Longitudinal and prospective assessment of prenatal maternal sleep quality and associations with newborn hippocampal and amygdala volume

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ABSTRACT

Background: The rapid maturation of the fetal brain renders the fetus susceptible to prenatal environmental signals. Prenatal maternal sleep quality is known to have important health implications for newborns including risk for preterm birth, however, the effect on the fetal brain is poorly understood.

Method: Participants included 94 pregnant participants and their newborns (53\% female). Pregnant participants ($M_{\text{age}} = 30; SD_{\text{age}} = 5.29$) reported on sleep quality three times throughout pregnancy. Newborn hippocampal and amygdala volumes were assessed using structural magnetic resonance imaging. Multilevel modeling was used to test the associations between trajectories of prenatal maternal sleep quality and newborn hippocampal and amygdala volume.

Results: The overall trajectory of prenatal maternal sleep quality was associated with hippocampal volume (left: $b = 0.002, p = .24$, right: $b = 0.004, p = .11$). Prenatal sleep quality was not associated with amygdala volume.

Conclusion: These findings highlight the implications of poor prenatal maternal sleep quality and its role in contributing to newborn hippocampal development.

1. Introduction

The prenatal period is characterized by exceptionally rapid maturation. In the span of nine months, the single-celled zygote becomes a human newborn capable of regulating and sustaining homeostatic processes (Demers et al., 2021a; Thomason, 2020). The fetal brain transforms rapidly, with the fetus forming approximately 200 billion neurons by the end of the second trimester (Ackerman, 1992). Neurogenesis commences around nine weeks into gestation (Bourgeois, 1997; Kolb, and Fantie, 2008); neurons are produced at a rate of more than 300,000 nerve cells per minute (Ackerman, 1992). Such rapid intrauterine development increases fetal susceptibility to prenatal environmental signals. As proposed by the Fetal or Developmental Origins of Adult Disease Hypothesis, environmental signals can promote or jeopardize fetal development, altering the maturation of physiological systems with lifelong consequences for health and disease (Barker, 1998, 2002; Kwon and Kim, 2017).

Poor sleep quality and short sleep duration are public health concerns that may have intergenerational consequences. During pregnancy, approximately 75\% of people experience worsening sleep quality...
(Lucena et al., 2018; Mindell et al., 2015), making poor prenatal sleep health a pervasive problem. Disturbed sleep during pregnancy can impact offspring physical health including preterm birth and low birth weight as well as high blood pressure and body mass index in childhood (Okun et al., 2011; Wang et al., 2017; Harskamp-van Ginkel et al., 2020). Only a handful of studies have looked at the associations between prenatal maternal sleep and postnatal outcomes in humans. Prenatal maternal sleep predicts newborn event related potential (ERP) responses to auditory stimuli (Lavonius et al., 2020), infant negative affectivity (Ciccoli et al., 2022), and socioemotional development (Trauman et al., 2015). Recent reviews have identified prenatal maternal sleep health as an understudied and potentially critical process that may influence the developing fetus (Johnson and Louis, 2022; Mindell et al., 2015; Moreno-Fernandez et al., 2020). While the pathways by which sleep disturbances impact the fetus are unknown, maternal sleep disturbances impact physiological processes such as inflammation and stress reactivity (Bleker et al., 2017; Bublitz et al., 2018; Okun et al., 2007), which are known to shape fetal brain development (Davis et al., 2020b; Davis et al., 2017; Graham et al., 2018; Sandman et al., 2018).

Growing preclinical literature indicates that poor prenatal maternal sleep impacts offspring neurodevelopment in rodents (Vanderplow et al., 2022) and that the developing hippocampus, a region involved in memory consolidation and learning (Han et al., 2020; Peng et al., 2016), may be particularly susceptible (Argeri et al., 2016; Pires et al., 2020). Sleep deprivation in pregnant dams causes impairments in hippocampus-dependent memory in the offspring (Pires et al., 2021). Evaluation of underlying mechanisms illustrates that maternal sleep deprivation compromises offspring hippocampal function (Zhao et al., 2015), including neurogenesis during both prepubescence (Han et al., 2020; Zhao et al., 2014) and adulthood (Motta-Teixeira et al., 2018). Effects can be detected as early as infancy as pups born to sleep-deprived dams display compromised hippocampal neurogenesis (Peng et al., 2016) and synaptic plasticity (Yu et al., 2018) compared to controls. Together, these findings demonstrate that prenatal maternal sleep may sculpt neurogenesis and synaptic plasticity, thus altering neural circuit development.

Guided by preclinical work indicating that sleep disruption affects the hippocampus, the present study examined the impact of prenatal maternal sleep health on newborn hippocampal volume. The hippocampus largely develops in utero, with major cell proliferation commencing around the fourth week of gestation and progressing to the development of hippocampal fissures by the 22nd week of gestation (Thomason, 2020) and hippocampal development is susceptible to prenatal environmental influences (Avishai-Eliner et al., 2002; Bock et al., 2015). Although the link between prenatal maternal sleep and fetal hippocampal development is unknown in humans, research with non-pregnant individuals suggests that hippocampal development is susceptible to sleep disruptions (Akers et al., 2018; Mirescu et al., 2006). For these reasons, the hippocampus was identified as the primary region of interest.

Similar to the hippocampus, the amygdala is another region that is susceptible to prenatal perturbations (e.g., prenatal stress and inflammation; Buss et al., 2012; Graham et al., 2018). The amygdala, implicated in fear and emotion regulation (Barrett et al., 2007; Peng et al., 2018), undergoes substantial development in utero and is among the first of the subcortical regions to develop embryonically, with its earliest traces found around seven gestational weeks (Buss et al., 2012; Humphries et al., 2006). Unlike the hippocampus, prenatal sleep has not been linked to offspring amygdala volume. However, because the prenatal environment has been linked to development of the amygdala (Rifkin-Graboi et al., 2013; Demers et al., 2022) and as evidence suggests poor sleep health is associated with amygdala function in non-pregnant populations (Prather et al., 2013; Yoo et al., 2007), the amygdala was included as a secondary outcome of interest.

The present study investigates the link between prenatal maternal sleep quality and newborn hippocampal and amygdala volume. Assessing hippocampal and amygdala morphology shortly after birth allows for the identification of prenatal influences prior to the intervening effects of postnatal life (Demers et al., 2022, 2021b). Further, sleep quality is dynamic over pregnancy and there are dramatic changes in fetal brain development across gestation (Lyu et al., 2020; Nevar ez-Brewster, 2022; Whitaker et al., 2021). Sleep disruptions early in gestation are strongly linked to preterm birth (Okun et al., 2011), and rodent work suggests that the timing of exposure to prenatal maternal sleep disturbances differentially affects offspring behavioral outcomes in pups exposed to sleep deprivation early and late gestation (Peng et al., 2016). Thus, there may be sensitive windows for timing of exposure to prenatal sleep deprivation. We, therefore, evaluated whether links between prenatal maternal sleep quality and newborn hippocampal and amygdala volume differ based on timing of exposure.

2. Materials and methods

2.1. Study Overview

Pregnant participants reported on sleep quality longitudinally throughout gestation and provided demographic information. Subjective maternal prenatal sleep quality was assessed three times between eight and 39 gestational weeks ($M_{\text{Gestational Age (GA) early}} = 16.9, SD_{\text{GA early}} = 4.3$), ($M_{\text{GA middle}} = 28.4, SD_{\text{GA middle}} = 3.8$), ($M_{\text{GA late}} = 35.3, SD_{\text{GA late}} = 1.6$). Neonatal hippocampal and amygdala volume were assessed during natural sleep at 44 postconceptional weeks ($M = 44.22, SD = 2.56$, range $= 42-56$ weeks). Postconceptional weeks was defined as the sum of weeks’ gestation at birth and weeks from birth to the MRI scan. Participants were compensated at each time point in which data was collected. This study was approved by the University of Denver and the Colorado Multiple Institutional Review Board, and all participants provided written and informed consent.

2.2. Participants

Participants included 94 pregnant individuals and their newborns from the Care Project, a longitudinal study investigating the influence of maternal mental health during pregnancy on offspring developmental outcomes (see Davis et al., 2018 for more details). Participants were recruited from obstetrics and gynecology clinics in and around Denver, Colorado. Participants meeting inclusion criteria were contacted by a research assistant, the study protocol was described, and interested participants were then consented. Initial inclusion criteria for participants’ enrollment in the study were a) maternal age between 18 and 45 years, b) singleton pregnancy, c) gestational age (GA) less than 25 weeks at time of enrollment, and d) proficiency in English. Initial exclusion criteria at recruitment included a) current drug or methadone use, b) major health conditions requiring invasive treatments (e.g., dialysis, blood transfusions, chemotherapy), c) current or past symptoms of psychosis or mania based on the Structured Clinical Interview (SCID) for DSM-5, and d) current participation in cognitive behavioral therapy or interpersonal therapy. Additional exclusion criteria for the current study included a) miscarriage or fetal demise of the current pregnancy ($n = 2$), b) major fetal or chromosomal anomalies ($n = 1$) or neonatal complications requiring a NICU stay ($n = 0$) and c) any MRI contraindications ($n = 4$, e.g., oxygen support). Of the 101 newborns who attended the MRI scan, six were unable to be scanned (e.g., the newborn did not fall asleep during the scanning window), and one did not yield imaging data (e.g., the newborn woke up in the scanner). Thus, 94 mother-newborn dyads were included in the present study. The newborns that were unable to be scanned did not differ from the remaining sample on income, gestational age at birth, and cohabitation status ($all \; n < 2.02$, all $p > .09$).

Pregnant participants were, on average, 30 years old ($SD_{\text{age}} = 5.29$) at time of enrollment. More than half (56.4%) obtained at least a college degree and the majority (89.4%) were cohabitating with a partner at
time of enrollment. Participants identified as 58% non-Latinx White, 16% Latinx/Hispanic, 11% African American/Black, 3% Asian American/Asian, 1% Native Hawaiian/Pacific Islander, and 11% multiracial. Further, participants reported a median household annual income of $72,000, with 29% of participants living at or below the 200% federal poverty line. Five percent (n = 4) of pregnant participants reported prenatal substance use. Newborns (53.2% female) were, on average, 39 gestational weeks at birth (range = 34.86–41.71). See Table 1 for more participant details.

2.3. Measures

2.3.1. Sleep quality

Prenatal maternal sleep quality was collected using the Pittsburg Sleep Quality Index (PSQI; Buysse et al., 1989). The PSQI is a 19-item self-report questionnaire consisting of seven subscales (sleep latency, sleep quality, sleep efficiency, and daytime dysfunction), weighed on a 0–3 scale. The subscale scores are then added, yielding an overall subjective sleep quality score that ranges from zero to 21. Higher scores are indicative of poor sleep quality (Buysse et al., 1989). The PSQI has previously demonstrated acceptable internal reliability (α = .83; Buysse et al., 1989). Additionally, the PSQI possesses good convergent and discriminant validity when used early in pregnancy (Zhong et al., 2015; Skouteris et al., 2009; Jomeen and Martin, 2007). In our sample, 63% percent of participants reflected “poor sleeper” scores (PSQI score ≥ 5; Tomfohr et al., 2015) at the beginning of pregnancy. The percentage of “poor sleepers” increased from 63% in the beginning of pregnancy to 81% late in pregnancy, which is consistent with existing findings (Lucena et al., 2018). Internal consistency of PSQI subscales was acceptable across all timepoints (all α > .73). In our sample, one participant had missing sleep data in early (1%), and in middle (1%) pregnancy, and seven later in pregnancy (7%). Gestational age at each prenatal assessment was computed using the date of PSQI completion and used to compute PSQI trajectories based on gestational weeks at assessment.

2.3.2. Magnetic resonance imaging acquisition

Newborns were scanned during natural and unsedated sleep. A Siemens Skyra 3 T MRI system equipped with a 20-channel head coil at the Brain Imaging Center at the University of Colorado Anschutz Medical Campus was used. Prior to scanning, newborns were fed, swaddled, and placed into the scanner with their heads secured in a vacuum-fixation device to limit scan noise due to motion. Newborns wore earplugs and headphones to prevent wakefulness from the acoustic noise of the scan. Newborns were monitored by a research staff member who was in the scanner for the entirety of the scan and caregivers remained in the scan room if they chose to do so.

T1-weighted (T1w) images were obtained using a three-dimensional magnetization-prepared rapid gradient echo sequence (repetition time = 1900 ms; echo time = 3.07 ms; inversion time = 900 ms; flip angle 9°; 4 min 26 s) and T2-weighted (T2w) images were obtained with a 3D fast turbo spin echo sequence (repetition time 3200 ms; echo time = 408 ms; flip angle 90°; 4 min 13 s). The spatial resolution was a $0.82 \times 0.82 \times 0.8\text{mm}$ voxel for T1w and $0.86\text{mm} \times 0.86\text{mm} \times 0.8\text{mm}$ voxel for T2w.

2.3.3. Magnetic resonance imaging processing

Image quality control (QC) feedback was provided using a four-point scale (0–3) (Blumenthal et al., 2002) adapted in-house for newborn

| Table 1 | Sample Characteristics (N = 94). |
|---------|----------------------------------|
| Maternal characteristics | M (SD) or % |
| Age at enrollment | 30.45 (5.29) |
| Obstetric complications | 33.3% |
| No complications | 38.7% |
| One complication | 28% |
| Two or more complications | 72,000 (50,117.26)$^b$ |
| Annual household income ($) | 3.56 (2.89)$^b$ |
| Household INR | 22.3% |
| Cohabitation status | 94% |
| Cohabiting with partner | 9.6% |
| Living alone | 1.1% |

Note:

| Note | |
|-----|-----|
| $^a$ | median used, |
| $^b$ | An outlier for income (i.e., SD ≥ 5 above the mean) was converted to the value 3 SDs above the mean, preserving its rank as the highest value; INR = Income to needs ratio, MRI = magnetic resonance imaging, NICU = neonatal intensive care unit |

scanning (Gilmore et al., 2020). Criteria for exclusion was a QC score of 0, indicating artifact contamination (mainly due to subject motion) rendering the image processing unreliable. T2 images were imputed via the convolutional neural network approach PGAN trained on the UNC-EBDS neonate data (Gilmore et al., 2020) if the corresponding T1 images passed quality control (QC scores of 2–3) and T2 images failed or were of borderline failure in quality control (QC score of 1). Nine T2 scans were imputed based on image quality scoring. Exclusion of participants with imputed T2 data did not alter findings and were therefore included in final analyses (See Supplement 2). The T1w and T2w brain images were corrected for intensity non-uniformity via N4 (Turkison et al., 2010), and rigidly transformed to a pediatric neonate atlas in...
stereotaxic space (Fonov et al., 2011). Brain masking was performed via the 3D UNet-based infant brain masking tool in ANTSpyNet (Tustison et al., 2021) using both T1w and T2w images jointly, including also extra-axial cerebrospinal fluid spaces in the brain mask. All brain masks were corrected manually in itkSNAP (Yushkevich et al., 2006).

Tissue segmentation (into whole brain white matter, gray matter, and cerebrospinal fluid), regional parcellation, as well as hippocampus and amygdala segmentation were performed using a multi-modality (T1w and T2w), multi-atlas segmentation workflow with the in-house, open-source MultiSegPipeline software (Cherel et al., 2015), which employs atlas-registration and label fusion from the ANTs toolset (Tustison et al., 2021). Hippocampus and amygdala regions are defined as in Moog et al., 2018 (see Fig. 1). Total intracranial volume was calculated as the sum of the brain tissue volumes of gray matter (GM), white matter (WM), and cerebrospinal fluid (CSF). Covarying by intracranial volume is common practice (Moog et al., 2018; Demers et al., 2022) in studies comparing regions of interest across individuals as it reduces inter-individual variations in brain volume due to head size. The segmentation quality of all images was visually assessed and rated using a four-point scale (0–3) for anatomical accuracy. No participants were excluded from analyses based on segmentation quality.

2.3.4. Sociodemographic characteristics

Maternal age, socioeconomic status, cohabitation with a partner, marital status, educational attainment, and race and ethnicity were collected via maternal interview at the first prenatal research visit. A family income-to-needs ratio (INR) was calculated by dividing the total reported household income by the poverty threshold corresponding to the number of persons living in the household at the time of study entry, specified by the U.S. Census Bureau for that year.

2.3.5. Pregnancy and birth outcomes

Prenatal obstetric complications, newborn sex, gestational age at birth, and 5-minute Apgar scores were collected from medical records. Additionally, birth weight percentile was calculated using gestational age at birth and newborn sex. Gestational age at birth (GAB) was calculated using early ultrasound measures and/or date of last menstrual period applying the American College of Obstetricians and Gynecologists (ACOG) guidelines. Postconceptional age at scan was computed as GAB plus weeks from birth to MRI scan (Committee on Obstetric Practice, the American Institute of Ultrasound in Medicine, and the Society for Maternal-Fetal Medicine, 2017). Obstetric complications were calculated as a sum score indicating the presence or absence of a series of pregnancy-related complications, including prenatal infection, pregnancy-included hypertension, gestational diabetes, oligohydramnios, polyhydramnios, preterm labor, vaginal bleeding, placenta previa, or anemia (Hobel, 1982). 28% of participants experienced two or more obstetric complications on this index. There were no missing data related to pregnancy and birth outcomes.

2.4. Analytical approach

2.4.1. Evaluation of covariates

Bivariate correlations were conducted to test intracranial volume (ICV) and postconceptional age at scan (sum of GAB and weeks from birth to scan), sex at birth, birth weight percentile, prenatal income, parity, and obstetric complications as potential covariates since these have been previously associated with brain volume in the literature (Makropoulos et al., 2016; Moog et al., 2018; Nolvi et al., 2020). Additionally, the relation between hippocampal and amygdala volume and region-specific segmentation quality scores was tested. Variables were included as covariates if they were associated with hippocampal or amygdala volumes at alpha < .05. An independent samples T-test and a one-way ANOVA were additionally conducted to test parity (primiparous, multiparous) and obstetric complications (zero, one, two, or more) during the current pregnancy as potential covariates. Continuous variables were tested in bivariate correlations, see Table 2. Newborn hippocampal and amygdala brain volume did not differ as a function of parity (all t’s < 1.59, all p’s > .12), or obstetric complications (all F’s < 0.65, all p’s > .52). However, newborn ICV, birth weight percentile, biological sex, and postconceptional age at scan were associated with newborn hippocampal and amygdala brain volume and thus, were

![Fig. 1. Regions of Interest for the Present Study Note. 3D visualization of representative example of hippocampus and amygdala segmentation on MRI T1 (T2) weighted scan. Purple = amygdala; Green = hippocampus; Left = darker color; Right = brighter color.](image-url)
Birth, ICV, postconceptional age, and birth weight percentile were then tested whether the trajectory of sleep quality was associated with any prenatal variable. Follow-up analyses were employed to test whether associations persisted after covarying intracranial volume, age at scan, sex at birth, and birthweight percentile. There was no missing data present at level 2.

### 3.2. Prenatal sleep quality and newborn hippocampal volume

Neither the overall trajectory of prenatal sleep quality (left: \( b = 0.00001, \ p = 0.85 \); right: \( b = -0.00003, \ p = .59 \)) nor level of sleep quality at any time during pregnancy predicted newborn amygdala volume (left: \( b = -0.02, \ p = .28 \); right: \( b = -0.02, \ p = .31 \), See Table 5).

### 4. Discussion

The present study provides novel evidence suggesting that sleep disruptions early in pregnancy may sculpt the fetal brain (Johnson and Louis, 2022; Mindell et al., 2015). The present study provides evidence that the trajectory of maternal sleep quality across gestation is associated with newborn bilateral hippocampal volume and further, that timing of exposure is critical. Timing effects additionally were observed such that poorer sleep quality during the first trimester most strongly predicted larger hippocampal volume. Specifically, lower sleep quality during the early in pregnancy was associated with larger newborn hippocampal volume, bilaterally (left: \( b = 0.01, \ p = 0.018 \); right: \( b = 0.01, \ p = .025 \); See Table 4 and Fig. 3). However, sleep later in gestation, was not associated with hippocampal volume (e.g., late gestation left: \( b = 0.002, \ p = 0.24 \); right: \( b = 0.004, \ p = .11 \); See Table 6). Additional sensitivity analyses showed that removing the four participants with substance use during gestation did not impact the pattern or significance of findings (See Supplement 1).

### Table 2

| Region-specific QC score | Right Hippocampal Volume | Left Hippocampal Volume | Right Amygdala Volume | Left Amygdala Volume |
|--------------------------|--------------------------|-------------------------|-----------------------|---------------------|
| ICV                      | .670**                   | .550**                  | .547**                | .534**              |
| Infant age at scan       | .407**                   | .398**                  | .131**                | .209                |
| Sex at birth             | -2.17                    | -1.12                   | -5.16**               | -3.51**             |
| BWP                      | .282**                   | .167                    | .136                  | .360**              |
| GAB                      | .021                     | .067                    | -.031                 | .130                |
| INR                      | .107                     | .047                    | .081                  | .095                |
| Region-specific QC score | -0.3                     | .05                     | .07                   | -.11                |

Note: ICV = intracranial volume, BWP = birthweight percentile, INR = income to needs ratio, QC = quality control. Infant age at scan was calculated as the sum of gestational age at birth plus weeks from birth to scan.

- \( p < .05 \)
- \( ** p < .01 \)
- \( *** p < .001 \)

Table 2: Bivariate Correlations of Potential Covariates with Amygdala and Hippocampal Volume.

### Table 3

| Multilevel Growth Models of Prenatal Maternal Sleep Quality. |
|--------------------------------------------------------------|
| Fixed Effects                                                | Quadratic Growth                                      |
| Linear Slope                                                  |                                                        |
| Intercept (\( \beta_0 \))                                    | 5.61                                                   |
| Linear Slope (\( \beta_1 \))                                 | 0.07 **                                                 |
| Quadratic Growth (\( \beta_2 \))                             | 0.0053 **                                               |
| Random Effects                                               |                                                        |
| Error (\( \epsilon_L \))                                    | 2.63                                                   |
| Intercept (\( \epsilon_i \))                                 | 11.51 **                                                |
| Slope (\( \tau_1 \))                                         | 0.01 **                                                 |

Note: \( * p < .05, \ * * p < .01, \ * * * p < .001 \). Intercept centered at eight gestational weeks.
in gestation may have intergenerational consequences.

Our findings build on previous preclinical studies illustrating that the hippocampus is susceptible to alterations in prenatal maternal sleep. In rodents, experimentally induced prenatal sleep deprivation causes decreases in offspring hippocampal neurogenesis and alterations in hippocampal synaptic plasticity (Peng et al., 2016; Yu et al., 2018; Zhao et al., 2015). We find that hippocampal volume was larger among neonates with fetal exposure to greater prenatal maternal sleep problems. It is not clear why sleep problems are associated with larger neonatal hippocampal volume. The hippocampus is a stress sensitive region, and it is plausible that disrupted sleep modifies the prenatal environment in ways that alter neurogenesis in the hippocampus (Zhao et al., 2015). Consistent with this possibility, recent rodent research indicates links between prenatal sleep disruption and increases in cortical synaptic density (Vanderplow et al., 2022). It is noteworthy that most preclinical studies employ sleep deprivation, a significant stressor different from sleep problems captured within the current study which include difficulty falling asleep, frequent night awakenings, daytime dysfunction, and subjective perceptions of overall sleep quality.

The pathways contributing to changes in hippocampal volume following prenatal maternal sleep disruptions are unknown. Prenatal sleep has been linked to dysregulation in both the Hypothalamic Pituitary Adrenocortical (HPA) axis and immune systems during the prenatal period (Bublitz et al., 2018; Chang et al., 2010), including elevations in circulating cortisol and cytokines (Bleker et al., 2017; Okun et al., 2007). As both the stress and immune systems directly impact fetal neurodevelopment (Curran et al., 2017; Graham et al., 2018; Sandman et al., 2018), disruptions to immune and HPA systems are potential mechanisms contributing to the association between prenatal maternal sleep health and newborn brain structure.

The current study’s longitudinal evaluation of sleep throughout gestation enables us to study the effects of timing of exposure on the fetal brain. Our findings suggest that sleep quality in the first trimester may have the most potent implications for the development of the hippocampus. The hippocampus begins to form as early as the 4th gestational week (Noorlander et al., 2006; Thomason, 2020). This finding that early gestation is a sensitive window for sleep disturbances is consistent with evidence that the developing fetus is particularly susceptible to early
changes across pregnancy (Nevarez-Brewster et al., 2022) and differ
evaluated the longitudinal and prospective
determination of object pregant maternal sleep quality using actigraphy or polysomnography would complement subjective sleep perceptions. Additionally, preconception sleep parameters were not assessed and thus, future research could test links between sleep quality from preconception through pregnancy and fetal brain structure. Another strength of this study was the collection of newborn imaging data. We
during gestation when the fetal brain may be most vulnerable to maternal sleep disruptions as well as patterns of sleep over pregnancy that are most impactful on the fetal brain.

The present findings posit prenatal maternal sleep health as a process implicated in the programming of the developing fetal brain. This work lays foundational knowledge for future studies to further understand the intergenerational impact of prenatal sleep health. Recent findings suggest cognitive behavioral therapy for insomnia can improve subjective and objective sleep during pregnancy while also improving prenatal maternal mood (Tomfohr-Madsen et al., 2016). Ultimately, the prenatal period is an optimal time in development for intervention and prenatal maternal sleep is amenable to intervention (Davis and Narayan, 2020a). Thus, an improved knowledge of the intergenerational impact of prenatal sleep disruptions may support the development of prenatal sleep interventions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data is available upon request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2022.101174.
