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The Effect of Maternal Stress on Birth Outcomes: Exploiting a Natural Experiment

Florencia Torche

Abstract A growing body of research highlights that *in utero* conditions are consequential for individual outcomes throughout the life cycle, but research assessing causal processes is scarce. This article examines the effect of one such condition—prenatal maternal stress—on birth weight, an early outcome shown to affect cognitive, educational, and socioeconomic attainment later in life. Exploiting a major earthquake as a source of acute stress and using a difference-in-difference methodology, I find that maternal exposure to stress results in a significant decline in birth weight and an increase in the proportion of low birth weight. This effect is focused on the first trimester of gestation, and it is mediated by reduced gestational age rather than by factors affecting the intrauterine growth of term infants. The findings highlight the relevance of understanding the early emergence of unequal outcomes and of investing in maternal well-being since the onset of pregnancy.

Keywords Stress · Birth weight · Gestational age · Preterm birth · Natural experiment

> *And surely we are all out of the computation of our age, and every man is some months older than he bethinks him; for we live, move, have a being, and are subject to the actions of the elements, and the malice of diseases, in that other World, the truest Microcosm, the Womb of our Mother.*
> (Sir Thomas Browne 1672:XXXIX)

Introduction

A growing body of evidence shows that early conditions have important consequences for health, educational, and socioeconomic outcomes. Recent research

F. Torche (✉)
Department of Sociology, New York University, New York, NY, USA
e-mail: florencia.torche@nyu.edu

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has highlighted the interaction between genes and environment during the first years of life and has made a case for investment in development and health early in life (e.g., Heckman 2006; Shonkoff and Phillips 2000). While some research has restricted this concern to determinants after birth, there is no good reason to do so. If, as the epidemiological literature on fetal origins suggests, *in utero* conditions start a cascade of events that affect individual outcomes in adulthood, attention should be placed on this critical period.

This article focuses on one such condition—maternal stress—and its effect on infants' birth weight. Using a major earthquake that struck Chile in 2005 as a source of acute maternal stress, and applying a difference-in-difference methodology, I find that infants exposed to the earthquake in the first trimester of gestation had significantly lower birth weight and reduced gestational age than those unexposed or exposed later in the pregnancy.

This question matters because stress is highly prevalent in human populations. Chronic stress emerging from factors such as enduring economic strain and discriminatory experiences; and acute stress from severe life events such as war, natural disaster, divorce, and job loss affect a large proportion of the population (Schneiderman et al. 2005). Many sources of stress are unequally distributed along socioeconomic and racial lines, so that the poorest nations and individuals within nations are at higher risk of exposure (Pearlin et al. 2005; Turner et al. 1995; Wisner et al. 2004). The influence of stress on birth weight is relevant because birth weight is a marker of early health status, and it has effects on development and well-being throughout childhood and adulthood (Conley et al. 2003). Low birth weight and preterm birth are leading causes of infant mortality (Mathews and MacDorman 2008) and have been found to increase the risk of neurologic disorders, chronic lung disease, deafness, and blindness during infancy (Pallotto and Kilbride 2006; Paneth 1995). As postulated by the fetal origins hypothesis, birth weight may be correlated with cardiovascular disease and diabetes in adulthood (Barker et al. 1993; Hales et al. 1991). Furthermore, birth weight is correlated with more than health outcomes. Cross-sectional studies have shown an association between birth weight and early cognitive performance, educational attainment, employment, and earnings (Boardman et al. 2002; Case et al. 2005; Currie and Hyson 1999). Researchers using sibling and twin models to account for environmental and genetic confounders have also reported an effect of birth weight on socioeconomic outcomes (Almond et al. 2005; Behrman and Rosenzweig 2004; Black et al. 2007; Conley and Bennett 2000; Oreopoulos et al. 2008).

A plausible biological mechanism linking maternal stress and birth outcomes indicates that the stress response triggers the production of placental corticotrophin-releasing hormone (CRH), which in turn results in reduced gestational age and low birth weight (Hobel and Culhane 2003; Lockwood 1999). Most studies of human populations report an association between stress and birth weight, usually by inquiring about life events or chronic sources of stress among expecting women (Dole et al. 2003; Hedegaard et al. 1996). A lingering concern, however, is that women who experience and report more stress may have systematically different genetic endowments, engage in different behaviors, or be selected by any other attribute correlated with birth outcomes, which prevents extricating the influence of stress from its correlates. Even if observed confounders, such as smoking or health

risk factors, are controlled for, it is impossible to rule out all potential sources of a spurious association. In fact, the very findings of extant research suggest that unobserved selectivity may be a major limitation. For example, a population-based prospective study (Hedegaard et al. 1996) found no association between stressful life events and birth outcomes independent of women's appraisals. In contrast, life events *assessed by women as highly stressful* were related to low birth weight, suggesting the potential influence of omitted variables related to maternal appraisal.

To alleviate this problem, I use a major natural disaster—a 7.9-magnitude earthquake that struck the northern area of Chile in 2005—as an exogenous source of acute stress. Because the earthquake struck without warning, affected regions of the country with different intensities (including none at all), and had minimal spillover effects in terms of death and injury, population displacement, and health outcomes, it provides a powerful study setting. By merging a time series on birth outcomes with seismological data on earthquake intensity across locations, this study examines the influence of acute stress exposure on birth weight.

Some studies have used natural experiments to examine the effect of stress on birth outcomes. A landmark study by Glynn et al. (2001) exploited the 1994 Northridge, California, earthquake and found an association between early pregnancy exposure and reduced gestational length. With a sample of only 40 women and no controls for trends among unexposed women, however, the evidence is only suggestive. Other studies have used the assassination of a Prime Minister and the sinking of a ferry in Sweden (Catalano and Hartig 2001), the September 11, 2001, attacks in New York (Eskenazi et al. 2007), and the harassment in California of Arab and Arab American women after the September 11 attacks (Lauderdale 2006) as exogenous sources of stress.

This study builds on this emerging literature and examines the influence of an unambiguously stressful natural disaster at the population level. It also addresses poorly understood questions about the *timing* and *mechanism* of stress effects. Because specific systems in the human organism develop at distinct periods of gestation, the influence of stress on birth weight may be time-sensitive, operating during critical developmental windows (Gluckman and Hanson 2009). Furthermore, low birth weight can result from two distinct mechanisms—reduced gestational age and intrauterine growth restriction—which differ in etiology and consequences for later development (Hobel et al. 2008; Paneth 1995). Drawing on comprehensive birth registry data, I examine when during the pregnancy stress is more consequential, and the extent to which gestational age and intrauterine growth contribute to the effect of stress exposure on birth weight.

Background

Maternal Stress and Birth Weight: Accounting for Mechanisms

Studies of the association between maternal stress and birth weight focus on four types of psychosocial distress: major life events; short-term state and long-term trait anxiety; stress associated with discrimination and racism; and pregnancy-specific anxiety (Austin and Leade 2000; Hobel 2004). The processes linking stress to birth

outcomes are physiological and endocrine. Maternal stress has been implicated in the production, in both the mother and the fetus, of corticotrophin-releasing hormone (CRH), adrenocorticotrophic hormone (ACTH), and cortisol, which are in turn related to premature delivery (Glynn et al. 2001; Hobel 2004; Lockwood 1999).

Although evidence of the link between stress and cortisol-producing hormones is conclusive, the question about when during pregnancy stress is more detrimental is still unresolved. One approach indicates that maternal stress later in the pregnancy—particularly in the third trimester—is more influential. Some research suggests that stress-induced CRH alters the physiology of parturition, producing uterine contractions that result in early delivery (Majzoub et al. 1999; Mancuso et al. 2004; Wadhwa et al. 1998, 2004). An alternative hypothesis suggests that stress early in the pregnancy has greater consequences. As pregnancy advances, physiological changes lead to dampened maternal responses to stress (Glynn et al. 2001, 2004; De Weerth and Buitelaar 2005). These changes protect women from the consequences of stress later in the pregnancy but leave them vulnerable early on. Early maternal stress initiates a chain of events leading to preterm labor by triggering CRH gene expression in the placenta, which sets a biological clock for early delivery months later (Hobel 2004; McLean et al. 1995, 1999; Sandman et al. 2006).

Furthermore, the mechanisms whereby stress results in low birth weight are not fully specified. Most studies have found that maternal stress affects birth weight by shortening gestational age (Copper et al. 1996; Nordentoft et al. 1996). However, some support exists for an effect on intrauterine growth restriction (IUGR; Wadhwa et al. 2004), probably driven by higher levels of placental CRH resulting in decreased uteroplacental flow and hypoxemia, which are known risk factors for IUGR (Giles et al. 1996; Goland et al. 1993).

The 2005 Tarapaca Earthquake

The Tarapaca earthquake struck the northernmost region of Chile on June 13, 2005. It registered a magnitude of 7.9 on the moment-magnitude (MM) scale, a logarithmic scale with values ranging from 1 to 9.9, in which a one-unit increase indicates an earthquake approximately 30 times more powerful. Based on its MM score, the Tarapaca earthquake is classified as "disastrous."[1] The areas most affected were the Chilean cities of Iquique and Alto Hospicio and the surrounding towns, with a population of approximately 272,000.

Evidence indicates that earthquakes are a major source of physiological and psychological stress, as signaled by health indicators such as acute cardiac events and stroke (Dimsdale 2008; Leor et al. 1996), changes in brain function (Lui et al. 2009), and population reports of distress and anxiety immediately following the disaster (Siegel 2000). Even though earthquakes are expected in Chile because of the convergence of the *Nazca* and *South American* tectonic plates, it is impossible with the

[1] As a reference, the Northridge earthquake that affected Los Angeles, California, in 1994 had a magnitude of 6.7; the devastating 2008 Sichuan earthquake in China reached 7.9; and the recent 2010 earthquake in Chile (which has no geographic overlap with the disaster examined herein) reached an 8.8 magnitude.

technology currently available to predict when or where within the country an earthquake will occur.

In spite of its violence, the Tarapaca earthquake had few spillover effects. The earthquake's toll in terms of lives and property damage was small: 11 people died, 130 were injured, 180 residences were destroyed, and 0.035% of the population had to temporarily relocate to shelters (ONEMI 2005). This limited damage was the result of seismic preparedness and low population density. Chile has enforced a stringent building code for decades, and much infrastructure uses earthquake-proof technology (Hidalgo and Arias 1990). Low population density minimized problems associated with human concentration in disaster-affected areas. However, the economic consequences were more noticeable. Following the earthquake, the regional index of economic activity dropped by 20.7% compared with the same quarter one year before, and recovery did not begin until early 2006 (INE 2005, 2006). However, the economic dislocation mostly affected the mining industry. Given that mining is capital-intensive, the earthquake had little impact on employment. The unemployment rate in the June–August quarter increased to 12% compared with 11% for the same quarter a year earlier, a trend that does not depart from the rest of the country. Because the earthquake most heavily damaged sparsely populated rural villages, which accounted for less than 8% of the population in this affected region, displacement was reduced (Earthquake Engineering Research Institute 2005). The consequences for population health in terms of acute respiratory infections and other diseases were also minor. Limited spillover effects suggest the main vehicle whereby earthquake exposure affected those exposed *in utero* was the stress and anxiety it elicited among pregnant women.

Data, Variables, and Analytical Strategies

Data

The main data source is the file of Chilean birth certificates for 2004, 2005, and 2006 established by the Chilean Ministry of Health; there are more than 200,000 births a year. Each record includes information on gestational age at delivery; sex, weight, and height of the newborn; type of delivery (single or multiple); and medical attention. It also includes information on maternal age, education, marital status, and parity. Central for this analysis, the birth record includes the mother's county of regular residence. Chile has a total population of 16 million and an area of 285,860 square miles, divided into 350 counties. Accordingly, counties have an average area of 816 square miles and a population of 45,000. As a result, the county-level data provide a precise measure of geographical location. I merge information about maternal county of residence during pregnancy with information about the intensity of the earthquake across counties provided by the Chilean National Emergency Office (ONEMI) to produce a measure of the treatment.

Variables

The dependent variables are birth weight measured in grams, gestational age measured in weeks, and uterine growth measured as the gestational age–specific

birth-weight percentile.[2] In an alternative specification, these variables are dichotomized to produce the standard measures of low birth weight (<2,500 grams), preterm delivery (<37 completed weeks of gestation), and intrauterine growth restriction (birth weight below the 10th percentile of the weight distribution by gestational age[3]). These categorical thresholds identify infants who are most at risk for mortality, morbidity, and developmental problems (Kline et al. 1989), and they are used to target interventions to promote children's well-being in the developed and developing world (e.g., Bale et al. 2003; Brooks-Gunn et al. 1994).

Birth weight is recorded by the professional who attends the delivery (99.8% of deliveries are attended by a professional in Chile) and measured with little error (Mardones et al. 2008). Gestational age is more difficult to ascertain than birth weight (Behrman and Stith-Butler 2007). In the Chilean case, the health care provider estimates gestational age based on last menstrual period and early-pregnancy sonogram. The information is considered reliable for women with at least one prenatal care visit. Based on a large probability survey, the 2006 Socioeconomic Characterization (CASEN) Survey, I estimate these to be 87.9% of Chilean pregnant women (Ministry of Planning Chile 2006). For women who have not had a prenatal care visit, the attending professional estimates gestational age based on an interview with the mother. This estimation procedure reduces the proportion of missing data for gestational age, which is only 0.13% in the Chilean data set. The probable cost of reducing missing data for the gestational age variable is the loss in reliability. However, reduced reliability will result in bias only if there is a systematic association between under- or overestimation and treatment allocation, a very unlikely occurrence. In the most likely scenario of random misestimation, measurement error in the dependent variables will not induce bias.

Treatment

The Mercalli scale is used to quantify the intensity of the earthquake in different regions of the country. While the moment-magnitude scale measures energy released, the Mercalli scale evaluates the effect of the earthquake on the earth's surface, humans, objects of nature, and human-made structures on a 12-point ordinal scale with the following categories: instrumental (I), feeble (II), slight (III), moderate (IV), rather strong (V), strong (VI), very strong (VII), destructive (VII), ruinous (IX), disastrous (X), very disastrous (XI), and catastrophic (XII), with this last category, which has never (yet) been observed, identifying total destruction. Given that the Mercalli scale captures how people experience the earthquake, it is the preferred metric of the earthquake intensity *as felt by the population* (Scawthorn 2003).

I measure the intensity of the Tarapaca earthquake across counties, which varies from I (instrumental) to IX (ruinous), and implement an ordinal version of the treatment obtained by dividing the counties into three groups. High intensity (T_2) comprises counties where the earthquake intensity was very strong to ruinous

[2] This measure is preferred over the simple quotient between weight and gestational age because, given nonlinearities in fetal growth, this quotient is correlated with week of gestation.

[3] Given international and temporal variation in weight-by-gestational-age distributions, I use updated birth-weight curves for the Chilean population (Gonzalez et al. 2004) to calculate IUGR.

(VII to IX in the Mercalli scale), moderate intensity (T_1) includes counties where intensity was moderate to strong (IV–VI), and low intensity (T_0) encompasses counties where intensity is less than moderate (less than IV). I expect the effect of the earthquake to be pronounced in the high-intensity treatment group because its lower bound (VII, "very strong" in the Mercalli scale) defines a categorical boundary at which the earthquake is felt by the entire population and damage starts occurring (Ramirez and Peek-Asa 2005). The distinction between the moderate- and low-intensity groups is designed to capture potential dose-response effects of stress exposure.

Five time points are distinguished to examine the impact of the earthquake across gestational ages. In chronological order, t_0 identifies babies conceived after December 2003 and born before the earthquake (June 13, 2005). The variables t_1, t_2, and t_3 identify, respectively, infants who experienced the earthquake during the third, second, and first trimester of gestation; t_4 identifies those conceived after the earthquake and no later than March 2006.[4] Because multiple births are significantly lower-weight, the analysis is restricted to singletons, which represent 98.2% of total births. After these specifications, the analytical sample sizes for the high-intensity treatment level (T2) across the five time periods are the following: $t_0 = 3{,}610$, $t_1 = 1{,}066$, $t_2 = 1{,}087$, $t_3 = 956$, and $t_4 = 3{,}467$. The comparable figures for the moderate-intensity group (T1) are $t_0 = 3{,}071$, $t_1 = 1{,}003$, $t_2 = 990$, $t_3 = 927$, $t_4 = 3{,}073$, and those for the low-intensity group (T0) are $t_0 = 167{,}339$, $t_1 = 50{,}074$, $t_2 = 54{,}975$, $t_3 = 46{,}481$, $t_4 = 162{,}864$.

Statistical Method

I employ a difference-in-differences (DID) approach. The three aforementioned groups are distinguished based on treatment status: $T = 0$, 1, and 2, where $T = 0$ identifies pregnant women living in low-intensity areas of the country, and $T = 1$ and $T = 2$ identify, respectively, pregnant women living in moderate- and high-intensity areas. Individuals are observed in five time periods, where $t = 0$ indicates infants born before the earthquake, and the subsequent values refer to the four time points described in the previous section. This formulation is a straightforward extension of the simple case with two groups and two time points, expressed as follows: $\overline{Y}_0^T$ and $\overline{Y}_1^T$ are the sample averages of the outcome for the treatment group before and after the treatment, and $\overline{Y}_0^C$ and $\overline{Y}_1^C$ are the corresponding averages for the control group (subscripts identify time periods, and superscripts identify treatment status). The outcome Y_i is modeled by:

$$Y_i = \alpha + \beta T_i + \gamma t_i + \delta\,(T_i \times t_i) + \varepsilon_i,$$

where β is the treatment group–specific effect, which accounts for average permanent differences between treatment and control groups, and γ is a time trend that is common to control and treatment groups. The coefficient for the interaction term δ measures the pre-post difference in average outcome in the treatment group minus the pre-post difference in the average outcome in the control group—that is, $\widehat{\delta}_{DD} = ([\overline{Y}_1^T] - [\overline{Y}_0^T]) - ([\overline{Y}_1^C] - [\overline{Y}_0^C])$, which captures the true effect of the treatment. The DID methodology is designed to account for any systematic differences across

[4] Because one objective of the analysis is to examine the effect of the earthquake on gestational age, the time of the treatment is defined on the basis of estimated conception date rather than "counting back" from birth date.

treatment groups that emerge, for example, from socioeconomic composition, diet, or altitude, which are captured by the parameter β. The methodology controls also for any trends that may affect all treatment groups, including season of birth, the economic cycle, or any event affecting the entire country, which are captured by the parameter γ.

The unbiasedness of the difference-in-differences approach rests on the "parallel trends" assumption. This assumption requires that there be no treatment group–specific trends that could bias the estimates of treatment effects. This assumption is highly plausible in this setting because an earthquake is a random occurrence likely uncorrelated with population characteristics that affect birth outcomes. In order to further account for potential changes in the demographic or socioeconomic composition of the treatment group resulting from the earthquake, all models include controls for maternal age (<19 years old, 20–29, 30–34, and 35 and older), maternal education (primary, secondary, and postsecondary schooling), parity (1 birth, 2–3, and 4 or more), marital status (married or unmarried), and urban residence. Alternative specifications incorporate county fixed effects to account for unobserved factors at the community level, and weight the models by the propensity score of living in different treatment groups based on the aforementioned covariates to improve comparability across treatment groups (Imbens 2004). Results from these specifications (available from the author upon request) are substantively identical to those presented here.

Results

Birth Weight and Gestational Age

Table 1 presents the analysis for birth weight measured in grams, gestational age measured in weeks, and weight for gestational age measured as gestational age-specific birth weight. The effect of the treatment is evaluated across the five time points distinguished.

Model 1 predicts mean birth weight across time points for the three treatment groups. The parameter estimates of interest are the interaction terms between each time period and exposure to the treatment categories. Model 1 indicates that infants exposed to a high-intensity earthquake (T2) in their third or second trimester do not experience a significant decline in birth weight.[5] However, those exposed in the first trimester suffer a substantial decline in birth weight of 51 grams, on average, as indicated by the parameter estimate associated with the $t_3 \times T_2$ interaction term. Furthermore, birth weight returns to its pretreatment level among infants conceived after the earthquake in the high-intensity area. The trend for the moderate-intensity group also reveals a drop in mean birth weight of about 13 grams among infants exposed in the first trimester, although this decline fails to reach significance. There is virtually no change across time periods in the low-intensity treatment group. Figure 1 plots the predicted mean birth weight across time points and treatment

[5] Because data for the entire population of Chilean births are used, significance tests are used only heuristically, implicitly invoking a super-population.

Table 1 Difference-in-difference analysis of the effect of maternal stress on birth weight, gestational age and uterine growth: Chilean births, 2004–2006

	Model 1		Model 2		Model 3	
	Birth Weight[a]		Gestational Age[b]		Uterine Growth[c]	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Low Intensity ($T = 0$)						
Moderate Intensity ($T = 1$)	20.343*	(9.470)	0.037	(0.032)	1.103*	(0.527)
High Intensity ($T = 2$)	44.470***	(8.628)	0.130***	(0.029)	1.182*	(0.480)
Born Before Earthquake ($t = 0$)						
Third Trimester of Gestation ($t = 1$)	10.031***	(2.626)	0.021*	(0.009)	−0.196	(0.146)
Second Trimester of Gestation ($t = 2$)	−1.866	(2.534)	0.006	(0.008)	−0.157	(0.141)
First Trimester of Gestation ($t = 3$)	−8.507**	(2.704)	−0.057***	(0.009)	0.048	(0.150)
Conceived After Earthquake ($t = 4$)	−1.508	(1.797)	−0.059***	(0.006)	0.533***	(0.100)
t_0 (born before earthquake) × T_1						
t_1 (third trimester) × T_1	9.341	(16.508)	0.031	(0.065)	−0.318	(1.086)
t_2 (second trimester) × T_1	6.921	(16.456)	0.040	(0.065)	1.934	(1.084)
t_3 (first trimester) × T_1	−13.806	(15.067)	−0.022	(0.067)	0.516	(1.118)
t_4 (conceived after earthquake) × T_1	12.009	(11.510)	0.054	(0.045)	−0.003	(0.752)
t_0 (born before earthquake) × T_2						
t_1 (third trimester) × T_2	2.630	(18.055)	0.026	(0.060)	0.304	(1.006)
t_2 (second trimester) × T_2	17.444	(17.916)	0.013	(0.060)	1.404	(0.998)
t_3 (first trimester) × T_2	−50.840**	(18.834)	−0.188**	(0.063)	−0.871	(1.049)
t_4 (conceived after earthquake) × T_2	8.726	(12.322)	0.043	(0.041)	0.239	(0.686)
Intercept	3310.5***	(3.119)	38.950	(0.010)	49.327***	(0.173)
N	500,983		500,983		500,983	

Notes: Linear regression model with robust standard errors. The sample includes all singleton infants conceived between December 2003 and March 2006 and born in Chile. Controls for the following covariates are added: maternal age (<19 years old, 20–29, 30–34, 35 and older), education (primary, secondary, postsecondary schooling), parity (1 birth, 2–3 births, 4 or more births), marital status (married, not married), and urban residence.

[a]Birth weight is measured in grams.

[b]Gestational age is measured in weeks.

[c]Gestational age–specific birth weight percentile.

*$p < .05$; **$p < .01$; ***$p < .001$

groups using the parameter estimates from the model.[6] The marked drop in mean birth weight among those exposed to high-intensity earthquake effects in the first trimester suggests that the effect of acute maternal stress is tightly focused early in the pregnancy; the small but insignificant drop in the moderate-intensity areas is not inconsistent with a dose-response pattern.

[6] Predicted values in all models identify modal categories for all covariates: women 20–29 years of age, with secondary education, with no previous live births, single, and living in urban areas.

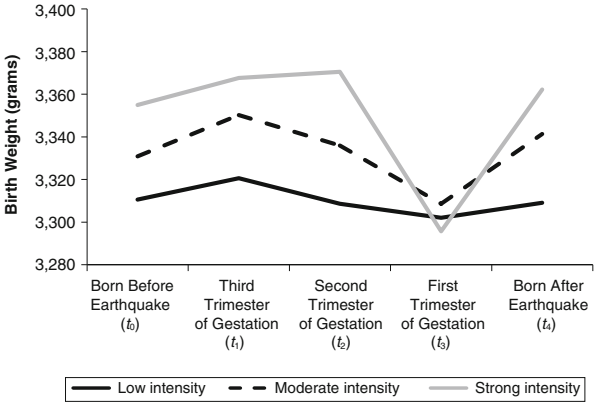

Fig. 1 Predicted mean birth weight for Chilean births, by treatment status and timing: 2004–2006. Obtained from parameter estimates of Model 1, Table 1

To evaluate the magnitude of the effect in the high-intensity area, it is useful to compare it with interventions targeted at reducing low birth weight. Evaluations of the Supplemental Nutrition Program for Women, Infants, and Children (WIC), the most important nutritional supplementation program in the United States, found a 63-gram increase in birth weight among enrolled pregnant women (Bitler and Currie 2005:84), which compares with the 51-gram average decline among infants in the high-intensity area. While the effect of the WIC intervention is measured only among women who received WIC, the earthquake-related drop is particularly remarkable because it is an intent-to-treat effect among the entire population of pregnant women, which likely includes women who did not suffer from anxiety as a result of the earthquake.

Model 2 in Table 1 examines the effect of earthquake-induced maternal stress on gestational age. Figure 2 plots the trends based on the model's parameter estimates and shows a significant decline among infants in the high-intensity area of approximately one-fifth of a week, focused on the first trimester of gestation. Gestational age returns to pre-earthquake levels for those conceived after the earthquake. As in the case of birth weight, the decline is minor and statistically insignificant in the moderate-intensity group and null in the low-intensity one. Model 2 suggests then that the effect

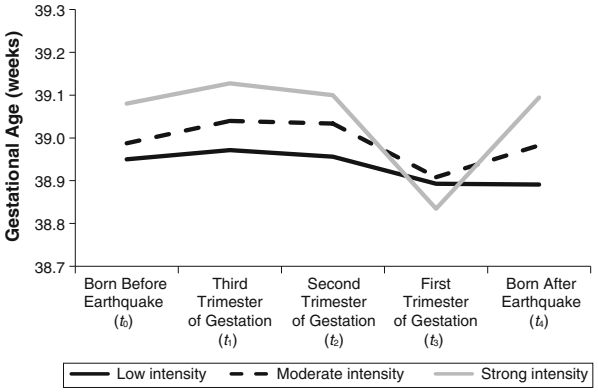

Fig. 2 Predicted mean weeks of gestation for Chilean births, by treatment status and timing: 2004–2006. Obtained from parameter estimates of Model 2, Table 1

of maternal stress on birth weight is at least partly driven by a reduction in gestational age. Given that this effect is restricted to the first trimester of gestation, this finding is consistent with the hypothesis of a biological clock for preterm delivery initiated early in the pregnancy, when the mother is most vulnerable.

Model 3 examines the effect of stress on uterine growth, and Fig. 3 reports the predicted trends. A small and statistically insignificant decline in fetal growth is found among infants in the high-intensity group exposed in the first trimester, with no significant change across the period considered in the moderate- and low-intensity groups. As a whole, these results support the hypothesis that the influence of maternal stress on birth weight is largely mediated by reduced gestational age. Although controlling for this presumed mediator in the model predicting birth weight is inappropriate because gestational age is observed post-treatment (e.g., Gelman and Hill 2007:188–192), the evidence strongly suggests that the effect of acute stress exposure on weight at birth is driven by a reduction of weeks of gestation.

Low Birth Weight, Preterm Birth, and Intrauterine Growth Restriction

Findings indicate that exposure to an acute stressor results in a substantial reduction in mean birth weight among the population exposed early in the pregnancy, and this effect appears to be mediated by reduced gestational age. However, an analysis based on continuous versions of the dependent variables may have limitations. As shown in Fig. 1, there is a substantial gap in baseline birth weight between high- and low-intensity groups, and the earthquake-induced drop in birth weight in the former group is virtually of the magnitude of this gap. This raises the question, Even if the population-level effect of exposure to a high-intensity earthquake is substantial—51 grams, on average—does it result in an increase in births most at risk of poor outcomes later in life, or does it just alter birth weight within a plausibly optimal range?

To address this question, Table 2 presents the analysis of the probability of low birth weight (<2,500 grams), preterm birth (<37 weeks of gestation), and intrauterine growth restriction (birth weight <10th percentile for gestational age [IUGR]). These categorical thresholds have been identified as markers for increased mortality, morbidity, and developmental problems. Thus, this analysis provides a direct evaluation of the effect of

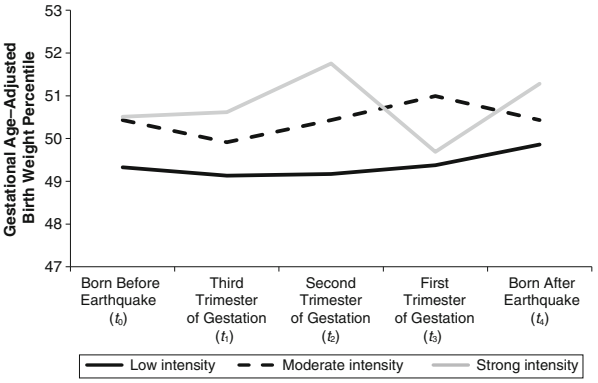

Fig. 3 Predicted mean uterine growth for Chilean births, by treatment status and timing: 2004–2006. Obtained from parameter estimates of Model 3, Table 1

the stressor on the proportion of births most at risk. Given that the interaction effects that are the basis of the DID approach are not interpretable in nonlinear models such as probit or logit (Ai and Norton 2003), I use linear probability models. Robust standard errors account for the built-in heteroskedasticity in these models.

The findings are clear. Model 1 in Table 2 indicates that the probability of low birth weight in the high-intensity group rises from 4.7% before the earthquake to 6.5% among those exposed during the first trimester, but not in later periods of gestation. The probability of low birth weight returns to

Table 2 Difference-in-difference analysis of the effect of maternal stress on low birth weight, preterm birth and intra uterine growth restriction (IUGR): Chilean births 2004–2006

	Model 1		Model 2		Model 3	
	Low Birth Weight[a]		Preterm Delivery[b]		IUGR[c]	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Low Intensity ($T = 0$)						
Moderate Intensity ($T = 1$)	−0.007	(0.004)	−0.005	(0.004)	−0.007	(0.004)
High Intensity ($T = 2$)	−0.007	(0.004)	−0.008*	(0.003)	−0.007	(0.004)
Born Before Earthquake ($t = 0$)						
Third Trimester of Gestation ($t = 1$)	−0.007***	(0.001)	−0.008***	(0.001)	−0.001	(0.001)
Second Trimester of Gestation ($t = 2$)	−0.0005	(0.001)	−0.002*	(0.001)	0.001	(0.001)
First Trimester of Gestation ($t = 3$)	0.001	(0.001)	0.002	(0.001)	0.0003	(0.001)
Conceived After Earthquake ($t = 4$)	0.002**	(0.000)	0.002**	(0.000)	−0.001	(0.001)
t_0 (born before earthquake) × T_1						
t_1 (third trimester) × T_1	−0.002	(0.009)	−0.007	(0.008)	0.001	(0.008)
t_2 (second trimester) × T_1	−0.005	(0.009)	−0.007	(0.008)	−0.006	(0.008)
t_3 (first trimester) × T_1	0.009	(0.009)	0.003	(0.009)	−0.0002	(0.008)
t_4 (conceived after earthquake) × T_1	0.003	(0.006)	−0.006	(0.006)	0.004	(0.006)
t_0 (born before earthquake) × T_2						
t_1 (third trimester) × T_2	0.001	(0.008)	−0.002	(0.008)	0.006	(0.007)
t_2 (second trimester) × T_2	−0.007	(0.008)	−0.006	(0.008)	0.008	(0.007)
t_3 (first trimester) × T_2	0.017*	(0.008)	0.026**	(0.008)	−0.005	(0.008)
t_4 (conceived after earthquake) × T_2	−0.002	(0.006)	0.002	(0.005)	−0.0004	(0.005)
Intercept	0.054***	(0.001)	0.060***	(0.001)	0.066***	(0.001)
N	500,983		500,983		500,983	

Notes: Linear probability models with robust standard errors. The sample includes all singleton infants conceived between December 2003 and March 2006 and born in Chile. Controls for the following covariates are added: maternal age (<19 years old, 20–29, 30–34, 35 and older), education (primary, secondary, postsecondary schooling), parity (1 birth, 2–3 births, 4 or more births), marital status (married, not married), and urban residence.

[a] <2,500 grams.

[b] <37 completed weeks of gestation.

[c] <10th percentile of the birth weight for gestational age distribution, based on curves adjusted for the Chilean population (Gonzalez et al. 2004).

*$p < .05$; **$p < .01$; ***$p < .001$

baseline levels among infants conceived after the earthquake. An increase in the probability of low birth weight emerges also in the moderate-intensity group, although it is minor and fails to reach significance. Model 2, predicting the probability of preterm birth, shows an increase from 5.2% to a substantial 8.0% for infants in the high-intensity group exposed during the first trimester of gestation, while according to Model 3, the increase in the probability of IUGR fails to reach significance. These findings are consistent with the hypothesis that the main avenue for the effect of stress on birth weight is an increase in the probability of preterm delivery and indicate that maternal stress exposure in early pregnancy does not simply alter mean birth weight within a plausibly optimal range, but rather increases the proportion of births most vulnerable to poor health and developmental outcomes.

Robustness and Sensitivity Analyses

The unbiasedness of the DID methodology used in this analysis rests on the assumption that the counterfactual birth-weight trends across treatment groups would be the same in absence of the earthquake, so that any change could be attributed to the stressor. In addition to demographic and socioeconomic composition, two potential sources of bias should be explored. First, a stressful event may result in a spontaneous abortion or miscarriage (Mulder et al. 2002; Nepomnaschy et al. 2006). If the most vulnerable pregnancies were lost, yielding a healthier exposed population eligible for live birth, the outcomes of the survivors would be different from the counterfactual population outcome.

If fetal deaths increased in the area stricken by the earthquake but not in others, underestimation of the earthquake's effect due to a "culling of the weakest" may occur. I examine this possibility by exploiting the records on spontaneous abortions and miscarriages from the Chilean Ministry of Health. The number of reported fetal deaths in the treated area was 3, 13, and 5 for those who experienced the earthquake during their first, second, and third trimester, respectively. These figures compare with an average of seven fetal deaths per trimester in the treated area over the entire 2004–2006 period, excluding the 9 months of *in utero* exposure to the earthquake. These figures are not consistent with a "culling of the weakest" hypothesis. Furthermore, if some spontaneous abortions and miscarriages, particularly early ones, went unnoticed or unreported, this analysis would *underestimate* the negative stress effects on birth outcomes.

Second, the response to the earthquake in the high-intensity area may have induced a compositional change based on unobserved characteristics of mothers. In particular, the earthquake may have been followed by selected out-migration, altering the composition of the babies eligible for life birth. If, for example, healthier women were overrepresented among the out-migrants, the increase in low birth weight may be due to the selective reduction of the population, which violates the "parallel trend" assumption.

To assess this possibility, I use the large-scale probability 2006 Socioeconomic Characterization (CASEN) survey to identify women with children born between mid-June 2005 and March 2006 (i.e., who are likely to have been

pregnant during the earthquake). I examine the proportion of women who changed county of residence after the earthquake by relying on the survey question, "Were you living in [current county of residence] in 2002?" If women were not living in their current county four years ago, the survey asked, "In which county were you living in 2002?"

Even if the 2002–2006 comparison captures migratory flows before the earthquake, it provides a close approximation to earthquake-induced migration. Overall, only 10.5% of women changed counties between 2002 and 2006 in Chile. This proportion was slightly higher in the treated area, reaching 11.5%. However, detailed analysis of the migrants' counties of destination indicates that 38% of those who emigrated from a county in the high-intensity area moved to another county within the same area. As a result, only 7.1% of the population living in the high-intensity area in 2002 had moved to another region of the country by 2006. Even if the influence of selective out-migration cannot be fully ruled out, these small percentages suggest that, if it exists, it should be minor.

Discussion

There is growing awareness that individuals are sensitive to the external environment during the uterine period, and that *in utero* exposures have lasting consequences over the life course. Understanding the influence, timing, and mechanisms of specific insults, however, poses a major challenge because they do not usually emerge in isolation. By exploiting a major earthquake as an exogenous source of stress, I isolate the influence of one such condition—acute maternal stress—on birth weight and address important unsolved questions about the timing and mechanism of the stress effect.

The analysis shows a significant decline in mean birth weight and an increase in the probability of low birth weight among the population exposed to a high-intensity earthquake. This effect is focused on the first trimester of gestation and is largely mediated by a reduction in gestational age, rather than by factors affecting the intrauterine growth of term infants. The findings are consistent with the hypothesis that early-pregnancy acute stress—when the woman is physiologically more vulnerable—triggers a placental clock for premature delivery. Although this hypothesis is new, it has received growing support in recent research and is consistent with the notion of other biological clocks applied to aspects of maturation in extrauterine life, such as puberty and senescence. By using an ordinal version of the treatment—distinguishing high-, moderate-, and low-intensity groups—I found a strong negative effect on birth outcomes in the high-intensity treatment group, a negative but insignificant change in the moderate-intensity group, and no influence in the low-intensity group.

The findings have implications for questions regarding the stratification of health outcomes. A major concern in the social sciences is the mechanisms that account for socioeconomic and racial inequality in early health conditions. It is difficult, however, to judge the extent to which observed disparities result from nutritional

deficits; elevated stress triggered by deprivation, discrimination, or severe life events; infection; strenuous workloads; or exposure to environmental toxins, among other causes because these factors are typically correlated. The literature has suggested, but has not proven, that stress is a central mediator for the noxious effect of poverty and racial discrimination on birth weight and prematurity of infants (e.g., Collins et al. 2000; Kramer et al. 2001). Precisely by isolating maternal stress from its unfortunately common correlates, this analysis provides compelling evidence in support of a central mediating role of stress in the emergence of the "first injustice" and in the intergenerational reproduction of disadvantage (Gortmaker and Wise 1997).

This study is subject to a number of caveats. I exploit a natural disaster as an exogenous source of acute stress (Rosenzweig and Wolpin 2000). This strategy rests on the assumption that there are no alternative paths of influence, other than stress, whereby exposure to this major earthquake has a detrimental effect on birth weight—an assumption called exclusion restriction (Angrist et al. 1996). Very limited spillover effects in terms of loss of life, injury, displacement, employment, and health outcomes support this assumption, but cannot fully rule out alternative pathways of influence.

Additional caveats concern the type of stress being studied and the unit of analysis for which the effect is measured. The generalizability from an acute stressor, such as an earthquake, to chronic sources of stress is a remaining question. Although research suggests similar physiological and endocrine responses to both sources of stress (Sapolsky 2004), the literature on allostatic load suggests that the cumulative wear and tear that results from chronic stress is particularly detrimental (McEwen 1998) and cautions against extrapolation of these findings. In terms of the unit of analysis studied, the causal inference literature warns about the violation of the stable unit treatment value assumption (SUTVA), the assumption that the effect of a particular treatment is independent of others receiving the treatment (see, e.g., Rubin 1980). Insofar as individual stress levels depend on support networks or interactional dynamics (Aneshensel 1992; House et al. 1988; Norbeck et al. 1996), the observed population-level effect of stress most likely differs from an aggregate of individual-level effects measured in isolation. At one level, this is not a concern. To the extent that individuals are usually embedded in social networks, measuring population-level effects is more relevant than considering individuals in fictitious isolation. A further question, however, refers to the effect of circumstances that induce distress among specific individuals, without social ramifications.

In spite of these caveats, the findings are clear and robust. They contribute to an emerging body of evidence showing that maternal stress, particularly in early pregnancy, substantially affects birth outcomes. However, only the accumulation of evidence from a series of studies will produce a conclusive answer. In particular, studies that use "varying envelopes" for stress—different sources of stress, equivalent in terms of their essential characteristics but not subject to the same source of potential bias (Rosenbaum 1984, 2001)—and that examine the potential heterogeneity of stress response across the population are needed to further understand the influence of maternal stress on the life chances of the next generation.

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