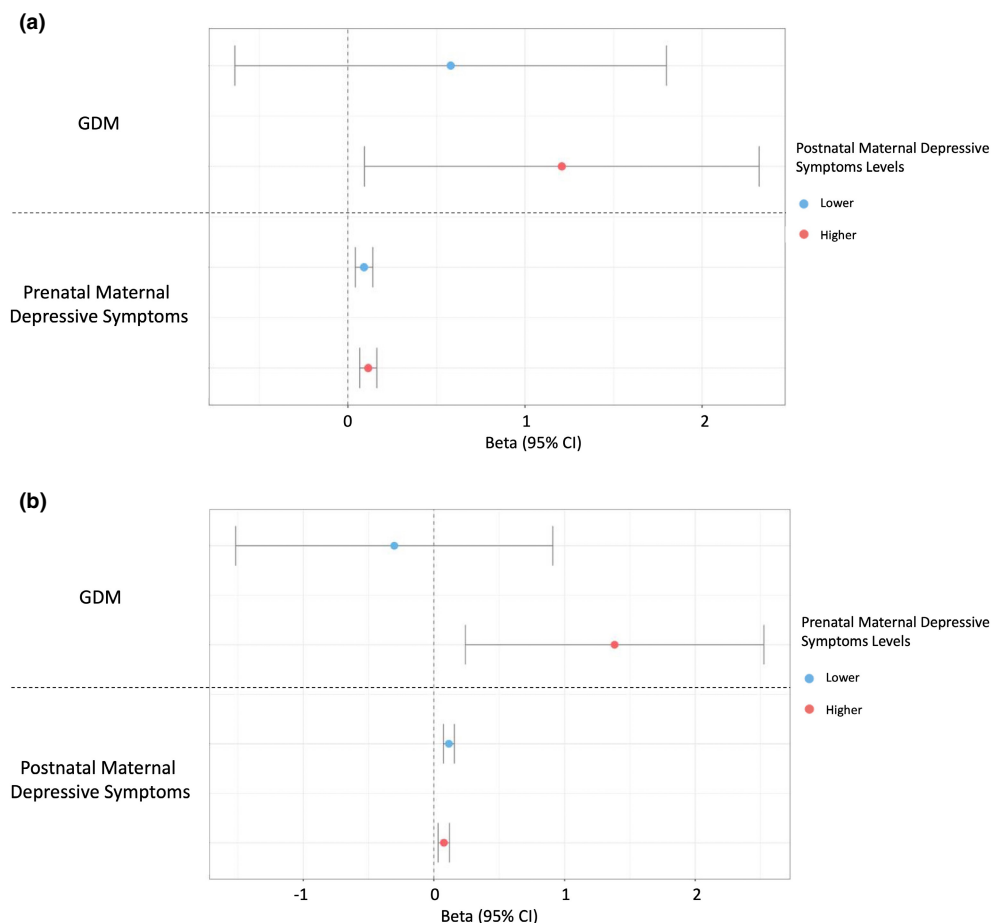


FIGURE 2 Association between gestational diabetes mellitus (GDM) and (a) prenatal maternal, (b) postnatal maternal depressive symptoms (y -axis) with child autism problems on the DSM-oriented child behavior checklist (CBCL) scale (x -axis) stratified by lower and higher levels of postnatal maternal depressive symptoms. Error bars reflect univariate and fully adjusted odds ratios (ORs) with 95% confidence intervals (CIs).

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child autism spectrum problems stratified by sex

Due to analyses revealing an effect of GDM on externalizing and internalizing problems in male children only, *post-hoc* analyses stratified by child-assigned sex at birth were conducted to understand the potential role of sex in the association between GDM and child autism spectrum problems. *Post-hoc* linear regression models showed no three-way interaction effect of GDM and prenatal and postnatal maternal depressive symptoms on child autism spectrum problems in sex-stratified models. *Post-hoc* analyses stratified by child sex revealed a similar, but non-significant, two-way interaction effect of GDM and prenatal maternal depressive symptoms on child autism spectrum problems in both sexes. We, therefore, examined the main effects in sex-stratified analyses. In the adjusted models stratified by male sex, we observed a significant main effect of GDM ($\beta = 1.30 \pm 0.59$), prenatal maternal depressive symptoms ($\beta = 0.12 \pm 0.03$), and postnatal maternal depressive symptoms ($\beta = 0.09 \pm 0.02$) with increased autism spectrum problems (Figure 1b). In the adjusted models stratified by the female sex, no main effect of GDM on child autism spectrum problems was observed (Figure 1b). However, in the adjusted models stratified by the female sex, we observed significant main effects of both prenatal maternal depressive symptoms ($\beta = 0.05 \pm 0.02$) and postnatal maternal depressive symptoms ($\beta = 0.07 \pm 0.02$) with increased child autism spectrum problems (Figure 1b).

Associations of GDM and prenatal and postnatal maternal depressive symptoms with child clinically relevant symptoms

Logistic regression models showed no significant two or three-way interaction effects of GDM and prenatal and postnatal maternal depressive symptoms on any of the symptom scales when dichotomized into non-clinical versus clinically elevated symptoms (Table 2; Figure 3). In the fully adjusted models, GDM was associated with clinical levels of autism spectrum problems (OR 2.88; 95% CI 1.54, 5.17) (Figure 3). *Post-hoc* analyses stratified by child sex revealed an association between GDM and clinical levels of autism spectrum problems in male children only (OR 3.26; 95% CI 1.58, 6.41). GDM was not associated with clinical levels of externalizing or internalizing problems. In the fully adjusted models, prenatal maternal depressive symptoms were associated with clinical levels of internalizing problems (OR 1.04; 95% CI 1.01, 1.07), but not with clinical levels of externalizing problems or autism spectrum problems. Finally, postnatal maternal depressive symptoms were associated with clinical levels of externalizing problems (OR 1.06; 95% CI 1.03, 1.09), internalizing problems (OR 1.04; 95% CI

TABLE 2 CBCL clinical thresholds.

	GDM exposed (n=216)	Non-GDM exposed (n=2163)	Overall (n=2379)
Externalizing problems			
Below clinical cutoff	<210 (<97%)	<2085 (<97%)	<2295 (<97%)
Above clinical cutoff	<10 (4%)	<85 (5%)	<90 (<4%)
Internalizing problems			
Below clinical cutoff	205 (94.9%)	2070 (95.7%)	2275 (95.6%)
Above clinical cutoff	11 (5.1%)	93 (4.3%)	104 (4.4%)
Autism spectrum problems			
Below clinical cutoff	199 (92.1%)	2091 (96.7%)	2290 (96.3%)
Above clinical cutoff	17 (7.9%)	72 (3.3%)	89 (3.7%)

Abbreviations: CBCL, child behavior checklist; GDM, gestational diabetes mellitus.

1.01, 1.06), and autism spectrum problems (OR 1.05; 95% CI 1.02, 1.08).

DISCUSSION

The present study is the first to examine the interaction effects of GDM and prenatal and postnatal maternal depressive symptoms on behavioral outcomes during early childhood. Additionally, this study is the first to control for pre- and postnatal maternal depressive symptoms when examining associations between GDM and child autism-related outcomes.

When examining the interactive and main effects of GDM and prenatal and postnatal maternal depressive symptoms on child externalizing and internalizing behaviors, we demonstrated an association between GDM and prenatal and postnatal maternal depressive symptoms with both increased externalizing and internalizing problems. *Post-hoc* analyses revealed an association of GDM with child externalizing and internalizing problems for male children only, whereas pre- and postnatal maternal depressive symptoms were similarly linked to child externalizing and internalizing problems in both sexes. Although several prior studies have identified associations between pre- and postnatal maternal depression with child behavioral problems (Bagner et al., 2010; Leis et al., 2014; Madigan et al., 2018; O'Donnell et al., 2014), to our knowledge, this is the first study to identify links between GDM and child behavioral outcomes when controlling for both pre- and postnatal maternal depression. One prior report demonstrated an association between GDM and pre-pregnancy BMI with increased child externalizing and internalizing problems (Krzeczkowski et al., 2019). However, this study also

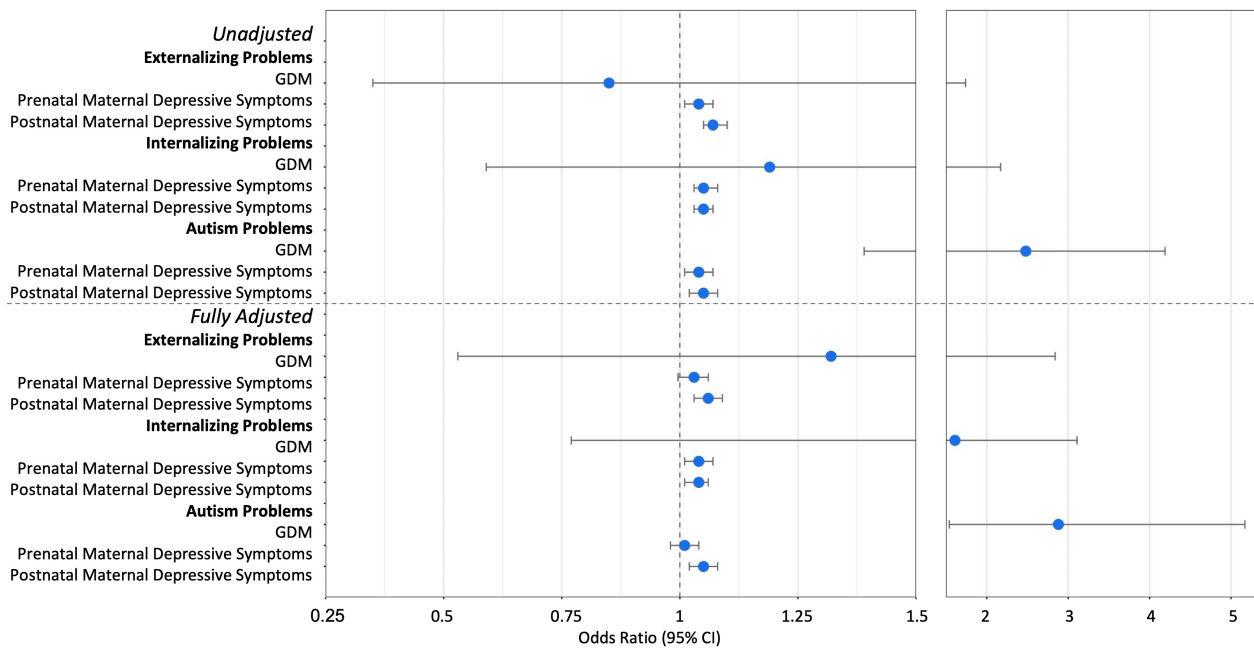


FIGURE 3 Association between gestational diabetes mellitus (GDM) and prenatal and postnatal maternal depressive symptoms (*y*-axis) with clinical behavioral outcomes on the child behavior checklist (CBCL) (*x*-axis). Error bars reflect univariate and fully adjusted odds ratios (ORs) with 95% confidence intervals (CIs).

found that maternal PPD and SES were postnatal effect modifiers (Krzeczkowski et al., 2019). Although we did not have data on household SES to include in the present report, postnatal maternal depressive symptoms were not an effect modifier in our analyses examining child externalizing or internalizing outcomes.

We additionally examined the interactive and main effects of GDM and prenatal and postnatal maternal depressive symptoms with child autism spectrum problems derived from the CBCL DSM-oriented scales. We demonstrated a significant three-way interaction effect between GDM and prenatal and postnatal maternal depressive symptoms with child autism spectrum problems. To further interpret this three-way interaction, we stratified by lower and higher levels of perinatal maternal depressive symptoms, based on a median split, in follow-up analyses. In children of mothers with either lower levels of prenatal or postnatal depressive symptoms, GDM status was not associated with increased child autism spectrum problems. In children of mothers with higher levels of prenatal or postnatal maternal depressive symptoms, both GDM status and maternal depressive symptoms were each associated with increased autism spectrum problems. Since we only observed an association between GDM and child autism behaviors at higher levels of prenatal or postnatal maternal depressive symptoms, our findings suggest perinatal maternal depressive symptoms acted as an effect moderator such that lower levels of perinatal maternal depressive symptoms were protective and higher levels of perinatal maternal depressive symptoms potentiated the effects of in utero exposure to GDM on child autism problems.

Research under the DOHaD framework postulates that exposure to an adverse in utero environment is associated with an increased risk for adverse physical health, developmental, or psychiatric outcomes through fetal programming mechanisms. Our findings linking GDM and prenatal maternal depression to increased autism spectrum problems are supported by animal studies that have demonstrated associations between increased maternal inflammation and HPA axis upregulation during pregnancy with behavioral changes in offspring (Money et al., 2018; Salari et al., 2016). Other studies have demonstrated intergenerational transmission of maternal stress based on transgenerational epigenetic alterations (Yehuda & Lehrner, 2018). In a two-hit animal model of prenatal maternal stress that was used to examine the interaction of prenatal psychological and immune stress, results revealed increased adverse maternal pregnancy outcomes, increased gestational length variation, and upregulation of uterine mRNA expression (Verstraeten, McCreary, Weyers, et al., 2019). A separate two-hit animal model of prenatal maternal stress demonstrated sex-specific consequences on offspring adult behavior (Verstraeten, McCreary, Falkenberg, et al., 2019).

Several developmental programming studies have demonstrated adverse in utero exposures result in different phenotypes for male and female offspring (Aiken & Ozanne, 2013). In the current analysis, GDM was linked to behavioral outcomes only in males, whereas pre- and postnatal maternal depressive symptoms similarly impacted both sexes. Although ASD, externalizing problems, and diagnoses associated with externalizing problems, such as ADHD, are all more prevalent among males (Santos et al., 2022), it is also possible that GDM

affects child neurobehavior in a sexually dimorphic manner. Animal models of GDM have demonstrated male, but not female, offspring display increased repetitive behaviors, but no differences in sociability (Aviel-Shekler et al., 2020), significantly increased HPA axis stress responses, and impaired sensorimotor gating (Bronson et al., 2017), and memory impairment (Zou et al., 2021). While not directly comparable, an animal model of prenatal maternal overweight or obesity demonstrated maternal high-fat diet resulted in decreased fetal and adult brain serotonin (5-HT) availability in males only via a feedback loop where increased inflammation dependent on macrophage Toll-like receptor 4 signaling resulted in excess microglial phagocytosis of 5-HT neurons in the dorsal raphe nucleus of males only (Ceasrine et al., 2022).

Recent clinical research studies have also demonstrated the presence of sexual dimorphism in the association between in utero exposure to GDM and child health outcomes, although none related to neurobehavioral outcomes. Three studies reported a sexually dimorphic association between GDM and increased risk for being overweight during early childhood, adolescence, and adulthood for males only (Le Moullec et al., 2018; Li et al., 2017; Regnault et al., 2013) and one study reported an association for females only (Tam et al., 2017). Prior research reporting on the association between GDM and offspring neurocognitive, neurobehavior, or language development has not examined potential sex-specific effects through stratified analyses (Cai et al., 2016; Camprubi Robles et al., 2015; DeBoer et al., 2005; Dionne et al., 2008; Fraser et al., 2012; Ghassabian et al., 2016; Krzeczowski et al., 2019; Nelson et al., 2000). Therefore, future studies examining the effects of GDM on child neurodevelopmental outcomes should consider sex-stratified analyses.

We also observed perinatal maternal depressive symptoms moderated the association between GDM and child autism behaviors. Several prior studies have reported associations between GDM and perinatal maternal depression (Delanerolle et al., 2021; Wilson et al., 2020). However, to our knowledge, this is the first study to report perinatal maternal depressive symptoms as a moderator in the association between GDM and child autism behaviors. Our findings are in part supported by a study that reported an association of adverse maternal experiences including prior experiences of trauma with postnatal maternal depressive symptoms and child social-emotional problems, only among mothers with diabetes during pregnancy (Rayport et al., 2022). ASD is estimated to be 40%–80% heritable; however, both genetic and non-genetic factors can modulate the penetrance of autism risk genes, which results in a highly heterogeneous ASD phenotype (Rylaarsdam & Guemez-Gamboa, 2019). In the present study, we utilized the CBCL autism problem scale, which is not a diagnostic measure, but rather a measure of autism behaviors. ASD is hypothesized to originate in utero, likely to due to interactive prenatal environmental exposures and genetic influences. As previously discussed, GDM and prenatal

maternal depression may have overlapping biological mechanisms such as increased prenatal maternal inflammation and/or HPA axis upregulation. However, the association between GDM and child autism behaviors moderated via postnatal maternal depression may have independent pathways. A recent Japanese study identified an association between mothers' broader autism phenotype (BAP) with both increased risk of postpartum depression and insecure maternal attachment (Hirokawa et al., 2019). Data from the same cohort reported an association between maternal BAP and reduced consumption of folate, vitamin C, vitamin D, and Omega-3 fatty acids during pregnancy (Hirokawa et al., 2020). Although we did not have measures of maternal BAP in this study, it is possible maternal BAP accounted for some of the variance in the association between GDM and child autism problems moderated by higher levels of maternal perinatal depressive symptoms.

Finally, we examined associations of GDM and prenatal and postnatal maternal depressive symptoms with clinical levels of child externalizing, internalizing, and autism spectrum problems via logistic regression analyses. Multivariate analyses revealed that GDM was not associated with clinical levels of externalizing or internalizing problems. The strongest association observed in our analyses was between GDM and autism spectrum problems (OR 2.99; 95% CI 1.54, 5.17), even when controlling for pre- and postnatal maternal depressive symptoms. Sex-stratified analyses revealed this association was only observed in male children (OR 3.26; 95% CI 1.58, 6.41). In the present analysis, we reported a higher OR than prior studies that have examined the association between GDM and the prevalence of ASD. For example, the most recently published systematic review and meta-analysis estimated that GDM was associated with an increased prevalence of ASD with a pooled OR of 1.42 (95% CI 1.22, 1.65) (Rowland & Wilson, 2021). A separate recent Swedish population-based cohort study corroborated these findings (OR 1.42; 95% CI 1.32, 1.56) (Chen et al., 2021). However, this study also reported significant associations between GDM and the prevalence of ADHD (OR 1.13; 95% CI 1.05, 1.22), comorbid ASD and ADHD (OR 1.26; 95% CI 1.09, 1.44), and intellectual disability without ASD (OR 1.62; 95% CI 1.40, 1.88) (Chen et al., 2021). Our increased OR is expected, as the clinical cutoff point for autism spectrum problems on the CBCL is not equivalent and more liberal than criteria for an ASD diagnosis.

Strengths and limitations

The strengths of our analysis include leveraging the ECHO study to have a large sample size, which included participant representation from five U.S. states; enrolling a diverse participant population, with more than half of maternal participants self-identifying as being from an underrepresented minority group; and having both prenatal and postnatal assessments of maternal depressive symptoms and child behavioral outcomes for over 2000

participants. However, several limitations must be taken into consideration when interpreting our findings.

First, data were not originally collected with the intention of the proposed analyses. Since the current study was observational and included participants with available longitudinal data, the results may not be representative. Secondly, information about how maternal GDM status was ascertained (maternal report vs. medical record abstraction) was not available for this analysis. An additional limitation was our reliance on parental reports of child behavior and the wide age range in which children were assessed on the CBCL (2–5 years of age). Recent research suggests small magnitudes of associations between maternal psychopathology and biases in reporting on child emotional and behavioral problems (Olinio et al., 2021), however, it is possible that maternal reporting of child behaviors was influenced by maternal depression. Future studies should also consider developing standardized objective measures of child externalizing or internalizing behaviors. Child externalizing, internalizing, and autism-related behaviors can vary greatly across development but show increasing stability during the toddler period. For example, more than 50% of children with disruptive behaviors at 3–4 years of age will continue to demonstrate these behaviors when entering school (Maheswari & Samundeeswari, 2018). In the present analysis, age at CBCL assessment was not distributed evenly across age bins. The majority of children were between 4 and 5 years of age at the time of CBCL assessment ($N=1816$). Therefore, we were unable to examine developmental implications related to the timing of CBCL assessment.

Our greatest limitation was the inability to stratify by clinically relevant levels of prenatal or postnatal maternal depression. Due to small cell sizes in the cross-tabulation between GDM and clinically relevant symptoms, we could not conduct secondary analyses to probe the interaction effect between GDM, prenatal, and postnatal maternal depression based on clinically relevant cutoffs with child autism spectrum problems. We therefore stratified by lower and higher levels of prenatal and postnatal maternal depressive symptoms based on a median split. It is noteworthy that median prenatal and postnatal depressive symptoms in the present analysis do not reflect a clinically relevant cutoff and are lower than the PROMIS-D T-score metric with a mean of 50 and standard deviation of 10 in the U.S. general population. One possible explanation for the lower observed levels of maternal perinatal depressive symptoms is that maternal depressive symptoms were measured using the EPDS, BSI-18, or PHQ-9 and these scores were later harmonized with PROMIS-D T scores. Finally, although we examined clinically relevant outcomes on the CBCL, we were likely underpowered to examine interactions in these analyses.

Several potential unobserved confounders should be explored in further analyses. For example, we did not include data on household socioeconomic information or maternal educational attainment, as these data were not available for

all participants in the current analyses. Due to some participants having multiple assessments of depressive symptoms in the prenatal or postnatal period, we averaged assessments within the prenatal period and postnatal period separately. We additionally did not have information on the gestational week of a GDM diagnosis, GDM severity or treatment, GDM management, other medical comorbidities, or perinatal depression treatment, which are all potential unobserved confounders. Finally, it is possible that prenatal and postnatal maternal perceived stress or anxiety are associated with child behavior, and these measures were not available for all participants in the current analyses.

Conclusions

In summary, pre- and postnatal maternal depressive symptoms were associated with externalizing and internalizing problems in both sexes, whereas GDM was associated with externalizing and internalizing problems in male children only. Additionally, we observed a three-way interaction between GDM, prenatal maternal depressive symptoms, and postnatal maternal depressive symptoms with autism spectrum problems. Stratified analyses revealed an association between GDM and child autism spectrum problems in children of mothers with higher levels of perinatal maternal depressive symptoms only. Finally, analyses stratified by sex revealed links between GDM and autism spectrum problems in male children only. Our findings have important research and clinical implications. They suggest sexually dimorphic effects of GDM on child behavioral outcomes. Future studies should attempt to identify biological mechanisms underlying resiliency in females exposed to GDM in utero due to the lack of associations with subsequent behavioral problems in the current analyses. Additionally, since both GDM and prenatal maternal depression are associated with epigenetic changes, increased inflammatory processes, and HPA-axis upregulation during pregnancy (Christian et al., 2009; Coussons-Read et al., 2007; Edalat et al., 2013; Money et al., 2018; Pantham et al., 2015; Richardson & Carpenter, 2007), identification of the interactions among underlying biological mechanisms is needed to mitigate adverse neurobehavioral outcomes. Further understanding of mechanisms may inform prophylactic programs during pregnancy with the potential to be translated into strategies that improve long-term child behavioral outcomes.

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DATA AVAILABILITY STATEMENT

De-identified data from the ECHO Program are available through NICHD's Data and Specimen Hub (DASH). DASH is a centralized resource that allows researchers to access data from various studies via a controlled-access mechanism. Researchers can now request access to these data by creating a DASH account and submitting a Data Request Form. The NICHD DASH Data Access Committee will review the request and provide a response in approximately 2–3 weeks. Once granted access, researchers will be able to use the data for 3 years. See the DASH Tutorial for more detailed information on the process.

ANALYTIC CODE

The analytic code necessary to reproduce the analyses presented in this paper is not publicly accessible. Requests to access the analytic code should be directed to the ECHO Data Analysis Center, echo-dac@rti.org.

PREREGISTRATION

The analyses presented here were not publicly preregistered.

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