Original Article

Dietary change mediates relationships between stress during pregnancy and infant head circumference measures: the QF2011 study

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Abstract

Prenatal maternal stress can adversely affect birth outcomes, likely reflecting effects of maternal stress hormones on fetal development. Maternal stress might also induce behavioural changes, such as dietary change, that might influence fetal development. Few studies have documented relationships between stress and dietary change in pregnancy. We analysed stress and dietary change among 222 pregnant women exposed to the 2011 Queensland Floods. We assessed women's objective hardship, subjective distress and cognitive appraisal of the disaster; changes in their diets and their associations with infants' gestational age, weight, length and head circumference at birth, head circumference to birth length ratio (HC/BL) and ponderal index. Greater objective hardship was correlated with more negative dietary change, skipped meals and skipped multivitamins. There were no direct effects of stress or dietary change on birth outcomes. However, we observed an interactive effect of dietary change and exposure timing on head circumference for gestational age (HC for GA) ($p=0.010$) and a similar trend for HC/BL ($p=0.064$). HC for GA and HC/BL were larger among children whose mothers experienced negative changes to their diet in early pregnancy compared with later pregnancy, consistent with a 'head-sparing' response with early gestation exposure. Further analyses indicated that dietary change mediates the relationship between objective hardship because of the floods and these outcomes. This is the first report of relationships among an independent stressor, dietary change and birth outcomes. It highlights another possible mechanism in the relationship between prenatal maternal stress and child development that could guide future research and interventions.

Keywords: pregnancy, women's health, infant growth, behaviour, Barker hypothesis, birth outcomes.

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Introduction

Maternal diet during pregnancy is a major predictor of newborn health outcomes (Darnton-Hill 2013). Inadequate nutrition, particularly during the first or last trimesters, might affect fetal growth, evident in measures such as birth weight and head circumference (Godfrey et al. 1996). In addition, research in the Developmental Origins of Health and Disease (DOHaD) highlights long-term effects of maternal diet during pregnancy. The changes in fetal growth and metabolism in response to an adverse intrauterine nutritional environment can affect risk of

cardio-metabolic diseases such as obesity and Type II Diabetes in adulthood (Barker 2004; Barker 2007).

Another aspect of the prenatal environment linked to infant and adult growth and metabolic patterns is prenatal maternal stress (PNMS) (Hochoer 2007; Beydoun & Saftlas 2008). Similar to maternal undernutrition, PNMS is associated with adverse birth outcomes (Hobel et al. 2008) such as smaller birth length (Lederman et al. 2004; Dancause et al. 2011; Frith et al. 2013), smaller weight (Lederman et al. 2004; Maric et al. 2010; Frith et al. 2013) and low birthweight (Xiong et al. 2008; O'Donnell & Behie 2013). Furthermore, PNMS has long-term effects on

growth and metabolism (Beydoun & Saftlas 2008), including increased risk of overweight and obesity in childhood (Dancause et al. 2012), adolescence (Li et al. 2010) and adulthood (Hohwu et al. 2014). This might reflect independent effects of maternal stress hormones, which can cross the placental barrier and affect fetal growth patterns and the development of central regulators of metabolism (Lazinski et al. 2008). Furthermore, stressful events are associated with changes in maternal behaviours (Rondo et al. 2003; Dunkel Schetter 2011), including maternal diet (Hurley et al. 2005). In the general population, high stress levels are associated with high fat diet (Ng & Jeffery 2003) and consumption of fast food and sweets (Steptoe et al. 1998), and women are more likely to eat less than to eat more in response to stress (Stone & Brownell 1994). Among pregnant women, perceived stress is associated with greater energy intake but lower intake of some micronutrients, and pregnancy-specific stress is associated with reduced protein intake (Hurley et al. 2005). Dietary patterns and stress during pregnancy likely interact to affect fetal and infant development, yet there are few studies of the relationships between maternal stress and diet during pregnancy on infant outcomes (Wadhwa et al. 2011).

This is partly a reflection of the difficulty in analysing PNMS. Research on maternal stress tends to focus on life-changing events such as divorce or job loss. However, these events might have gradual onsets that make it difficult to control for their timing in pregnancy, and might be associated with confounding behavioural, genetic or socioeconomic characteristics that also affect child development. For example, traits such as anxiety or depression might be associated with a mother's probability of experiencing job loss or divorce, and

might also affect child development through shared genetic risk factors or behavioural modelling. Furthermore, in these cases it is difficult to separate the components of the cascade of events leading to stress (King et al. 2012). A potentially stressful event that creates objective levels of hardship (that is, what happened) might evoke different responses (such as levels of subjective distress, or how the woman responded to the event) among different women. Response depends, in part, on an individual's cognitive appraisal of the stressor: if the individual believes that she has enough resources to cope with the stressor, it is characterized as positive stress; whereas when perceived demand exceeds perceived resources, it is experienced as negative stress (Lazarus & Folkman 1984).

Natural disasters are independent stressors that present opportunities to study the effects of maternal exposure to varying levels of objective hardship on infant outcomes, and to distinguish objective hardship from subjective distress and cognitive appraisal. Project Ice Storm, a study of stress during pregnancy following exposure to a severe ice storm, includes analyses of objective hardship (such as injuries, financial loss, number of days without electricity, time spent in temporary shelters), cognitive appraisal (evaluating the effects of the disaster as positive or negative) and subjective distress (severity of post-traumatic stress-like symptoms including intrusive thoughts, hyperarousal and avoidance) because of the storm, and multiple measures of child development. Results demonstrate effects of objective hardship on children's physical development (Dancause et al. 2012; Dancause et al. 2013; Liu et al., 2016), and interactive effects of objective hardship and subjective distress (Dancause

Key messages

- The advantage of studying prenatal maternal stress from a natural disaster is that the objective exposure is independent of the women's own influence, avoiding genetic confounds between stress in pregnancy and outcomes.
- Among women who were pregnant during the Queensland floods, greater objective hardship, subjective distress and having a negative cognitive appraisal of the flood were associated with a less nutritional change in diet, more skipped meals and skipped prenatal vitamins.
- Greater maternal stress predicted poorer maternal diet which then predicted larger head circumference (HC) and a tendency towards 'head-sparing' (HC/birth length) when flood exposure was early in gestation.

et al. 2011). Effects vary depending on the timing of exposure in pregnancy (Laplante et al. 2004; Laplante et al. 2007; Dancause et al. 2011). However, although these studies highlight the importance of the type of stress and its timing, they do not address the mechanisms underlying the effects of objective hardship.

As noted above, one possible pathway linking objective hardship to child development is through effects on maternal behaviours, especially dietary patterns. Thus, our goal was to determine: (1) relationships between measures of stress exposure and response (objective hardship, subjective distress and cognitive appraisal) and maternal diet following a natural disaster; and (2) the potential mediating role of maternal diet in the relationship between PNMS and birth outcomes. We used the 2011 Queensland Flood Study (QF2011) as a case study. In December 2010 and January 2011, the Australian state of Queensland experienced its worst flooding in 30 years. Three-quarters of the state was declared a disaster area, and more than 200 000 people were affected (Van Den Honert & Mcaneney 2011; King et al. 2015). QF2011 builds upon our past studies of maternal stress following natural disasters (King et al. 2012) by examining maternal stress following exposure to the Queensland floods, and multiple longitudinal measures of child development (King et al. 2015). QF2011 also includes assessments of maternal dietary change in response to the disaster, which allows us to analyse dietary change as a mediating factor in the relationship between maternal stress and birth outcomes.

Methods

Ethics approval was granted in April 2011 by the Mater Hospital research ethics committee. All participants provided written informed consent.

Participants

QF2011 includes 230 women who were pregnant and residing in the general vicinity of Brisbane Australia at the peak of the flooding on 10 January 2011. They

were recruited between 4 April 2011 and mid-January 2012. The present study includes 222 women with singleton pregnancies who gave birth between 15 January and 16 October 2011, for whom data on stress, dietary change and birth outcomes were available. All participants were at least 18 years of age at recruitment and spoke English fluently.

Participants were recruited in three different ways (King et al. 2015). First, all new and existing participants recruited for the M@NGO study, a randomized controlled trial comparing midwifery group care with standard care, were invited to participate in QF2011. M@NGO recruitment involved face-to-face, phone and e-mail recruiting following a routine mail-out describing the study to all women attending the antenatal clinic at the Mater Mother's Hospital. Second, women who were pregnant and eligible for QF2011, but not eligible for M@NGO, or who were approached after M@NGO recruitment ceased, were invited to participate. A flyer was included in the routine mail-out, and a researcher in the antenatal clinic recruited participants face-to-face on site. Finally, advertisements were placed in local newspapers, on the radio and online for women who had been pregnant at the time of the floods.

Instruments

Women completed questionnaire packets at recruitment and 12 months post-flood (January 2012), with the exception of approximately 50 women who were recruited more than 10 months after the flood; these women completed only the post-flood questionnaire.

Predictor variables

QF2011 Dietary Scale

We developed a questionnaire, administered at recruitment, asking women about changes to their usual diet and multivitamin use during the floods. For meals, we asked whether the woman skipped meals and how many, with the following response options: 0 (Never skipped a meal), 1 (Skipped 1–2 meals), 2 (3–5 meals), 3 (6–10 meals) and 4 (Skipped more than 10 meals in total). For multivitamins, we asked whether the woman

used multivitamins, whether she skipped multivitamins because of the flood and, if so, for how many days: 0 (Never skipped vitamins), 1 (Skipped 1–2 days), 2 (3–5 days), 3 (6–10 days) and 4 (Skipped more than 10 days in total).

Food category scores

For change to food intake we asked about changes in consumption of 12 categories with 5 response options: −2 (consumed much less than usual), −1 (less than usual), 0 (no change), +1 (more than usual) or +2 (much more than usual) and the number of days during which women experienced this change. The categories included the following (with examples in each category): milk/dairy; meats, fish, legumes and other proteins; fruits/vegetables; sweets; salty snacks; soft drinks (soda and other sugary carbonated drinks); caffeine; take away meals; prepared frozen foods; restaurant meals/eating out; canned food and alcohol. Because so few women reported consuming alcohol, it was removed from further analyses, leaving 11 food categories. Change responses in each dietary category were multiplied by the number of days over which the change occurred. For example, a woman who reported eating ‘much less than usual’ (−2) for the milk/dairy category for 14 days would have a value of −28 for that category, and a woman who reported more than usual (1) for the ‘soft drinks’ category for 8 days would have a value of +8 for that category. These scores were then categorized on a scale from −4 to 4 depending on the severity of the decrease: −4 (score less than −70), −3 (−70 to −36), −2 (−35 to −7), −1 (−6 to −1); or increase: 1 (1–6), 2 (7–35), 3 (36–70) and 4 (more than 70).

Diet change score

Next, in order to provide an index of the overall quality of the change in food consumption because of the floods, these scores were grouped into one composite score named Diet Change. First, the score of each food category was weighted based on its relative magnitude of importance to fetal growth, and the quality of its importance (that is, positively or negatively affecting growth), following guidelines outlined in the Nutrient

Reference Values for Australia and New Zealand (New Zealand Ministry of Health 2006; Australian National Health and Medical Research Council & New Zealand Ministry of Health, 2014). The milk/dairy, protein and fruits/vegetables categories were assigned a weight of +3, being favourable for fetal growth. We assigned soft drinks a weight of −3; sweets, snacks and coffee a weight of −2; and takeaway, frozen food, eating out and canned food a weight of −1. Multiplying each food category score (ranging from −4 to 4) by its weight (−3, −2, −1 or 3) provides an index of the quality of the diet change by category. Thus, for example, a major increase (+4) in milk/dairy (weight of 3) contributes positively to the Diet Change score (+12), and a major decrease (−4) contributes negatively (−12). Similarly, a major increase (+4) in soft drinks (weight of −3) contributes negatively to the Diet Change score (−12), and a major decrease (−4) contributes positively (+12). These individual food category values were then summed to create the Diet Change score, with positive scores indicating an overall beneficial change, and negative scores indicating an overall detrimental change.

Objective hardship

Objective hardship because of the floods was measured through a tailor-made questionnaire targeting experiences related to four categories of exposure used in other natural disaster studies: threat of injury or death, loss, scope and change (King et al. 2012). Each category in the Queensland Flood Objective Stress Scale (QFOSS) had a maximum score of 50 points for a total maximal score of 200 points, with higher scores indicating greater objective hardship (King et al. 2015). The questionnaire was distributed at recruitment, and again 12 months post-flood (January 2012) in order to update the values of financial loss, property damage, experiences dealing with insurance companies and similar questions for which women might not have had complete responses at recruitment. Thus, final scores integrate recruitment questionnaire and post-flood questionnaire values (King et al. 2015). Scores were right-skewed and were log-transformed for analyses.

Cognitive appraisal

Cognitive appraisal of the flood was assessed at recruitment and 12 months post-flood based on responses to the question: 'If you think about all of the consequences of the 2011 Queensland flood on you and your household, would you say that the flood has been': 1 (Very negative), 2 (Negative), 3 (Neutral), 4 (Positive) or 5 (Very positive)? Thus, lower scores indicate more negative appraisal of the event, and higher scores indicate more positive appraisal. Responses on recruitment questionnaires were used in analyses.

Subjective distress

Subjective distress because of the floods was assessed with three instruments administered at recruitment and at 12 months post-flood. The 13-item Peritraumatic Distress Inventory (PDI) (Brunet et al. 2001) and the 10-item Peritraumatic Dissociative Experiences Questionnaire (PDEQ) (Marmar et al. 1997) were used to retrospectively assess emotional distress and panic-like physical reactions that occurred at the time of the flood. Severity of PTSD symptoms, including intrusive thoughts, hyper-arousal and avoidance, was assessed using the 22-item Impact of Event Scale-Revised (IES-R) (Weiss & Marmar 1997). Participants responded on a 5-point Likert scale, from 'not at all' to 'extremely,' the extent to which each behaviour described how they felt during the preceding seven days in relation to the floods. Higher scores on all scales represent greater subjective distress.

A Composite Score for Mother's Subjective Stress, termed COSMOSS, was created from these three variables using principal component analysis (Wold et al. 1987). The factor was computed with weighted regression predictions, using the component score coefficients as weights and the standardized subjective stress variables as predictors:

$$\text{COSMOSS} = 0.358 \cdot \text{IESR} + 0.397 \cdot \text{PDI} + 0.387 \cdot \text{PDEQ}.$$

The COSMOSS score using values from the recruitment questionnaires was used in analyses. Higher scores represent greater subjective distress.

Exposure timing

Timing of exposure to the floods during pregnancy was calculated by comparing the flood peak (10 January 2011) with the birth date, adjusted for gestational age at birth. Thus, this variable represents the number of days the mother had been pregnant on 10 January 2011. Continuous values were used in analyses, with low values indicating exposure during early pregnancy and higher values indicating exposure late in pregnancy. For ease of interpretation, these values were converted to weeks of pregnancy in figures.

Covariates

Participants completed questionnaires assessing years of schooling and household income; parity; positive mental health based on the Mental Health Continuum (Keyes 2002); and state and trait anxiety based on the State-Trait Anxiety Inventory (STAI) (Spielberger et al. 1983). We also included two social support scales: one assessing the number of people that the participant can count on for support, and the other their satisfaction with their support. Socioeconomic status was assessed using the Hollingshead Social Position Criteria (Hollingshead 1973), and compared with the Australian Bureau of Statistics (ABS) Socio-Economic Indexes for Areas (SEIFA) score for each participant's residential area. We analysed hospital records to collect data on depressive symptoms assessed with the Edinburgh Postpartum Depression Scale (EDPS) (Cox et al. 1987) and maternal body mass index (BMI, kg/m²) at the first prenatal booking-in appointment at the hospital.

Outcome variables

Data on birth outcomes were collected from the Mater Mother's Hospital Obstetric Database (MatriX, Meridian Health Informatics, NSW), where the majority of women gave birth. We collected data on gestational age (GA, $n=222$), weight (BW, $n=219$), length (BL, $n=219$) and head circumference (HC, $n=217$) at birth. Sex- and gestational age-

specific *z*-scores were computed for birth weight (BW for GA), birth length (BL for GA) and head circumference (HC for GA) based on comparison to U.S. references (Olsen et al. 2010), chosen as the most complete comparison set for all three measures. We also computed head circumference to birth length ratio (HC/BL) and ponderal index ((BW/BL³) × 1000).

Statistical analysis

We first computed descriptive statistics for predictor variables, outcomes and covariates, and conducted *t*-tests to compare means between women who experienced no dietary change with those whose diets changed in response to the floods. *P*-values were adjusted for multiple testing using the Bonferroni correction. We analysed correlations between three key diet variables – the composite diet change score, skipping vitamins and skipping meals – and stress variables, as well as infant characteristics and maternal BMI.

Next, we analysed relationships between dietary change and birth outcomes, moderated by timing of exposure to the flood. Moderation analyses were conducted using multiple regressions, and version 2.11 of the PROCESS macro for SPSS (Hayes 2013) was used to probe significant interactions. We first entered maternal BMI if it was significantly correlated with the outcome, and covariates that differed among dietary groups. We then entered objective hardship, subjective distress and cognitive appraisal; the dietary variable (Diet Change, Skipped Meals or Skipped Vitamins); exposure timing and, finally, the interaction between the dietary variable and exposure timing. *P*-values for the interaction terms were adjusted for multiple testing using the Bonferroni correction.

Finally, we analysed the mediating effect of Diet Change in the relationship between PNMS and birth outcomes, moderated by timing of exposure. Moderated mediation analyses were conducted using version 2.11 of the PROCESS macro for SPSS (Hayes 2013) using bootstrapping procedures. A 95% confidence interval that did not include 0 was considered significant. We entered maternal BMI if it was significantly

correlated with the outcome, and covariates that differed among dietary groups; objective hardship, subjective distress and cognitive appraisal; Diet Change and exposure timing. Analyses were conducted with SPSS 20.0.

Results

Sample characteristics

Of the 222 women, 217 provided data on marital status and 192 provided data on education. Most were either married or in common-law relationships (93.1%). The women were well educated, with 19.3% completing an apprenticeship or certificate programme and 69.3% completing an undergraduate degree. The Hollingshead index of socioeconomic status (SES), available for 146 families, indicated that 72 women (49.3%) were in the upper SES, 49 (33.6%) in upper-middle, 22 (15.1%) in middle and 3 (2.1%) in lower-middle SES. On 10 January 2011, 92 women (41.4%) were in their first trimester of pregnancy, 87 (39.2%) in their second trimester and 43 women (19.4%) in their third trimester. The sample included 116 male and 106 female infants.

Descriptive statistics

Based on Diet Change scores, 61 women experienced negative change in response to the floods (Diet Change scores ranging from −1 to −72), 157 experienced no dietary change (Diet Change score = 0) and 4 experienced positive change (Diet Change scores ranging from 2 to 7). Given the small number of women in the positive change group and the small degree of their diet change, these women were included in the 'no change' group in descriptive analyses. Table 1 presents descriptive statistics for predictor, control and outcome variables, as well as *t*-tests analysing differences among women who experienced no change or positive dietary change compared with those whose diets changed negatively in response to the floods. Objective hardship and three measures of subjective distress (IESR, PDI, COSMOSS) differed among groups. In general,

Table 1. Means (SDs) for the PNMS variables, covariates and outcome variables among women with no dietary change and with dietary change, with *p*-values for group differences. Full sample *n* = 222

	Full sample (<i>n</i> = 222) Mean (SD)	<i>n</i>	Negative change (<i>n</i> = 61) Mean (SD)	No change or positive change (<i>n</i> = 161) Mean (SD)	<i>p</i> - Value [†]
PNMS variables					
Objective hardship	20.1 (16.5)	222	30.5 (17.7)	16.2 (14.5)	<0.001
Cognitive appraisal	2.7 (0.7)	222	2.5 (0.8)	2.8 (0.7)	0.39
IESR	6.7 (11.3)	222	12.3 (14.4)	4.8 (9.4)	<0.001
PDI	11.7 (8.5)	222	14.6 (8.9)	10.6 (8.1)	<0.01
PDEQ	5.9 (7.2)	222	7.6 (7.5)	5.2 (6.8)	0.13
COSMOSS	0.00 (1.00)	222	0.41 (1.08)	−0.15 (0.93)	<0.01
Exposure timing (days) *	116.0 (73.8)	222	117.8 (77.3)	115.5 (73.1)	>0.99
Covariates					
Maternal BMI	24.4 (4.8)	208	24.8 (4.1)	24.1 (5.0)	>0.99
Years of education	14.5 (1.8)	166	14.7 (1.7)	14.5 (1.9)	>0.99
SES: Hollingshead	52.3 (11.0)	140	50.4 (11.3)	53.3 (10.9)	>0.99
SES: Seifa score	1050 (59)	222	1051 (55)	1049 (62)	>0.99
Parity	0.7 (0.9)	209	0.8 (1.0)	0.7 (0.9)	>0.99
State anxiety	36.9 (9.1)	222	40.8 (9.0)	35.3 (8.7)	<0.01
Depression	5.1 (3.9)	174	6.4 (4.3)	4.7 (3.6)	0.19
Positive mental health	50.2 (11.7)	222	47.6 (12.7)	51.2 (11.2)	0.38
Social support: num.	4.3 (2.3)	137	4.2 (2.5)	4.3 (2.2)	>0.99
Social support: sat.	5.2 (0.9)	137	5.1 (0.9)	5.2 (0.9)	>0.99
Outcome variables					
Gestational age (GA)	39.2 (1.7)	222	39.2 (0.9)	39.2 (2.0)	>0.99
Birth weight (BW, gms)	3519 (525)	219	3635 (467)	3480 (545)	0.47
BW for GA	0.26 (0.82)	219	0.44 (0.87)	0.21 (0.79)	0.54
Birth length (BL, cms)	51.7 (3.1)	219	51.9 (2.6)	51.5 (3.3)	>0.99
BL for GA	0.47 (0.98)	219	0.53 (1.03)	0.44 (0.96)	>0.99
Head circum. (HC, cms)	34.8 (1.7)	217	35.1 (1.3)	34.7 (1.8)	0.78
HC for GA	0.34 (0.87)	217	0.52 (0.87)	0.30 (0.87)	0.94
HC:BL	0.67 (0.03)	217	0.68 (0.04)	0.67 (0.03)	>0.99
Ponderal Index	25.5 (3.1)	219	26.1 (3.4)	25.3 (2.9)	0.99

*112 days = 16 weeks pregnancy; 119 days = 17 weeks pregnancy. [†]Adjusted with Bonferroni correction for multiple testing.

scores were higher among women who experienced negative dietary change. PDEQ scores, cognitive appraisal and exposure timing did not differ among dietary groups. Covariates did not differ among dietary groups with the exception of state anxiety scores, which were higher among women who experienced negative dietary change (indicating greater state anxiety). Thus, state anxiety was included as a covariate in moderation and mediation analyses. Outcome variables did not differ among dietary groups.

Correlations

Correlations (Table 2) showed that the higher the objective hardship and subjective distress, the more negative the dietary change and the more the mothers skipped both meals and vitamins. Similarly, negative cognitive appraisal of the flood was associated with more negative dietary change and more skipped meals. Maternal BMI was correlated with gestational age ($r = -0.280$, $p < 0.001$) and HC for GA ($r = 0.140$, $p = 0.042$), and was included as a covariate in analyses

Table 2. Correlations between dietary variables and PNMS variables, maternal BMI and infant characteristics

	Diet change [†]	Skipped meals [‡]	Skipped vitamins [‡]
Objective hardship	−0.386**	0.409**	0.315**
Cognitive appraisal	0.265**	−0.304**	−0.122
IES-R	−0.281**	0.325**	0.284**
PDI	−0.179**	0.310**	0.222*
PDEQ	−0.194**	0.241**	0.250**
COSMOSS	−0.199**	0.333**	0.257**
Exposure timing (days)	−0.095	0.066	0.103
Maternal BMI	−0.085	0.180**	0.164*
Sex (0 = boys; 1 = girls)	−0.103	−0.021	−0.057
BW for GA	−0.092	0.027	0.049
BL for GA	0.005	−0.009	−0.010
HC for GA	−0.025	0.066	0.167*
HC/BL	−0.016	0.040	0.105
Ponderal index	−0.122	0.037	0.038

[†]Pearson correlation. [‡]Spearman's rank correlation. * $p < 0.05$. ** $p < 0.01$.

of these outcomes. Correlations between objective hardship, cognitive appraisal, subjective distress and scores for the 11 food categories are shown in Table S1.

Moderation analyses: effects of dietary change and exposure timing on birth outcomes

Multiple regression analyses (Table 3) indicated no effects of Skipped Meals or Skipped Vitamins on any birth outcomes. Furthermore, Diet Change had no effect on gestational age, BW for GA, BL for GA or ponderal index. However, we observed an interactive effect of Diet Change and exposure timing, which explained 4.1% of variance in HC for GA. In the full model without the interaction term, greater maternal BMI predicted greater HC for GA ($p = 0.078$). There were no direct effects of state anxiety ($p = 0.363$), objective hardship ($p = 0.427$), subjective distress ($p = 0.337$), cognitive appraisal ($p = 0.322$), Diet Change ($p = 0.769$) or exposure timing ($p = 0.241$). However, the interaction between Diet Change and exposure timing ($p = 0.010$) suggests that effects of Diet Change on HC for GA are moderated by timing of exposure to the floods. For infants exposed in early gestation, the more negative the Diet Change score (reflecting a more detrimental dietary change) the greater the HC for GA, whereas for exposure in late gestation, the more negative the diet change the smaller the HC for GA (Fig. 1a). When mothers experienced no diet

Table 3. Summary of regression analyses testing the effects of dietary change on birth outcomes, moderated by timing of exposure

Outcome	Dietary predictor variable	Model R^2 *	Interaction R^2 change	p -Value: Diet by timing interaction [†]
Gestational age (GA)	Diet change	0.109	0.003	>0.99
	Skipped meals	0.106	0.002	>0.99
	Skipped vitamins	0.113	0.006	0.88
BW for GA	Diet change	0.053	0.018	0.14
	Skipped meals	0.041	0.011	0.36
	Skipped vitamins	0.040	<0.001	>0.99
BL for GA	Diet change	0.022	<0.001	>0.99
	Skipped meals	0.020	0.003	>0.99
	Skipped vitamins	0.024	<0.001	>0.99
HC for GA	Diet change	0.087	0.041	0.01
	Skipped meals	0.040	0.002	>0.99
	Skipped vitamins	0.059	0.003	>0.99
HC/BL	Diet change	0.115	0.023	0.06
	Skipped meals	0.094	<0.001	>0.99
	Skipped vitamins	0.084	<0.001	>0.99
Ponderal index	Diet change	0.049	0.021	0.10
	Skipped meals	0.024	0.001	>0.99
	Skipped vitamins	0.029	0.001	>0.99

*Full model includes State Anxiety scores, as well as GA in analyses of HC/BL and ponderal index, and maternal BMI in analyses of GA and HC for GA; dietary predictor variable (Diet Change, Skipped Meals or Skipped Vitamins); objective hardship (QFOSS), composite subjective stress (COSMOSS) and cognitive appraisal; exposure timing; and the interaction between the dietary variable and exposure timing. [†]Adjusted using the Bonferroni correction for multiple testing.

change, the timing of the floods in gestation made no difference to HC for GA; similarly, there was no effect of diet change when the flood occurred in mid-gestation.

Consistent with these results, the interaction between Diet Change and exposure timing had a marginally significant ($p=0.064$) effect on HC/BL, explaining 2.3% of the variance. In the full model without the interaction term, the later the gestational age at the time of exposure the smaller the HC/BL ($p<0.001$). There were no direct effects of state anxiety ($p=0.777$), objective hardship ($p=0.311$), subjective distress ($p=0.983$), cognitive appraisal ($p=0.814$), Diet Change ($p=0.823$) or exposure timing ($p=0.172$). However, the interaction between Diet Change and exposure timing ($p=0.064$) suggests that effects of Diet Change on HC/BL are moderated

by timing of exposure to the floods. For infants exposed in early gestation, the more negative the Diet Change score, reflecting a more detrimental dietary change, the larger the HC/BL, whereas for exposure in late gestation the more negative the diet change the smaller the HC/BL (Fig. 1b).

Moderated mediation analyses

We observed a mediating effect of Diet Change in the relationship between objective hardship and HC for GA, moderated by exposure timing (Index of Moderated Mediation $CI=-0.003$, -2.8×10^{-4} ; Fig. 2a and Fig. 2b). Objective hardship was negatively associated with Diet Change ($\beta=-3.86$, $p<0.001$), such that greater hardship predicted more negative dietary change. Diet Change, in turn, was negatively associated with HC for GA among children exposed in early gestation ($\beta=-0.042$, $p=0.011$), such that more negative dietary change predicted larger values; and positively associated with HC for GA among children exposed in late gestation ($\beta=0.041$, $p=0.006$), such that more negative dietary change predicted smaller values. The overall indirect effect of objective hardship on HC for GA through Diet Change was significant for children exposed to the floods in early ($CI=0.022$, 0.384) and late gestation ($CI=-0.355$, -0.031).

Similarly, we observed a significant mediating effect of Diet Change in the relationship between objective hardship and HC/BL, moderated by exposure timing (Index of Moderated Mediation $CI=-8.4 \times 10^{-5}$, -6.0×10^{-6}). Objective hardship was negatively associated with Diet Change ($\beta=-3.65$, $p<0.001$), such that greater hardship predicted more negative dietary change. Diet Change, in turn, was negatively associated with HC/BL among children exposed in early gestation ($\beta=-0.001$, $p=0.046$), such that more negative dietary change predicted larger values; and positively associated with HC/BL among children exposed in late gestation ($\beta=0.001$, $p=0.032$), such that more negative dietary change predicted smaller values. The overall indirect effect of objective hardship on HC/BL through Diet Change was significant for children exposed to the floods in both early ($CI=4.9 \times 10^{-4}$, 0.01) and late ($CI=-0.01$, -1.4×10^{-4}) gestation.

Fig. 1. Relationship between dietary change and head circumference for gestational age (a) and head circumference to birth length ratio (b) by timing of exposure. For illustrative purposes, the figures use a value of 4-day gestation for early exposure and 263-day gestation for late exposure, and Diet Change scores of 0 (No change), -15 (Moderate negative change) and -30 (Severe negative change), although the analyses use continuous variables for days of gestation and Diet Change.

Fig. 2. Summary of mediation of dietary change in the relationship between objective hardship and head circumference for gestational age (a) and head circumference to birth length ratio (b), moderated by timing of exposure.

Discussion

The goal of this study was to analyse the role of dietary change in the relationship between PNMS and infants' birth outcomes. Higher objective hardship and subjective distress were associated with a negative change in diet, such as eating less dairy and more sweets, and skipping more meals. The effect of these dietary changes on birth outcomes was evident when considering the timing of exposure to the Queensland floods during gestation: more negative dietary change predicted larger HC for GA among infants exposed in early gestation, but smaller values among children exposed in late gestation. We observed a similar trend for HC/BL ratio. These results are consistent with a pattern of head sparing or brain sparing, which suggests that the fetus will preferentially direct resources to brain growth during times of nutritional or other intrauterine stress, at the expense of linear or visceral growth (Militello et al. 2009; Kaur et al. 2012). Thus, the larger HC for GA and HC/BL among children exposed to negative maternal dietary change in early gestation could reflect an adaptation of the fetus to the intrauterine environment.

Some studies (Militello et al. 2009; Kaur et al. 2012), but not all (Vik et al. 1997; Maulik 2006), suggest that head sparing is more likely to occur with late gestation exposure to an adverse intrauterine environment,

whereas early exposure results in symmetric reductions in all growth measures. In contrast, we observed a head-sparing trend with early-gestation exposure to PNMS and dietary change. However, symmetric and asymmetric growth patterns have been mostly analysed for small for gestational age (SGA) infants (David et al. 1995), whereas in our sample, only 4 infants (1.8%) had low birthweight (<2500 g), and none were SGA (BW for GA z -score < -2). Thus, although the floods were stressful, the level of assault was not severe enough to cause major disruptions in growth. Our results might suggest that the adaptive capacity of the fetus to a moderate stressor and to moderate dietary change is more evident in early gestation, but might be limited in later gestation when major growth patterns are already established.

In contrast to Project Ice Storm, which indicated interactive effects of objective hardship and subjective distress on birth lengths (Dancause et al. 2011), the current study showed no direct relationships between flood exposure and birth outcomes. This might reflect the moderate nature of the stressor. For example, mean IES-R scores in this study (6.7, SD = 11.3) were lower than in Project Ice Storm (11.9, SD = 12.6), as was the percentage of women with scores suggestive of post-traumatic stress disorder (7.7% vs. 14.0%). We might thus expect less pronounced effects of subjective distress in QF2011 than in Project Ice Storm.

Despite these differences, some similarities are evident. In Project Ice Storm, objective hardship predicted larger head circumferences and HC/BL. A further interactive effect of subjective distress and timing was observed among boys: predicted HC/BL ratios were larger among boys exposed to greater subjective distress in early gestation, and smaller with late gestation exposure. The current study highlights a positive indirect effect of the pathway from objective hardship to dietary change to HC/BL ratio in early pregnancy, and a negative effect on HC for GA in late pregnancy, consistent with the overall patterns in Project Ice Storm. Together, these results suggest that the timing and type of the stressor might underlie conflicting relationships between PNMS and head circumference observed in past studies (Lou et al. 1994; Lederman et al. 2004; Maric et al. 2010; Tegethoff et al. 2010). Furthermore, results of the current study suggest that dietary change might represent one underlying pathway in the relationships observed.

Limitations

There are a number of limitations to our analyses, reflecting the difficulties of designing studies after natural disasters. First, we designed the dietary questionnaire quickly in the weeks following the peak of the flooding in order to include it in ethics applications and be ready to begin data collection a scant 10 weeks post-flood. As such, there was insufficient time to validate the questionnaire before use. As well, the dietary questionnaire was administered as late as several months after the floods, when women's recollections might be biased. To address this potential limitation we examined the dates that the questionnaires were completed and found near-zero correlations between days since the flooding and Diet Change scores, suggesting that there was no systematic bias in reporting. Studies analysing repeated administration of Food Frequency Questionnaires (FFQs) show correlations of approximately 0.5–0.7 between FFQs administered from 3 to 10 years apart (Rohan & Potter 1984; Willet et al. 1988; Willet 2013). Recall is more accurate among people with greater education, more stable diets, and vegetarian diets (Kuzma & Lindsted 1990). Given the

dramatic nature of the Queensland floods, we expect that memories of the situation were particularly salient and, therefore, easier to recall. However, we expect that women with less stable diets had poorer recall, resulting in over-reporting of 'no change'. Thus, although the validity of our data may be enhanced by having a relatively well-educated sample, the actual degree of dietary change may be underestimated with our questionnaire.

Similarly, our indices reflect only the relative change in a woman's diet because of the floods, not her absolute nutritional patterns. For example, we cannot distinguish between women with low and high intakes in each category, or women whose regular diets have been affected because of recommendations from their health care providers or symptoms such as morning sickness, but only the degree of change because of the floods. In addition, each woman might interpret the extent of dietary change differently. Furthermore, our weighting of dietary quality, although based on our expectations of relationships between food categories and fetal growth, reflects a subjective evaluation of dietary change. More fruit and vegetables might indeed be beneficial to a woman's diet, and more soft drinks are likely detrimental, but these broad characterizations, rather than precisely quantifying dietary changes, are meant to provide a single index that can direct more detailed future research. Finally, the questionnaire assessed diet during the flood only, representing a brief time window during pregnancy. The generalization of our results is further limited by a sample biased towards high SES.

One might be concerned about recall bias in women's reporting of their stress from the floods since women were recruited anywhere from 2½ months to one year after the flood. Correlations between the time delay since the floods and questionnaire completion suggest that there is no delay-related recall bias with respect to either objective hardship or cognitive appraisal. There was a small, but significant, correlation between time delay and subjective distress ($r=0.27$, $p<0.001$) with women reporting increasing distress the longer the time since the flood. Given that time delay explains only 7% of the variance in subjective distress, and that our results highlighted the role of

objective exposure, any potential recall bias from the delays ought not to influence our conclusions.

Conclusions

Despite these limitations, this study highlights a number of points for future research. First, our data emphasize the importance of the timing of stress and dietary change during pregnancy. Relationships between PNMS, dietary change and child development might be obscured if timing is not precisely considered. Second, our data demonstrate that stress from a natural disaster is associated with dietary change, and that maternal diet represents a mediator in the pathway between PNMS and birth outcomes. This underscores the importance of designing future studies to analyse PNMS and dietary change together. Furthermore, these relationships could inform our development of PNMS interventions. Whereas exposure to stressors is inevitable, maternal dietary change in response to the stressor represents a potentially modifiable mechanistic pathway that could be targeted in interventions to improve health outcomes among pregnant women and their children.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contributor statement

KND developed the dietary questionnaire with other authors, conducted literature reviews, wrote much of the manuscript and supervised the work of DMutran.

DMutran conducted the original literature review, conducted many of the analyses and wrote much of the manuscript.

GE supervised the analyses and interpretation of results, wrote the analysis section and assisted in the editing of the manuscript.

DPL developed the study design and objective hardship questionnaire (with SKing), and contributed to the interpretation of the results and the editing of the manuscript.

SKildea HS and DMcIntyre were integral in the development of the QF2011 project on site in Australia, oversaw the collection of data, assured the integrity of the information in the manuscript with respect to data collection and the interpretation of data with respect to pregnancy and diet, and contributed to the editing of the manuscript.

SKing founded the QF2011 project and developed the objective hardship questionnaires, with the support of the co-investigators, oversaw the development of the manuscript and edited it and is responsible for the overall integrity of the work.

All authors read and approved the final version of the manuscript submitted.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1 Pearson correlations between PNMS variables (Objective hardship, QFOSS; Cognitive appraisal; and Subjective distress, COSMOSS) and scores in each food category