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Disaster-related prenatal maternal stress influences birth outcomes: Project Ice Storm

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ABSTRACT

Background: Previous research suggests that prenatal maternal stress (PNMS) impacts birth outcomes, but many human studies cannot distinguish between the effects of different types of stressors or examine effects of exposure timing on outcomes.

Objectives: Our goal was to determine how timing and severity of exposure during pregnancy to objective and subjective stress due to a natural disaster influenced gestation length and fetal growth patterns.

Methods: We assessed objective and subjective PNMS levels among 172 women exposed to an ice storm during or shortly before pregnancy. We analyzed associations between PNMS levels and outcomes (gestation length, birth weight, birth length, head circumference, and growth ratios), controlling for other variables such as age, obstetric complications, socioeconomic status, and trait anxiety.

Results: Gestation lengths and predicted birth weights were shorter among participants exposed to the ice storm during early to mid pregnancy, compared to 3 rd trimester and pre-pregnancy exposure. Birth lengths were shorter in the sample compared to population references, and predicted values were shorter among participants with a "discrepancy" between their objective and subjective PNMS levels. High objective PNMS levels predicted smaller head circumferences in early pregnancy, but we also observed patterns in predicted values of head circumference to birth length ratios suggesting the sparing of brain development relative to birth length among boys in early pregnancy. These sparing effects decreased in later pregnancy.

Conclusions: Exposure to stressful events during pregnancy influences birth outcomes independently of other factors. Exposure timing, newborn sex, and the type of stressor influence the effects observed.

1. Introduction

Past studies have shown that prenatal maternal stress (PNMS) can adversely impact pregnancy outcomes. Human studies investigating pregnancy-related stress or anxiety [1], life events [2–5], and anxious [6] or depressive [7–9] symptoms suggest that exposure during pregnancy might be associated with worse birth outcomes, such as preterm birth, smaller birth weight, and smaller head circumference [10]. A number of mechanisms are likely involved, including maternal stress hormones which, at high levels, can cross the placenta and thereby impact fetal development [11]. Timing of exposure can impact the effects observed. For example, exposure to an earthquake during pregnancy was associated with shortened gestation length, but effects were strongest among women exposed during their first trimester [12]. Some effects also vary by newborn sex. For example, increased maternal cortisol levels are associated with decreased neuromuscular and physical maturation among males, but might be associated with increased maturation among females depending on exposure timing [13].

Unfortunately, our understandings of the effects of PNMS on birth outcomes are still limited because of the challenges of designing human studies of PNMS. In many cases the "stressor" examined, such as maternal anxiety or job loss, could be associated with maternal traits such as personality which could potentially have effects on the unborn child genetically, or with household characteristics known to be associated with birth outcomes, such as socioeconomic status (SES). Furthermore, it is often difficult to pinpoint the exact timing of the stressor. Humans cannot be randomly assigned to stress or non-

Abbreviations: PNMS, (prenatal maternal stress); SES, (socioeconomic status); IES-R, (Impact of Events Scale Revised); GHQ, (General Health Questionnaire); LES, (Life Experiences Survey).

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stress groups, so many studies use retrospective designs that assess stressors after children's births. Consequently, results might be biased because women who have poor pregnancy outcomes might recall their pregnancies as being stressful [14]. Despite efforts to improve birth outcomes, preterm birth and low birth weight remain leading causes of infant morbidity and mortality, with health effects that persist across the lifespan [10]. More research on the contributions of PNMS to this public health concern is required.

Project Ice Storm provides an opportunity to examine the effects of an independent stressor on a number of birth outcomes prospectively. Beginning on January 4, 1998, a series of ice storms in Canada's St. Lawrence River Valley caused power outages for more than 1.4 million Québec households ranging from a few hours to more than six weeks during the coldest period of the year. Around 600,000 people moved out of their homes to escape the cold, 100,000 of these into temporary emergency shelters. Thousands of people were injured or hospitalized and 28 people died as a result of hypothermia, accidents, carbon monoxide poisoning, or fire due to unconventional heating methods. The ice storm resulted in $1 Billion worth of insurance claims, $3 Billion of lost income to businesses, $1 Billion in hydroelectric infrastructure repairs, and job loss for more than 46,000 people. It has been described as Canada's most costly natural disaster in history [15,16].

In June of the same year, we assessed objective hardship and subjective distress dimensions of PNMS among women who were pregnant during the storm, or who became pregnant in the following three months. We have since analyzed a number of physical, behavioral, and developmental measures among their children [17–21]. This project differs in several ways from other human studies of PNMS. First, the ice storm was a sudden, random act of nature that impacted thousands of women without systematic associations between impact severity and personal characteristics such as trait anxiety or SES. Second, we were able to distinguish between objective hardship (i.e., what happened) and subjective distress (i.e., how the women reacted), which is nearly impossible in studies of antenatal anxiety or life events. Finally, because the exact parameters of the storm were well documented (e.g., date of onset, days during which power was out), we can pinpoint the exact week or weeks of pregnancy during which participants were affected.

Our objective was to determine whether exposure to objective and/or subjective PNMS due to the ice storm impacted birth outcomes, including gestational age at birth, birth weight, head circumference, birth length, ponderal index, and head circumference to birth length ratio. We investigated whether effects were moderated by exposure timing or sex of the newborn. Based on results of animal and human studies, we hypothesized that PNMS would negatively impact birth outcomes independently of potential confounding factors such as SES and maternal anxiety. Furthermore, since susceptibility to PNMS might vary for boys and girls and over the course of gestation, we hypothesized that newborn sex and exposure timing would impact the effects observed.

2. Materials and methods

This study was approved by the Research Ethics Board of the Douglas Hospital Research Center.

2.1. Participants

Shortly after the ice storm, we contacted obstetricians associated with the four major hospitals in the Montérégie, a region southeast of Montreal that endured the longest electrical power losses from the storm. These obstetricians identified patients who were pregnant during or who conceived within three months of the storm when stress hormones could still be elevated, and were ≥18 years of age. The first questionnaire, “Reactions to the storm,” was mailed from the doctors' offices on June 1, 1998 to 1440 women. Of 224 women who responded, 178 consented to follow-up and were sent the second questionnaire, “Outcomes of the pregnancy,” six months after their pregnancy due date. Of these, 176 returned the questionnaire; one did not include complete information on birth outcomes and three pregnancies had not ended in a live birth. Thus, the present study is based on 172 mothers of singleton newborns (88 boys, 84 girls) who were in their 1st (n = 50), 2nd (n = 44), or 3rd (n = 41) trimester during the storm or who became pregnant within the following three months (n = 37).

Compared to women who were sent the first questionnaire but did not respond, responders were slightly older (29.6 years old compared to 28.5 years among non-responders, p = 0.002) and were about 3.5 weeks further along in their pregnancies at the time of the first questionnaire (p = 0.001). Response rate was higher in the south and eastern regions of the Montérégie (19.4%) compared to the western region, closer to Montréal (11.2%) (p<0.001). Finally, level of education was higher for respondents than in the Montérégie in general: 61.0% of respondents had a college degree or higher, and 33.1% had a university degree or higher, compared to regional figures of 45.3% and 20.9%, respectively, for women ages 20–44 in the 2001 census [22].

2.2. Predictor variables

Objective PNMS: We assessed the severity of storm-related events experienced by pregnant women based on responses to the first questionnaire items tapping into four categories of exposure used in other disaster studies: Threat, Loss, Scope, and Change [23]. Because each natural disaster presents unique experiences, questions pertaining to each category must be tailor-made. Our scale [17] included questions specific to the ice storm, such as days without electricity, danger due to falling ice or tree branches, and spending time in temporary shelters. Each dimension was scored on a scale of 0–8, ranging from no exposure to high exposure. A total objective PNMS score was calculated by summing scores from all four dimensions using McFarlane's approach [24]. In the present study, scores ranged from 0 to 24 out of a possible 32 points.

Subjective PNMS: We assessed women's psychological reaction to the storm in the first questionnaire using a validated French version of the Impact of Event Scale — Revised (IES-R) [25]. This 22-item scale, widely used for assessing distress following trauma exposure, describes symptoms from three categories relevant to post-traumatic stress disorder: Intrusive Thoughts, Hyperarousal, and Avoidance. Participants responded on a 5-point Likert scale, from “*Not at all*” to “*Extremely*,” the extent to which each behavior described how they felt over the preceding seven days. Items were written to reflect symptoms relative to the ice storm. The total score was used in analyses.

Maternal Psychological Functioning: Maternal non-storm-related psychological functioning was assessed in the first questionnaire with the General Health Questionnaire-28 (GHQ-28), a self-report screening tool for psychiatric symptoms [26]. The GHQ-28 includes seven items in each of the anxiety, depression, dysfunction, and somatization sub-scales. Items are scored on a 4-point Likert scale indicating the degree to which symptoms were experienced in the preceding two weeks. Following the scoring method recommended by the assessment author, we re-coded each item as either 0 (a rating of 0 or 1) or 1 (a rating of 2 or 3) [26]. The anxiety scale was used as a potential covariate in analyses.

Maternal Life Events: Maternal life events were assessed in the second questionnaire using the Life Experiences Survey (LES) [27], a self-report measure that lists 57 life changes, such as death of a spouse or a work promotion. We reduced this to 29 events by eliminating items unlikely to have occurred in this sample (such as “combat experience”). Respondents indicated whether the event occurred or not, gave its approximate date, and then rated its impact on a 7-point Likert scale ranging from "*Extremely Negative*" to "*Extremely Positive*". We focused on stressful events that might have impacted outcomes of the infants included in the study by asking women to indicate events occurring in the preceding 18 months, that is, the six months since the baby's due date, nine months of pregnancy, and three months before conception. The total impact of life events was used in the present study. Scores ranged from −28, indicating an overall negative impact, to +13, indicating an overall positive impact.

Other Maternal and Paternal Factors: Information on the mother's age, marital status, both parents' education and job status, and household income was collected during our first questionnaire. SES was computed using the Hollingshead Social Position criteria [28]; larger scores represent lower SES. During the second questionnaire, we obtained information on obstetric complications, cigarette and alcohol use, and maternal and paternal height. Obstetric complications, such as pre-eclampsia or gestational diabetes, were assessed from maternal reports with the checklist used by Kinney [29] and hospital records. Severity was rated with the McNeil-Sjöström Scale [30] and the number of moderate-to-severe complications was used in analyses. Maternal cigarette and alcohol use were reported as any use (yes/no) and frequency (cigarettes/day and alcoholic drinks/week) during pregnancy. Frequency was used in analyses. Height was not reported for five mothers and ten fathers. To reduce the number of missing data points, we replaced missing values with average maternal or paternal height, and used parental height for each participant in analyses.

Timing of Exposure: The timing during pregnancy of the mother's exposure to the ice storm was defined as the number of days between January 9th, 1998 – the peak of the ice storm – and the infant's due date. Third trimester exposure corresponds to due dates falling between 0 and 93 days following January 9th; 2nd trimester, 94–186 days; 1st trimester, 187–279 days; and preconception exposure, 280–360 days (conception within three months of January 9th, 1998).

2.3. Outcome measures

In Québec, all mothers receive a Vaccination Booklet at the baby's discharge into which hospital staffs transcribe several birth outcomes. In the second questionnaire, mothers were asked to copy birth information from this booklet including weight, length (crown to heel), head circumference, and gestational age. These maternal reports were then validated by medical records. Ponderal index ((birth weight/birth length^3)×1000) and head circumference to birth length ratio (head circumference/birth length) were calculated for each newborn. We compared birth weight, length, and head circumference for gestational age to Canadian population references [31] and calculated Z-scores for descriptive analyses. Prematurity was defined as gestational age <37 completed weeks. We did not have detailed information on preterm births (e.g., spontaneous, medically indicated) and thus analyzed prematurity only for descriptive purposes.

2.4. Statistical analysis

We conducted univariate analyses to determine if birth outcomes differed by sex. We used hierarchical linear regression analyses to examine associations between outcomes and PNMS. We first controlled for gestational age (where appropriate) and infant sex by entering these in steps 1 and 2. Parental factors that might impact birth outcomes, including maternal age, LES, anxiety, obstetric complications, cigarettes/day and alcoholic drinks/week; and parental SES and height were allowed to enter in step 3 during a stepwise procedure with a p-value of 0.05 to enter. Storm-related variables were entered in steps 4–7: objective PNMS (step 4), subjective PNMS (step 5), timing of exposure (step 6), and the squared value of timing (to account for any curvilinear effect, step 7). Finally, we entered interaction terms between objective and subjective PNMS; objective PNMS and timing; subjective PNMS and timing; objective PNMS and newborn sex; and subjective PNMS and newborn sex, in steps 8–12. Analyses were completed with SPSS 18.0.

3. Results

3.1. Sample characteristics

3.1.1. Newborn characteristics

Based on Z-scores, mean birth weight and head circumference for gestational age were consistent with Canadian standards. However, mean birth length for gestational age was nearly 1/3 of a standard deviation smaller than average, with Z-scores averaging −0.328 (SD=0.739) (Table 1). Thirteen children (7.6%) were premature – eight boys (9.1%) and five girls (6.0%) (p=0.567) – consistent with the prevalence of prematurity in Québec in 1999 (7.7%) [32].

3.1.2. Maternal characteristics

Mean maternal age at the newborns' births was 29.5 years (SD=4.6). The number of moderate-to-severe obstetric complications averaged 1.1 (SD=1.3). Most women (83.7%) did not smoke during pregnancy; those who did smoked, on average, 10.9 (SD=7.4) cigarettes per day. Most women (81.4%) also did not drink alcohol during pregnancy; those who did averaged 0.7 (SD=0.7) drinks per week. SES scores ranged from 73 (lower class) to 11 (upper class) and averaged 29.5 (SD=12.7, upper-middle class).

3.1.3. Gestational age

Mean gestational age at birth differed by trimester of exposure (p=0.047): gestational ages were shorter when the ice storm occurred during the 1st (M=38.9 weeks; SD=1.9) or 2nd (M=38.7; SD=2.2) trimester, compared to preconception (M=39.4; SD=1.9) and 3 rd (M=39.7; SD=1.5) trimester exposure. Curve analyses indicated a curvilinear (quadratic) relationship between gestational age and exposure timing (R^2=0.038, p=0.039), whereas the linear relationship was not significant (R^2=0.002, p=0.544). Thus the quadratic term for exposure timing was entered in regression analyses.

3.2. Regression analyses (Table 2)

3.2.1. Gestational age

Predictive variables for shorter gestational age included higher alcohol intake (4.0% of variance, p=0.009), higher SES (2.9%,

Table 1
Sample characteristics (M, SD) for child outcomes.

	Total sample	Boys (n=88)	Girls (n=84)	p-value
Gestational age (GA) (wks)	39.2 (1.9)	39.1 (1.9)	39.2 (1.8)	0.607
Birth weight (BW) (g)	3451.5 (559.4)	3479.4 (556.7)	3422.2 (564.1)	0.505
Birth length (BL) (cm)	50.2 (2.8)	50.3 (3.0)	50.1 (2.6)	0.646
Ponderal index	27.4 (3.6)	27.3 (3.7)	27.4 (3.5)	0.776
Head circumference (HC) (cm)	34.5 (1.6)	34.8 (1.7)	34.1 (1.5)	0.017
BW-GA Z-score	0.097 (0.927)	0.034 (0.864)	0.164 (0.991)	0.361
BL-GA Z-score	−0.328 (0.739)	−0.375 (0.761)	−0.277 (0.716)	0.387
HC-GA Z-score	0.008 (0.552)	0.010 (0.582)	0.005 (0.524)	0.954

Table 2
Summary of hierarchical linear regression analyses.

Predictor variables	Values in final model				Values after entry of each variable				
	B	SE *B*	β	B p-value	R^2	ΔR^2	F*	ΔF	ΔF p-value
Gestational Age (n = 172)									
(Constant)	39.075	0.805							
Sex	0.235	0.282	0.063	0.406	0.002		0.265		
Alcohol	−0.756	0.345	−0.166	0.030	0.041	0.040	3.629*	6.983	0.009
SES	0.026	0.011	0.174	0.025	0.070	0.029	4.237**	5.271	0.023
Life event impact	0.055	0.026	0.159	0.036	0.097	0.027	4.488**	4.942	0.028
Objective PNMS	−0.004	0.033	−0.010	0.898	0.101	0.004	3.719**	0.678	0.411
Subjective PNMS	−0.010	0.012	−0.070	0.383	0.102	0.002	3.141**	0.323	0.570
Timing	−0.011	0.006	−0.566	0.078	0.103	0.000	2.682*	0.042	0.837
Timing^2	0.000	0.000	0.561	0.078	0.120	0.017	2.772**	3.154	0.078
Birth weight (n = 172)									
(Constant)	−3729.519	711.232							
Gestational age	187.928	17.316	0.628	<0.001	0.426		126.369***		
Sex	−80.345	64.302	−0.072	0.213	0.432	0.006	64.353***	1.767	0.186
Objective PNMS	8.045	7.414	0.067	0.279	0.433	0.001	42.802***	0.263	0.609
Subjective PNMS	4.571	3.857	0.103	0.238	0.434	0.001	32.041***	0.296	0.587
Timing	−3.247	1.358	−0.579	0.018	0.435	0.001	25.556***	0.216	0.643
Timing^2	0.011	0.004	0.724	0.004	0.452	0.017	22.694***	5.175	0.024
Subj PNMS* Timing^2	0.000	0.000	−0.279	0.008	0.475	0.023	21.200***	7.155	0.008
Head circumference (n = 167)									
Constant	16.978	2.331							
Gestational age	0.460	0.057	0.511	<0.001	0.296		69.350***		
Sex	−0.607	0.204	−0.185	0.003	0.341	0.046	42.517***	11.339	0.001
Alcohol	−0.417	0.255	−0.104	0.104	0.357	0.016	30.212***	4.032	0.046
Objective PNMS	0.057	0.024	0.161	0.018	0.373	0.015	24.072***	3.989	0.047
Subjective PNMS	0.008	0.012	0.065	0.489	0.378	0.005	19.589***	1.411	0.237
Timing	−0.007	0.004	−0.425	0.108	0.379	0.001	16.293***	0.262	0.609
Timing^2	0.000	0.000	0.627	0.021	0.391	0.012	14.603***	3.149	0.078
Subj PNMS* Timing^2	0.000	0.000	−0.279	0.014	0.414	0.023	13.956***	6.130	0.014
Birth Length (n = 170)									
(Constant)	5.495	7.363							
Gestational age	0.842	0.104	0.513	<0.001	0.269		61.683***		
Sex	−2.680	0.916	−0.472	0.004	0.275	0.007	31.732***	1.571	0.212
Parental height	0.108	0.035	0.495	0.002	0.304	0.029	24.190***	6.874	0.010
Objective PNMS	−0.475	0.133	−0.785	<0.001	0.333	0.029	20.630***	7.226	0.008
Subjective PNMS	−0.118	0.044	−0.524	0.008	0.334	0.000	16.415***	0.037	0.847
Timing	−0.009	0.008	−0.331	0.214	0.340	0.006	13.964***	1.475	0.226
Timing^2	0.000	0.000	0.427	0.108	0.345	0.006	12.212***	1.461	0.229
Obj* subj PNMS	0.009	0.003	0.583	0.009	0.366	0.021	11.614***	5.209	0.024
Obj PNMS* Sex	0.183	0.077	0.558	0.018	0.388	0.022	11.252***	5.665	0.018
Ponderal index (n = 170)									
(Constant)	33.923	10.956							
Gestational age	0.291	0.158	0.139	0.067	0.032		5.526*		
Sex	0.261	0.530	0.036	0.623	0.032	0.000	2.750	0.006	0.939
Parental height	−0.115	0.051	−0.164	0.025	0.062	0.031	3.682*	5.402	0.021
Alcohol	−1.194	0.665	−0.136	0.074	0.091	0.029	4.153**	5.282	0.023
Objective PNMS	0.216	0.062	0.281	0.001	0.154	0.063	5.971***	12.122	0.001
Subjective PNMS	−0.006	0.022	−0.020	0.800	0.154	0.000	4.949***	0.020	0.888
Timing	−0.008	0.011	−0.226	0.466	0.165	0.011	4.566***	2.069	0.152
Timing^2	0.000	0.000	0.124	0.689	0.166	0.001	3.994***	0.161	0.689
Head circumference by birth length (n = 166)									
(Constant)	111.614	10.290							
Gestational age	−0.283	0.146	−0.138	0.055	0.013		2.237		
Sex	−1.103	0.684	−0.155	0.109	0.023	0.009	1.890	1.536	0.217
Parental height	−0.189	0.049	−0.266	<0.001	0.090	0.067	5.333**	11.964	0.001
Alcohol	−1.171	0.625	−0.135	0.063	0.129	0.039	5.945***	7.172	0.008
Smoking	0.139	0.051	0.198	0.008	0.159	0.031	6.070***	5.855	0.017
Objective PNMS	0.266	0.058	0.347	<0.001	0.253	0.094	8.992***	19.996	<0.001
Subjective PNMS	−0.153	0.064	−0.544	0.018	0.263	0.009	8.045***	2.018	0.157
Timing	−0.005	0.011	−0.151	0.616	0.264	0.002	7.050***	0.326	0.569
Timing^2	0.000	0.000	0.103	0.731	0.264	0.000	6.227***	0.000	0.998
Subj PNMS* Sex	0.081	0.040	0.460	0.043	0.283	0.019	6.132***	4.146	0.043

* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.

p = 0.023), and negative life events (2.7%, p = 0.028). Exposure timing^2 had a small effect on gestational age that approached statistical significance in regression analyses, explaining an additional 1.7% of variance (p = 0.078).

3.2.2. Birth weight

Gestational age explained 42.6% of the variance in birth weight (p<0.001). Exposure timing^2 accounted for a further 1.7% (p = 0.024) and interacted with subjective stress to explain an additional 2.3% (p = 0.008). Based on the final regression model, higher subjective PNMS levels predicted lower birth weights in general, with mid-pregnancy exposure having the greatest impact (Fig. 1).

3.2.3. Head circumference

Gestational age accounted for 29.6% of the variance in head circumference (p<0.001) and sex for a further 4.6% (p = 0.001): as expected, boys had larger head circumferences than girls. Higher levels of alcohol intake were associated with smaller head circumferences (1.6%, p = 0.046). Controlling for these, objective PNMS accounted for 1.5% of variance (p = 0.047), with greater objective PNMS levels predicting larger circumferences. Finally, the effect of timing^2 approached significance at entry (1.2%, p = 0.078), and we observed a significant interaction between timing^2 and subjective PNMS (2.3%, p = 0.014). Based on the final model, mid- and late-pregnancy exposure had little impact on head circumference, but early-pregnancy exposure to high levels of subjective PNMS predicted smaller circumferences (Fig. 1).

3.2.4. Birth length

Gestational age explained 26.9% of the variance in birth length (p<0.001), and parental height accounted for a further 2.9% (p = 0.010). Objective PNMS explained 2.9% of variance (p = 0.008), and interacted with both subjective PNMS (2.1%, p = 0.024) and sex (2.2%, p = 0.018). Based on the final regression model, predicted birth lengths were shortest among infants of women with a "discrepancy" between their objective and subjective PNMS levels, that is, among women who reacted very little to high levels of objective PNMS (especially for boys) or who reacted very strongly to relatively low levels of objective hardship (especially for girls) (Fig. 2).

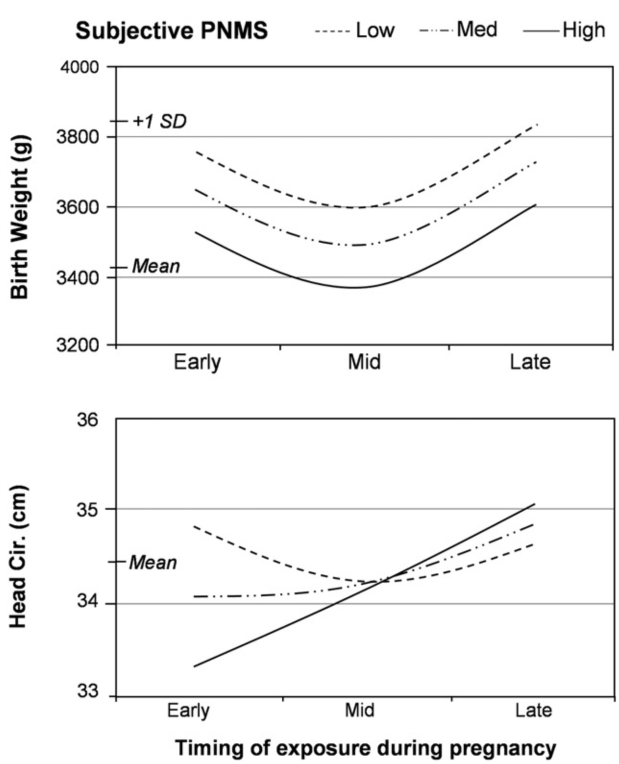

Fig. 1. Interactions between subjective PNMS and exposure timing: Predicted values for birth weight (top) and head circumference (bottom) based on final regression equations. Population means and SDs (where applicable) at 39 weeks gestation are indicated, based on Kierans et al. [31].

3.2.5. Ponderal index

Gestational age, parental height, and alcohol intake accounted for 9.2% of variance in ponderal index. Controlling for these, objective PNMS accounted for a further 6.3% (p<0.001): higher objective PNMS was related to larger ponderal indices, reflecting the effects of objective PNMS exposure on decreasing birth length but maintaining birth weight.

3.2.6. Head circumference to birth length ratio

Controlling for gestational age and sex, parental height accounted for 6.7% of variance in head circumference to birth length ratios (p = 0.001), alcohol use for 3.9% (p = 0.008), and smoking for 3.1% (p = 0.017). Objective PNMS accounted for 9.4% of variance (p<0.001), and subjective PNMS interacted with sex to explain a further 1.9% (p = 0.043). Based on the final regression model, subjective PNMS had little effect on girls' head circumference to birth length ratios, but a marked effect on boys': higher subjective PNMS levels predicted smaller head circumference relative to birth length among boys (Fig. 3).

4. Discussion

Exposure to PNMS influences a number of pathways that could affect birth outcomes. PNMS might be associated with maternal behavioral changes, such as impaired sleep and appetite. It also induces physiological changes, including heightened maternal stress hormones, to which the developing fetus might be particularly sensitive [11]. Prenatal exposure to glucocorticoids appears to be an important mechanism linking PNMS to birth outcomes. For example, prenatal administration of corticosteroids [33,34] and high levels of endogenous maternal glucocorticoids [35] are associated with lower birth weight and shorter gestation length.

The effects of PNMS vary based on the timing of exposure during pregnancy, and on the sensitivity of the systems developing at each stage of gestation. For example, subjective PNMS was positively correlated with dermatoglyphic asymmetry among children in Project Ice Storm exposed during gestational weeks 14–22, when the fingerprints develop, but not among the children exposed during other gestational stages [18]. Similarly, women exposed to an earthquake in early pregnancy appraised the event as more stressful and effects on gestation length were greater compared to later exposure [12], and first trimester exposure to the September 11th, 2001 U.S. World Trade Center (WTC) tragedy was associated with shorter gestation length among newborns at three hospitals near the site [36]. Studies of life events [3] and depressed mood [37] also suggest stronger effects of early pregnancy exposure. However, some studies suggest stronger associations between stressful life events and decreased gestation length at 30 weeks gestation compared to 16 weeks [2], and pregnancy-specific anxiety at 28–30 compared to 18–20 weeks [6]. Early to mid pregnancy appeared to be the most sensitive period for the effects of PNMS exposure on the birth outcomes we assessed, which mirrors our findings for intellectual abilities [19] and functional play [21] at age two.

Observations from exposure to Hurricane Katrina [38], the 1999 bombings of Belgrade [39], pregnancy-related anxiety [1,6] and distress [14,40], depressive symptoms [8,9], and psychosocial [41] and life events stress [42] suggest that greater exposure is associated with shorter gestation lengths [6,42], higher risk of preterm birth [1,8,9,14,38,41], lighter birth weights [39,40], and low birth weight [14,38,41]. In contrast, the severity of ice storm PNMS did not impact

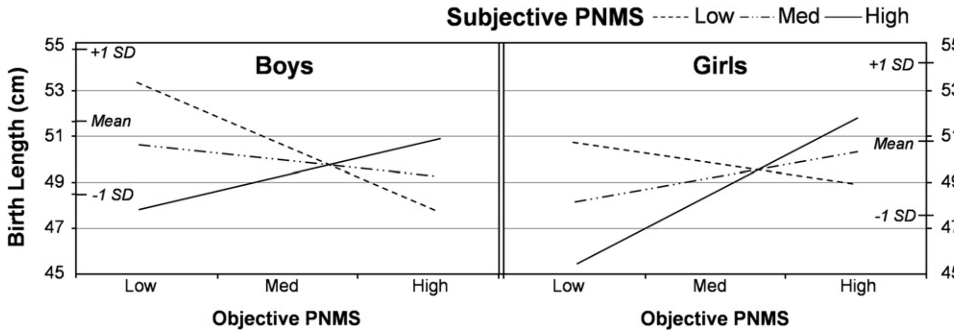

Fig. 2. Interactions between objective and subjective PNMS: predicted values for birth length for boys (left) and girls (right) based on final regression equation. Population means and SDs at 39 weeks gestation are indicated, based on Kierans et al. [31].

gestation lengths or birth weights in our sample. However, exposure timing impacted both of these outcomes, highlighting the importance of including timing in studies when possible.

Results depended not only on timing, but on type of stress: high levels of subjective PNMS in early pregnancy predicted smaller head circumferences, whereas objective PNMS predicted slightly larger head circumferences. These findings might help to contextualize seemingly conflicting results from other studies. For example, exposure to the bombings of Belgrade was associated with larger head circumferences [39], whereas exposure to the WTC tragedy was associated with smaller head circumferences [36]. Perhaps exposure to the bombings of Belgrade was more objectively stressful, whereas the WTC tragedy presented less objective stress, but women's subjective reactions to it were great. Results from studies of exposure to "life stress" are also conflicting: Lou et al. [4] observed smaller head circumferences, while Tegethoff et al. [42] observed larger circumferences. However, whereas the first study assessed a combination of stressors including employment status and housing; traumatic events as defined by the DSM-III-R, such as death of a relative or major illness; and use of drugs and alcohol during pregnancy [4], the second focused on perceived burdens (including work and relationships) [42]. These differences might explain the contradictory findings. The perceived burdens assessed by Tegethoff et al. [42] were associated with larger head circumferences, mirroring our results for objective PNMS exposure; whereas the host of stressors assessed by Lou et al. [4], which included traumatic events, were associated with smaller circumferences, as observed in our results for subjective PNMS exposure. (Tegethoff et al. [42] also observed that smaller head circumferences were associated with emotional symptoms, although results were not statistically significant). These findings highlight the importance of distinguishing between different types of stressors when assessing impacts of PNMS.

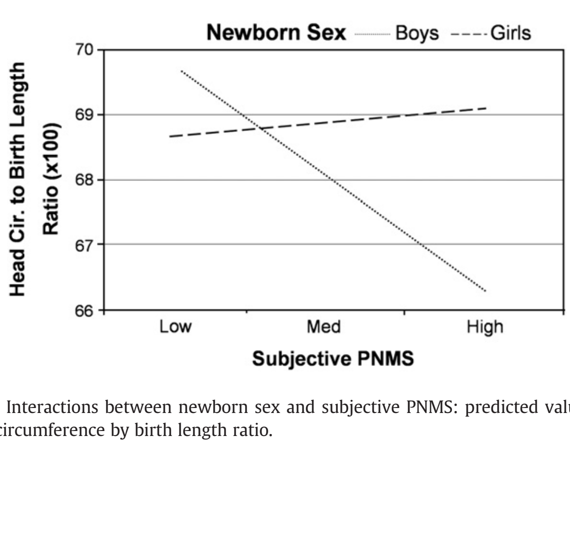

Fig. 3. Interactions between newborn sex and subjective PNMS: predicted values for head circumference by birth length ratio.

Our results also suggest interactions between objective and subjective PNMS. Predicted birth lengths were shortest among newborns of women who were exposed to high levels of objective PNMS but who reacted only minimally, or who had a highly reactive subjective response to low levels of objective PNMS. This would suggest that in the optimal maternal environment, level of distress is concordant with the level of objective threat, and that neither over-reacting, nor under-reacting, is ideal for fetal development. Yet, our results also suggest that any *in utero* exposure to the ice storm had a negative effect since our sample was shorter at birth, on average, than their population counterparts by one-third of a standard deviation. Early growth patterns have long-term implications for health. Linear growth retardation is associated with cognitive and developmental delays [43], and infants that are born small but experience rapid "catch-up" growth have increased risk for cardiometabolic diseases later in life [44]. The birth lengths in our sample, although shorter than expected, are largely within normal parameters – only one child was stunted (birth length for gestational age <-2 SD) – but the results highlight one factor that might contribute to the problem of poor linear growth early in life.

Finally, our results of head circumference to birth length ratios suggest that brain growth might be "spared" relative to other growth parameters, with differences based on newborn sex. Boys and girls have different fetal growth patterns in general, reflecting different "investments" in the placenta and "trade-offs" between growth of the brain and that of other systems [45]. Girls invest more in the placenta, which leaves relatively fewer resources to devote to brain growth, but provides a better buffer in the case of poor maternal nutrition. Since placental enzymes (specifically, 11β-HSD2) can convert cortisol to its inactive form, the placenta also provides some protection from high levels of maternal stress hormones [11]. Boys, on the other hand, invest less in placental growth, instead directing available resources to the brain. In the face of stressors, Eriksson and colleagues (2009) suggest that boys are more likely than girls to trade-off visceral growth to spare brain growth. Our results suggest that boys and girls have different sparing responses to subjective PNMS. Whereas girls' head circumference to birth length ratios remained relatively stable regardless of the severity of subjective PNMS, boys exposed to relatively low levels of subjective PNMS had high predicted ratios, potentially suggesting the shunting of resources from linear to brain growth. However, high levels of subjective PNMS exposure predicted smaller head circumference to birth length ratios among boys. Perhaps the capacity for trade-off is limited when stress levels are high and, if boys indeed invest less in the placenta, they might have less protection from maternal stress hormones compared to girls.

In contrast to several studies discussed above, trait anxiety was not related to outcomes in our sample. It is possible that levels were not high enough to cause disruption or that the relatively high SES in our sample afforded women opportunities to access services that might have buffered the physiological effects of anxiety. Our findings indicate that objective PNMS impacts birth outcomes even when social and socioeconomic conditions are favorable.

4.1. Study strengths, limitations, and future research questions

The strengths of this study include the independent nature of the stressor, which was not associated with variables such as education, personality, or family history; and the ability to separate women's objective hardships and subjective distress from trait anxiety levels and exposure to other life events. However, our stress assessments were primarily related to the ice storm, and although we assessed and controlled for maternal trait anxiety, we do not have detailed data on women's general stress reactivity patterns. Furthermore, since we assessed stress after a sudden and unpredictable event, some desirable data were impossible to collect. For example, we do not have data on maternal dietary patterns, which could have impacted some of the birth outcomes assessed. Analyses were also limited because of a small, unrepresentative sample, in which SES was skewed towards the affluent level.

Our findings suggest several important points for further research. First, future studies would benefit from including more extensive measures of growth, since effects of PNMS on specific growth components might vary. For example, shorter birth length might contribute to the lower birth weights observed in many studies, but birth length has not been analyzed in many PNMS studies. Second, objective and subjective PNMS have different effects on birth outcomes and might interact with one another. Future research aimed at disentangling the contributions of these components might clarify the mechanisms through which PNMS impacts the developing fetus. Finally, our analyses indicate different effects of PNMS on boys and girls, emphasizing the importance of analyzing sex-specific patterns of susceptibility or response to PNMS and their underlying mechanisms.

5. Conclusions

The effects of PNMS in this study were modest once several covariates were accounted for. However, considering the persistence and consequences of adverse birth outcomes, and the current lack of knowledge of the contributing factors [10], even modest effects might be relevant. PNMS could be particularly important where women are already at increased risk of adverse birth outcomes due to known contributing factors (such as poverty or cigarette and alcohol use), and where psychosocial stressors might exacerbate their risk. Although the ice storm caused injury, financial loss, and stress for affected families, when considered in perspective with other recent natural disasters – such as the 2010 earthquake in Haiti or flooding in Pakistan – the level of objective PNMS was much less extreme than that to which many women have been exposed. Nevertheless, the ice storm was sufficient to impact birth outcomes, highlighting the fragility of the developing fetus to PNMS. A deeper understanding of the mechanisms and effects of PNMS on birth outcomes might promote the development of intervention strategies for pregnant women exposed to psychosocial stressors, which could improve the outcomes of their pregnancy and the health status of their newborns.

Conflict of interest statement

The authors declare no conflicts of interest.

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