Within-mother analysis of seasonal patterns in health at birth

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A large literature describes relationships between month of birth, birth weight, and gestation. These relationships are hypothesized to reflect the causal impact of seasonal environmental factors. However, recent work casts doubt on this interpretation by showing that mothers with lower socioeconomic status are more likely to give birth in months that are associated with poorer birth outcomes. Seasonality in the numbers of conceptions in different months can also induce a mechanical correlation between preterm birth and month of birth. This paper analyzes the seasonality of health at birth using a large sample of 647,050 groups of US siblings representing 1,435,213 children. By following the same mother over time, we eliminate differences in fixed maternal characteristics as an explanation for seasonal differences in health at birth. We find a sharp trough in gestation length among babies conceived in May, which corresponds to an increase in prematurity of more than 10%. Birth weight conditional on gestation length, however, is found to be strongly hump-shaped over the year, with 8–9 additional g for summer conceptions. We examine several potential mechanisms for explaining seasonality in birth outcomes that have generally been dismissed in the literature on seasonality in rich countries, notably disease prevalence and nutrition. The May trough in gestation length coincides with a higher influenza prevalence in January and February, when these babies are nearing full term, whereas the hump shape in birth weight is associated with a similar pattern in pregnancy weight gain.

A venerable literature spanning many scientific fields has investigated the relationship between season of birth, health, and socioeconomic outcomes. Seasonal patterns have been found for birth outcomes, mental health, neurological disorders, body height, life expectancy, intelligence quotient, educational attainment, and income (1–8). As an indicator of the size of this literature, the work by Torrey et al. (4) identifies more than 250 studies solely on the relationship between season of birth and schizophrenia. Although winter births tend to be associated with poorer outcomes in most studies, seasonal patterns differ from country to country, over time, and between study populations. Still, it is often hypothesized that these relationships reflect causal effects of seasonal environmental factors.

However, several papers point out that women who give birth in different seasons tend to have different characteristics. For example, Lam et al. (9) show that there is greater birth seasonality in nonwhite than white births. Similarly, Darrow et al. (10) show that mothers with lower socioeconomic status tend to give birth in months with poorer average birth outcomes. Buckles and Hungerman (8) show that mothers' education, race, age, and marital status all fluctuate systematically over the year and argue that these fluctuations may explain much of the relationship between season of birth and outcomes. The issue of selection has long been recognized in the seasonality literature (11). Still, many season-of-birth studies do not control for maternal characteristics, or they include only broad socioeconomic proxies that are unlikely to capture the entire extent of selection.

In this paper, we analyze the seasonality of health at birth by comparing siblings conceived by the same mother at different times. Because the effects of seasonality are computed by following the same woman over time, they are not contaminated by socioeconomic differences between mothers who select into different conception months. We thereby contribute selection-free estimates to a literature that can be traced back for almost a century (12, 13).*

Furthermore, we shed light on potential mechanisms, especially infectious disease and nutrition, which have been downplayed in the previous literature (1). For example, influenza infections are known to trigger adverse birth outcomes (15–18), perhaps by causing inflammation, which has itself been linked to the cascade of events that trigger labor (19, 20). Additionally, vaccinated mothers have been shown to be less likely to deliver prematurely than unvaccinated mothers during influenza season (21, 22). However, to our knowledge, seasonal influenza epidemics have not been linked to seasonal patterns in health at birth in developed countries. Nutrition during pregnancy has been found to affect birth weight (23, 24), but the seasonality literature has hypothesized that nutrition is an unlikely driver of seasonal birth outcomes in developed countries, where food supply fluctuates little over the year (1).

Our birth data come from Vital Statistics Natality, comprising 3.2 million birth records for all births in New Jersey from 1997 to 2006, New York City from 1994 to 2004, and Pennsylvania from 2004 to 2010. These data include some information relevant to nutrition, including prepregnancy weight and weight gain during pregnancy, in addition to other characteristics of the mother such as race and education and health behaviors such as smoking. To test for the role of seasonal influenza, we merge influenza monitoring data collected by the Center for Disease Control from 1997 onward.

We focus on the month of conception rather than the month of birth, because seasonal fluctuations in the conception rate lead to a mechanical relationship between average gestation length and birth month (*Discussion*). We chose gestation length and birth weight as the outcomes of interest; these outcomes are the most commonly examined measures of infant health at birth, and also, these measures have been associated with child and adult outcomes (25).

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Results

We restrict attention to single births with nonmissing information on gestation length. To compare siblings, we further exclude mothers with no more than one birth during the observation period. These exclusions yield a sample of 1,435,213 births. Table 1 shows descriptive statistics for this sample as well as all births in

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*The sole previous paper using sibling comparisons that we are aware of is by Gavrilov and Gavrilova (14), who collected a sample of centenarians, their siblings, and spouses through internet search and found that centenarians are more likely than shorter-lived siblings to have been born in the fall. There may be some measurement issues involved with reconstructing siblingship groups in this fashion. More importantly, their analysis is at the birth month level and therefore, prone to the potentially strong conception rate confounder as discussed below.

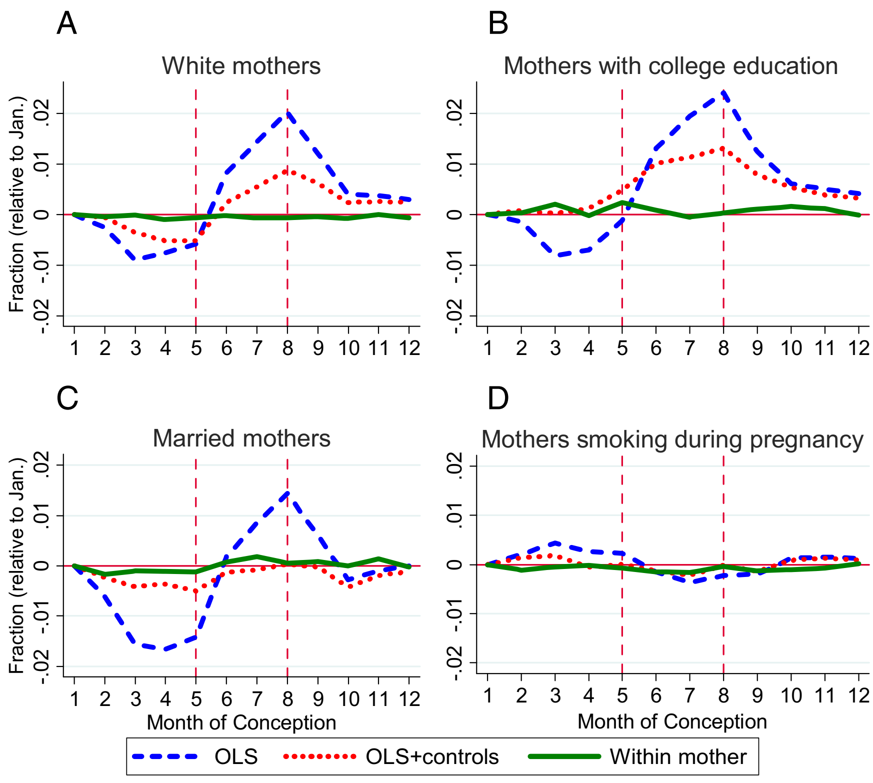

Fig. 1. Mother characteristics by month of conception. The coefficients from regressions of (*A*) a zero/one indicator for white mothers, (*B*) an indicator for mothers with more than 12 y of schooling, (*C*) an indicator for married mothers, and (*D*) an indicator for mothers smoking during pregnancy on month of conception indicator variables are displayed. January serves as the reference month. OLS regressions (dashed lines) control only for state-specific time trends. OLS + controls regressions (dotted lines) further control—except if coinciding with the dependent variable—for maternal race, education, age, marital status, and newborn's parity and sex. Within-mother regressions (solid lines) further add mother indicators. Numerical regression results are displayed in Table S1 (n = 1,435,213).

the United States over the past two decades. The fraction of white mothers is lower in the regional sample, but the other maternal and birth characteristics look fairly similar to those characteristics in the full sample of US births.

Socioeconomic characteristics are strongly associated with conception months. As the ordinary least squares (OLS) results in Fig. 1, dashed lines, indicate, mothers conceiving in the first one-half of the year are significantly more likely to be nonwhite, less educated, less likely to be married, and more likely to smoke during pregnancy than those mothers conceiving in the second one-half of the year ($P < 0.001$ in each regression). Controlling for a broad set of observable mother and birth characteristics (Fig. 1, dotted lines) weakens the seasonality in mothers' socioeconomic status (SES). However, a significant pattern remains in all cases (equality of month effects rejected with $P < 0.001$ in each regression). This finding indicates that the inclusion of even detailed observables is not sufficient to control for confounding because of selection into conception months.

Fig. 1, solid lines, shows the results from within-mother comparisons. We can think of these comparisons as regressions with a perfect control for the mother's type, which by construction, cannot vary with season of conception, because it is a fixed constant for each mother. Evidently, if we regress fixed characteristic of the mother, such as race, on this fixed constant for each mother, we would not expect to find any significant effect. Indeed, if it were not for a small amount of measurement error in measured race, it would not be possible to estimate such an equation. Hence, it is not surprising that including the mother fixed effects eliminates seasonality in maternal race (Fig. 1*A*). Similarly, there are only a small number of women who increase their education, and therefore, including the mother fixed effect eliminates seasonality in maternal education (Fig. 1*B*). These examples show that within-mother comparisons effectively control for selection into conception months.

Marital status and smoking behavior, however, might vary over time. For example, if mothers have a preference for certain conception months and if marital status and smoking correlate with whether a conception was planned, then one would expect seasonality in these characteristics to remain, even in within-mother comparisons. As the solid lines in Fig. 1 *C* and *D* show, however, within-mother comparisons eliminate the seasonality in these characteristics.

Table 1. Summary statistics for the study sample and the overall United States

	New Jersey 1997–2006; New York City 1994–2004; Pennsylvania 2004–2010: >1 birth per mother		United States 1989–2008: All births	
	Mean	SE	Mean	SE
Birth outcomes				
Gestation length (wk)	38.799	2.020	38.920	0.190
Birth weight (g)	3,335	565	3,338	25
Mother characteristics				
White	0.522	0.499	0.787	0.009
>12 y of education	0.494	0.500	0.449	0.042
Married	0.639	0.480	0.665	0.038
Smoking	0.102	0.302	0.135	0.028
Pregnancy weight gain (lb)	30.0	13.7	30.5	0.4
Prepregnancy weight (lb)	147.1	36.0	—	—
Number of births	1,435,213		78,176,946	
Number of mothers	647,050		—	

Sample restrictions: single births with nonmissing information on gestation length. Prepregnancy weight and mother identifiers are not available in the US-wide data.

In Fig. 2*A*, we repeat these regressions with gestation length as the dependent variable. Fig. 2*A*, dashed line, shows that the seasonal pattern in gestation length matches the seasonal pattern in maternal characteristics, in that there are worse outcomes in the first 5 mo of the year than in the second one-half of the year ($P < 0.001$). The gestation length decreases by about 0.1 wk from January to May and jumps back to the January level in June. Thereafter, it moves around a slightly lower level. The similarity between seasonality in maternal characteristics and seasonality in gestation length suggests that there may be little to learn from these OLS results about potential effects of the conception month on birth outcomes, because the observed seasonality in birth outcomes could be largely driven by selection into conception.

When controlling for maternal and birth characteristics (Fig. 2*A*, dotted line) and within-mother comparisons (Fig. 2*A*, solid line), the magnitude of the estimated conception month effects decreases slightly. However, the qualitative seasonal pattern is quite similar. The average gestation length decreases significantly by 0.8 wk ($P < 0.001$) during the first 5 mo of the year and returns to the January level in June, where it remains for the rest of the year. This finding indicates that the seasonal pattern in gestation length is not driven by mothers of different socioeconomic background selecting differently into conception months. The May decrease in gestation length by 0.8 wk leads to an increase in premature births of about 1 percentage point (Fig. S1*A*). Given an average prematurity rate of 7.6%, this estimate indicates a 13.2% increase. This result holds across maternal SES for both males and females and when excluding firstborn children (Fig. S2). The similarity of the seasonal pattern in gestation length across specifications and subgroups suggests that external environmental factors affecting the society as a whole might play an important role. One such potential factor is seasonal influenza.

Fig. 2*B* illustrates the average fraction of patients in reporting healthcare centers diagnosed with influenza-like illnesses for each conception month (this measure is the Center for Disease Control's standard influenza monitoring measure; additional details are in *Materials and Methods*) during the month of birth. The fraction of influenza patients at birth increases during the first conception months of the year, reflecting the start of the influenza season in late August. It peaks for May conceptions, which are scheduled to be born in mid-February and tend to suffer a shortened gestation, with deliveries taking place in late January and early February when seasonal influenza is at its peak (Fig. S3*A*). In the following conception months, the fraction strongly declines until August and then remains at a level slightly below January. The strong correlation of gestation length and the prevalence of influenza (the correlation coefficient is −0.71) is remarkable.

The relationship between seasonal influenza and gestation length is further explored in Fig. 3, which exploits year to year variation in both the extent and the timing of influenza epidemics. The fall of 2009 saw the arrival of the H1N1 pandemic, which not only began much earlier (and peaked earlier) than a regular influenza season but also involved many more cases (Fig. S3*B*). If influenza leads to preterm birth, then we might expect to see both a stronger seasonality in gestation length and a shifting of the pattern to earlier months in 2009 relative to other years. Fig. 3 shows exactly this pattern: infants conceived in February to May had shorter gestations in 2009. The seasonal effect is about 1.5 times as large in 2009 as in other years, and the trough is shifted to February/March. This pattern is evident in both the OLS (Fig. 3*A*) and the within-mother specification (Fig. 3*B*). Corresponding prematurity results are Fig. S1*B*.

In Fig. 4, we turn to the second birth outcome: birth weight. The OLS results (dotted line in Fig. 4*A*) indicate a seasonal pattern in birth weight that matches the seasonality in maternal characteristics. Newborns conceived in the first 5 mo of the year have significantly lower birth weight than newborns conceived in the second one-half of the year ($P < 0.001$). Average birth weight decreases by 10 g during the first 5 mo of the year and then increases by more than 20 g in June. It remains at this high level for the summer months and declines slightly during the fall. This seasonal pattern coincides with the socioeconomic selection into conception months (Fig. 1) even more strongly than in the case of gestation length.

Fig. 4*A*, dashed line, shows that controlling for a rich set of controls does little to dampen the strong seasonal pattern. However, Fig. 4*A*, solid line, shows the effects when comparing different births within the same mother. The decrease during the first 5 mo is less pronounced when we compare infants born to the same mother and is not significantly different from zero. For summer conceptions, however, average birth weight remains significantly higher, with about 8 additional g compared with January conceptions. This seasonal pattern is found across SES, child sex, and birth order groups (Fig. S4).

Because many low birth weight babies are premature, the seasonal pattern in birth weight might be driven by the strong seasonal pattern in gestation length shown in Fig. 2*A*. In particular, the jump in birth weight between May and June might reflect the dramatic change in average gestation length between these two months. In Fig. 4*B*, we repeat the birth weight regressions and include indicators for each week of gestational age. These figures continue to show a hump shape in birth weight with a gain of 8–9 additional g for summer conceptions compared with January conceptions. However, the jump in average birth weight between May and June disappears. Instead, birth weight begins to increase between April and May. This result

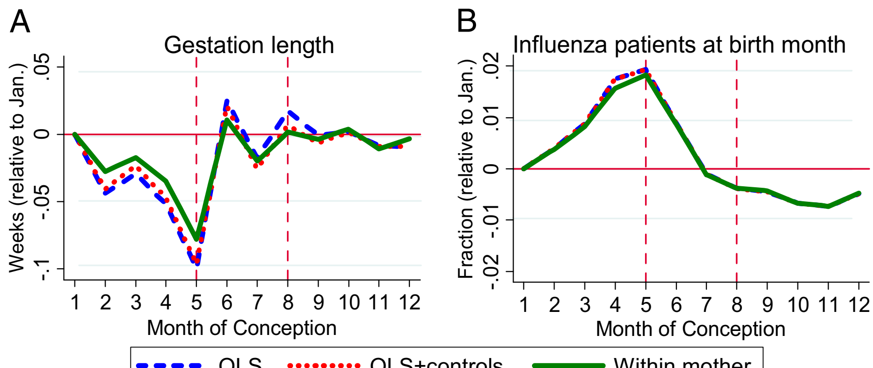

Fig. 2. Gestation length and influenza prevalence at birth by month of conception. The coefficients from regressions of (*A*) gestation length and (*B*) the fraction of patients visiting a healthcare center with influenza-like illnesses on the month of conception zero/one indicator variables are displayed. Numerical regression results are displayed in Table S2. Fig. 1 has additional notes.

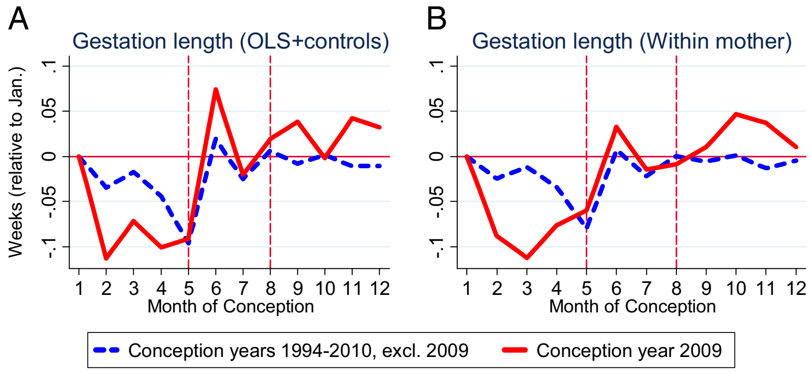

Fig. 3. Gestation length by month of conception (1994–2010 vs. 2009). The coefficients from regressions of gestation length on month of conception indicator variables are displayed. The solid line shows the coefficients for the conception year 2009, and the dashed line is the estimated effect for the years 1994–2010 (net of the 2009 effect). January serves as the reference month. The regression in *A* controls for a quadratic time trend, maternal race, education, age, marital status, and newborn's parity and sex, and the regression in *B* adds mother indicators.

suggests that shorter gestation length—potentially triggered by the prevalence of seasonal influenza at the month of birth—depresses the birth weight of May conceptions. However, the seasonal pattern in gestation does not serve as an explanation for the higher birth weights of summer conceptions.

One well-established determinant of birth weight is nutrition during pregnancy (23, 24), which can be proxied by maternal weight gain during pregnancy. Fig. 4*C* shows that there is a strong seasonal pattern in pregnancy weight gain. From January to June, average weight gain increases by about 0.8 lb. It remains at this level from June to August, before it declines back to about the level of January. Remarkably, this sizable hump shape hardly changes when additional controls are included and when we do within-mother comparisons. Additionally, the conception months of highest weight gain correspond to the months with highest birth weight.

A natural question to ask is whether these changes in weight gain over the year reflect differential maternal weight at birth or just a differential catch-up process because of seasonality in female body weight at conception. In Fig. 4*D*, we analyze prepregnancy weight. Indeed, prepregnancy weight decreases by 0.3–0.4 lb during the first months of the year and increases back to the initial level in November. However, prepregnancy weight remains constant in the middle of the year, indicating that changes in weight gain across these months do not seem to be related to differences in prepregnancy weight.

Discussion

Seasonal patterns in health at birth have been documented for almost a century. What has been unknown is the extent to which these associations are driven by socioeconomic selection into conception months. We address this issue by comparing birth outcomes for the same mother at different points in time. Our first set of results emphasizes the relevance of this empirical strategy. We show that the inclusion of observable mother characteristics is not sufficient to eliminate the strong seasonal selection found in our data. In contrast, comparing the effects of seasonality within mothers effectively controls for maternal characteristics that are associated with month of conception. We find strong seasonality in two central birth outcomes. Gestation length is lower for conceptions during the first months of the

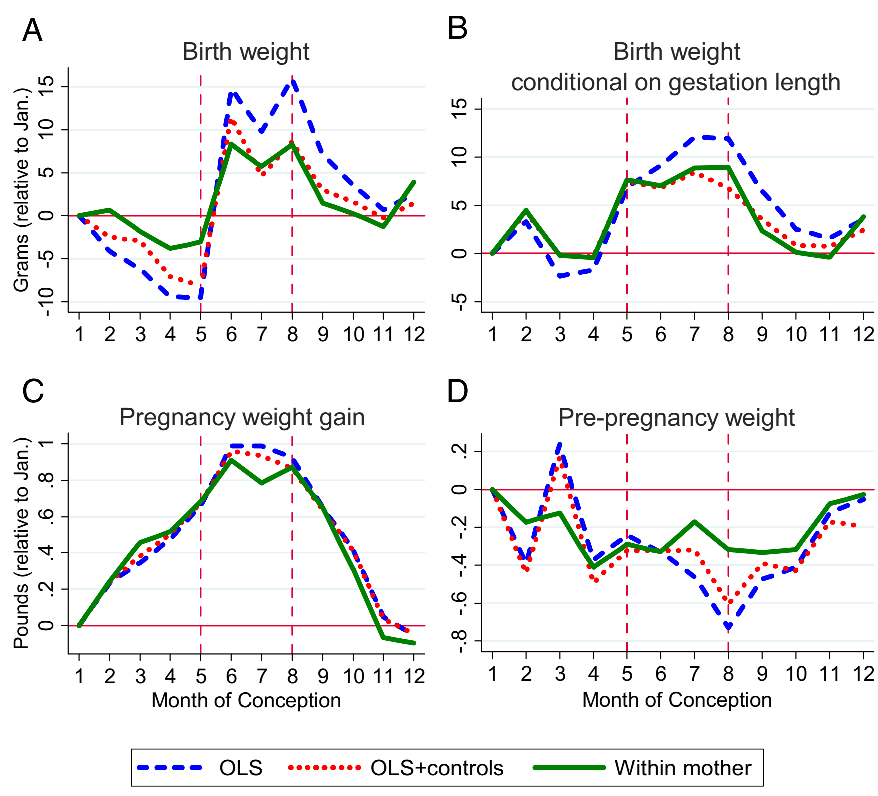

Fig. 4. Birth weight, pregnancy weight gain, and prepregnancy weight by month of conception. The coefficients from regressions of (*A*) birth weight, (*B*) birth weight conditional on gestation length, (*C*) maternal weight gain during pregnancy, and (*D*) prepregnancy weight on month of conception zero/one indicator variables are displayed. *B* regressions include zero/one indicator variables for each week of gestation length. Negative weight gain is coded as zero weight gain in the New Jersey and New York City data. Prepregnancy weight is not reported in New Jersey. Numerical regression results are displayed in Table S2. Fig. 1 has additional notes.

year, with a sharp minimum for May conceptions. Birth weight, however, is hump-shaped over the year, with the highest average weight for summer conceptions.

Some recent studies have argued that the seasonality of birth and later outcomes might be entirely driven by selection. Our results suggest the opposite conclusion. The seasonal effects on birth outcomes are so strong that the bias because of selection is relatively small. In other words, a high SES mother getting pregnant in an unfavorable month will, on average, experience similarly poor birth outcomes as the typical (lower SES) mother conceiving in this unfavorable month.

The seasonal pattern in birth outcomes that we find is similar to the results of other studies that examine seasonality at the level of the conception month (26). Findings from studies that analyze seasonality at the level of birth months, however, provide a broader range of results (reviews of the literature are in refs. 1, 6, and 7). One reason for these heterogeneous findings might be the fact that few papers adjust for the confounding role of fluctuations in the number of conceptions. It has long been known that human conception rates fluctuate considerably over the year and that these fluctuations are different across countries and times (9, 27, 28). To take an extreme example, if all conceptions occurred in mid-January, then all premature births would occur in September. We analyze this issue using data on all births in the United States over the past two decades and find that 21.8% of the seasonality in gestation length at the birth month level is mechanically caused by fluctuations in the conception rate over the year (Fig. S5). Our analysis suggests that an examination of seasonality at the birth month level that does not correct for seasonality in conceptions is likely to be severely biased, even if selection on SES is not a problem. Hence, this analysis provides a justification for focusing on month of conception rather than month of birth.

Many other mechanisms have been proposed for explaining seasonality in birth and later outcomes (4). Possibilities include seasonal variation in viral infections (29), seasonal allergies (30), pollution levels (31), eating patterns (24, 32, 33), temperature (6, 27, 34), and early fetal loss (9). One limitation of this research is that we cannot investigate all of the potential mechanisms that might generate seasonal effects. For example, given that our data are regional, it is not ideally suited for looking at the effects of variations in temperature or climate change, although these effects might be important.[†]

Given the data available on birth records, we can examine some maternal health behaviors that are known to affect birth outcomes, such as smoking (35, 36) or use of medical care. We showed above that there was little evidence of a seasonal pattern in smoking within mothers or marital status, two factors that could correlate with whether a conception was planned. We have also investigated seasonality in use of medical care. We find that mothers with conceptions in October or November are the least likely to initiate prenatal care in the first trimester, a pattern that does not match well with the seasonality in birth outcomes (Fig. S6*A*). There is also a study that has found a spike in Cesarean sections in December (37); this spike might matter for the seasonality in gestation length and birth weight, but we find little evidence of a seasonal effect within mothers (Fig. S6*B*). Similarly, although there is a lengthy literature examining the sex ratio at birth as an outcome (38), we do not find that sex ratio is related to season of birth (Fig. S6*C*). Finally, some studies have highlighted the fact that season of birth could have effects after birth through, for example, social phenomena that intervene after birth, such as schooling laws (8). This later point suggests that it is useful to start with an analysis of season-of-birth effects on health at birth.

[†]There is still much uncertainty concerning the association between temperature and birth outcomes. The work by Strand et al. (6) has a review.

Seasonal influenza has received little prior attention in the literature on seasonality of birth outcomes, despite the strong effects of influenza infections on health at birth found in previous studies (15–17, 39, 40). We find a strong and negative correlation of influenza with gestation length. The estimated correlation coefficient of −0.71 is even more notable given the discontinuous monthly pattern in both variables, which makes a spurious relationship unlikely. To our knowledge, this finding provides the strongest evidence to date that seasonal influenza might be a driver of the seasonality in gestation length.

An important caveat is that, in emphasizing the effect of influenza in apparently triggering preterm birth, we do not mean to dismiss the possibility that exposure earlier in the pregnancy could also have harmful effects on the developing fetus that are not reflected in shorter gestations or lower birth weights. For example, the works by Almond (39) and Kelly (40) suggest that surviving infants who were exposed to influenza during the first trimester of pregnancy may suffer lasting cognitive deficits.

Influenza-induced reductions in gestation seem to cause the relatively low levels of birth weight that we documented for conceptions during the first one-half of the year (Fig. 4 *A* and *B*). However, seasonal influenza fluctuations do not explain the high average birth weight of summer conceptions. We find strong seasonal effects on weight gain during pregnancy, with small effects on prepregnancy weight. Women gain almost 1 lb more when they conceive in June, July, or August than when they conceive in January, suggesting that gains in birth weight are driven, in part, by higher maternal weight gain during pregnancy.

In conclusion, by focusing on births to the same mother, our work provides evidence that there are seasonal patterns in birth weight and gestation that are not entirely driven by the fact that women with different characteristics tend to give birth at different times. We are also able to investigate several possible mechanisms for these seasonal effects. We find a strong relationship between influenza prevalence in the month of birth and prematurity: infants conceived in May are likely to be due in mid-February, which is the height of the flu season. Because influenza is known to cause premature labor, these infants are at higher risk of short gestation. Because they are of short gestation, they also tend to be lower birth weight. In addition, there seems to be another mechanism driving seasonal patterns in birth weight, which is that mothers who conceive during the summer months have higher pregnancy weight gain and hence, give birth to heavier infants.

Our results may have some implications for public policy, because they suggest that seasonal variations in nutrition matter for birth outcomes, even in rich countries, and that flu shots might be effective in fighting the seasonal deterioration in length of gestation. However, whether specific interventions are effective is a subject for future research.

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Materials and Methods

Birth Data. The regional birth data come from individual birth records and provide detailed information on birth outcomes, mother characteristics, and a code that allows us to match births to the same mother. The birth date is reported by month of birth, whereas gestation is coded in weeks. We calculate the month of conception, our key variable, by subtracting the rounded number of gestation months (gestation in weeks × 7/30.5) from the month of birth.

In addition to the sample restrictions described in the text, we exclude births that were conceived more than 6 mo before the beginning of the sample and less than 10 mo before the end of the sample, because for these conception months, only particularly long and short gestation lengths are observed, respectively [the work by Strand et al. (41) discusses this issue]. Controls are also included for missing values of explanatory variables.

Fig. S7 plots the number of conceptions over months by education group. Fig. S7 illustrates the two confounders involved in the relationship between season of birth and birth outcomes. Conception rates fluctuate strongly over the year, which leads to seasonality in gestation lengths, even in the absence of a causal effect of season of birth. Additionally, the composition of mothers conceiving over the year changes, such that seasonal differences in birth outcomes are confounded by differences in mothers' SES.

Influenza Data. The influenza data used in this study are collected by the Center for Disease Control's US Outpatient Influenza-Like Illness Surveillance Network. Each week, ∼1,800 outpatient healthcare providers around the country report data to the Center for Disease Control on the total number of patients seen and the number of those patients with influenza-like illness (ILI). We restrict the data to US Department of Health and Human Services regions 2 and 3, which include New Jersey, New York City, and Pennsylvania. The standard influenza measure derived from these data is the fraction of patients in reporting healthcare centers diagnosed with ILI. ILI is defined as fever [temperature of 100 °F (37.8 °C) or greater] and a cough and/or a sore throat without a known cause other than influenza. A plot of average ILI fractions by calendar week is shown in Fig. S3.

Analyses. The analyses are estimated using three types of linear regression models:

$$Y_i = \alpha + \Sigma\mu_c + \beta T_r + \varepsilon_i \text{ (OLS)}, \quad \textbf{[1]}$$

$$Y_i = \alpha + \Sigma\mu_c + \beta T_r + \delta X_{i,t} + \varepsilon_i \text{ (OLS + controls), and} \quad \textbf{[2]}$$

$$Y_i = \alpha + \Sigma\mu_c + \beta T_r + \delta X_{i,t} + \Sigma\nu_m + \varepsilon_i \text{ (within mother)}, \quad \textbf{[3]}$$

where i indexes the newborn, c is the month of conception, m is the mother, Y_i is a characteristic of the newborn's mother or a birth outcome, μ_c is a vector of zero/one indicators for each month of conception, T_r is a region-specific time trend at the monthly level, X_i is a vector of control variables, ν_m is an indicator variable for each mother, and ε_i is a residual. Control variables include (unless the variable listed is identical to the dependent variable) indicators for mother's age (<20, 20–24, 25–29, 30–34, and 35+ y), education (<12, 12, 13–15, and 16+ y), race, Hispanic ethnicity, and marital status as well as the newborn's parity and sex.

We estimate all three equations using both maternal characteristics and birth outcomes as dependent variables. The three maternal characteristics regressions test whether mothers select into conception months (Eq. **1**) and the extent to which additional controls (Eq. **2**) and mother indicators (Eq. **3**) control for this selection. The birth outcome regressions estimate the conception month effects given these different sets of controls.

The inclusion of mother indicators in Eq. **3** (so-called mother fixed effects) is equivalent to differencing all equation variables within different births of the same mother (42). This procedure controls for any characteristics of the mother that are constant over time. Notice that, given the inclusion of the mother indicators, the time trend T_r controls for the interval between conceptions (i.e., the maternal aging between pregnancies). [The inclusion of this control for maternal aging is necessary, because in the multiple birth sample, mothers are systematically younger at the beginning of the sample than at the end. Additionally, because one has to start the sample with some months (e.g., January, February, and March) and end it with some other months (e.g., November, December, and January), there will be a mechanical relationship between month of birth, maternal age, and other characteristics that are correlated with maternal age.]

1. Lee SJ, Steer PJ, Filippi V (2006) Seasonal patterns and preterm birth: A systematic review of the literature and an analysis in a London-based cohort. *BJOG* 113(11): 1280–1288.
2. Doblhammer G, Vaupel JW (2001) Lifespan depends on month of birth. *Proc Natl Acad Sci USA* 98(5):2934–2939.
3. Weber GW, Prossinger H, Seidler H (1998) Height depends on month of birth. *Nature* 391(6669):754–755.
4. Torrey EF, Miller J, Rawlings R, Yolken RH (1997) Seasonality of births in schizophrenia and bipolar disorder: A review of the literature. *Schizophr Res* 28(1):1–38.
5. Pintner R, Forlano C (1943) Season of birth and mental differences. *Psychol Bull* 40(1): 25.
6. Strand LB, Barnett AG, Tong S (2011) The influence of season and ambient temperature on birth outcomes: A review of the epidemiological literature. *Environ Res* 111(3):451–462.
7. Chodick G, Flash S, Deoitch Y, Shalev V (2009) Seasonality in birth weight: Review of global patterns and potential causes. *Hum Biol* 81(4):463–477.
8. Buckles K, Hungerman D (2012) Season of birth and later outcomes: Old questions, new answers. *Rev Econ Stat*, 10.1162/REST_a_00314.
9. Lam DA, Miron JA, Riley A (1994) Modeling seasonality in fecundability, conceptions, and births. *Demography* 31(2):321–346.
10. Darrow LA, et al. (2009) Seasonality of birth and implications for temporal studies of preterm birth. *Epidemiology* 20(5):699–706.
11. Goodenough FL (1941) Month of birth as related to socioeconomic status of parents. *J Genet Psychol* 59(1):65–76.
12. Faber H (1920) A study of growth of infants in San Francisco with a new form weight chart. *Arch Pediatr* 37(1):244–254.
13. Blonsky PP (1929) Frueh und Spaetjahrkinder. *Jb f Kinderheilk* 124(1):115–120.
14. Gavrilov LA, Gavrilova NS (2011) Season of birth and exceptional longevity: Comparative study of American centenarians, their siblings, and spouses. *J Aging Res* 2011:104616.
15. Harris J (1919) Influenza occurring in pregnant women. *JAMA* 72(4):978–980.
16. Rasmussen SA, Jamieson DJ, Bresee JS (2008) Pandemic influenza and pregnant women. *Emerg Infect Dis* 14(1):95–100.
17. Steinhoff MC, et al. (2012) Neonatal outcomes after influenza immunization during pregnancy: A randomized controlled trial. *CMAJ* 184(6):645–653.
18. Hardy JM, Azarowicz EN, Mannini A, Medearis DN, Jr., Cooke RE (1961) The effect of Asian influenza on the outcome of pregnancy, Baltimore, 1957-1958. *Am J Public Health Nations Health* 51:1182–1188.
19. Goldenberg RL, Culhane JF, Iams JD, Romero R (2008) Epidemiology and causes of preterm birth. *Lancet* 371(9606):75–84.
20. Uchide N, Ohyama K, Bessho T, Toyoda H (2005) Induction of pro-inflammatory cytokine gene expression and apoptosis in human chorion cells of fetal membranes by influenza virus infection: Possible implications for maintenance and interruption of pregnancy during infection. *Med Sci Monit* 11(1):RA7–RA16.
21. Omer SB, et al. (2011) Maternal influenza immunization and reduced likelihood of prematurity and small for gestational age births: A retrospective cohort study. *PLoS Med* 8(5):e1000441.
22. Richards JL, et al. (2013) Neonatal outcomes after antenatal influenza immunization during the 2009 H1N1 influenza pandemic: Impact on preterm birth, birth weight, and small for gestational age birth. *Clin Infect Dis* 56(9):1216–1222.
23. Institute of Medicine (1990) *Nutrition During Pregnancy* (National Academy Press, Washington, DC).
24. Ceesay SM, et al. (1997) Effects on birth weight and perinatal mortality of maternal dietary supplements in rural Gambia: 5 year randomised controlled trial. *BMJ* 315(7111):786–790.
25. Currie J (2009) Healthy, wealthy, and wise? Socioeconomic status, poor health in childhood, and human capital development. *Journal of Economic Literature* 47(1): 87–122.
26. Bodnar LM, Simhan HN (2008) The prevalence of preterm birth and season of conception. *Paediatr Perinat Epidemiol* 22(6):538–545.
27. Lam DA, Miron JA (1996) The effects of temperature on human fertility. *Demography* 33(3):291–305.
28. Seiver DA (1985) Trend and variation in the seasonality of U.S. fertility, 1947-1976. *Demography* 22(1):89–100.
29. Payne CM, Ray CG, Borduin V, Minnich LL, Lebowitz MD (1986) An eight-year study of the viral agents of acute gastroenteritis in humans: Ultrastructural observations and seasonal distribution with a major emphasis on coronavirus-like particles. *Diagn Microbiol Infect Dis* 5(1):39–54.
30. Wjst M, et al. (2005) Latitude, birth date, and allergy. *PLoS Med* 2(10):e294.
31. Currie J, Neidell M, Schmieder JF (2009) Air pollution and infant health: Lessons from New Jersey. *J Health Econ* 28(3):688–703.
32. Olsen J, Frische G, Poulsen AO, Kirchheiner H (1989) Changing smoking, drinking, and eating behaviour among pregnant women in Denmark. Evaluation of a health campaign in a local region. *Scand J Soc Med* 17(4):277–280.
33. Siega-Riz AM, Savitz DA, Zeisel SH, Thorp JM, Herring A (2004) Second trimester folate status and preterm birth. *Am J Obstet Gynecol* 191(6):1851–1857.
34. Basu R, Malig B, Ostro B (2010) High ambient temperature and the risk of preterm delivery. *Am J Epidemiol* 172(10):1108–1117.
35. Kyrklund-Blomberg NB, Cnattingius S (1998) Preterm birth and maternal smoking: Risks related to gestational age and onset of delivery. *Am J Obstet Gynecol* 179(4): 1051–1055.
36. Andres RL, Day MC (2000) Perinatal complications associated with maternal tobacco use. *Semin Neonatol* 5(3):231–241.
37. Dickert-Conlin S, Chandra A (1999) Taxes and the timing of births. *Journal of Political Economy* 107(1):161–177.
38. Trivers RL, Willard DE (1973) Natural selection of parental ability to vary the sex ratio of offspring. *Science* 179(4068):90–92.
39. Almond D (2006) Is the 1918 influenza pandemic over? Long-term effects of in utero influenza exposure in the post-1940 U.S. population. *Journal of Political Economy* 114 (4):672–712.
40. Kelly E (2011) The scourge of Asian Flu: In utero exposure to pandemic influenza and the development of a cohort of British children. *Journal of Human Resources* 46(4): 669–694.
41. Strand LB, Barnett AG, Tong S (2011) Methodological challenges when estimating the effects of season and seasonal exposures on birth outcomes. *BMC Med Res Methodol* 11(1):49.
42. Wooldridge JM (2002) *Econometric Analysis of Cross Section and Panel Data* (MIT Press, Cambridge, MA).

Supporting Information

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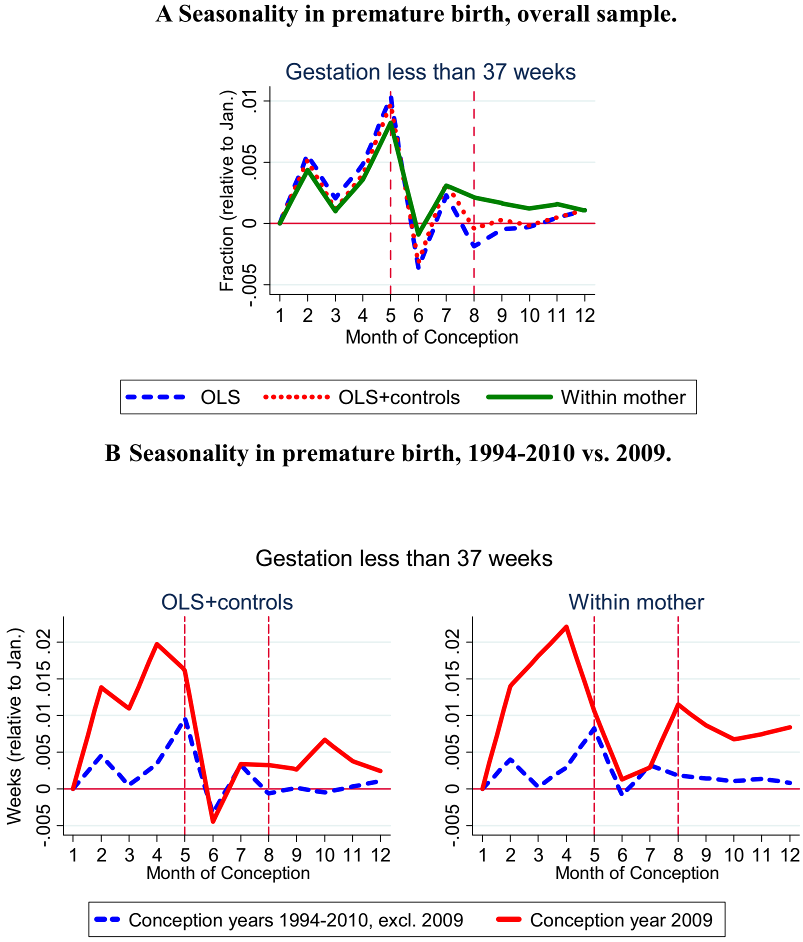

Fig. S1. (*A*) Seasonality in premature birth. The coefficients from regressions of a zero/one indicator variable for premature birth (less than 37 wk of gestation length) on month of conception indicator variables and additional controls are displayed. Fig. 1 has additional notes. The average rate of premature births in the data is 0.0763. (*B*) Seasonality in premature birth, 1994–2010 vs. 2009. The coefficients from regressions of a zero/one indicator variable for premature birth (less than 37 wk of gestation length) on month of conception indicator variables are displayed. The solid line shows the coefficients for the conception year 2009, and the dashed line is the estimated effect for the years 1994–2010 net of the 2009 effect. January serves as the reference month. The “OLS+controls” regression in *B* controls for a quadratic time trend, maternal race, education, age, marital status, and newborn’s parity and sex, and the “within mother” regression adds mother indicators. OLS, ordinary least squares.

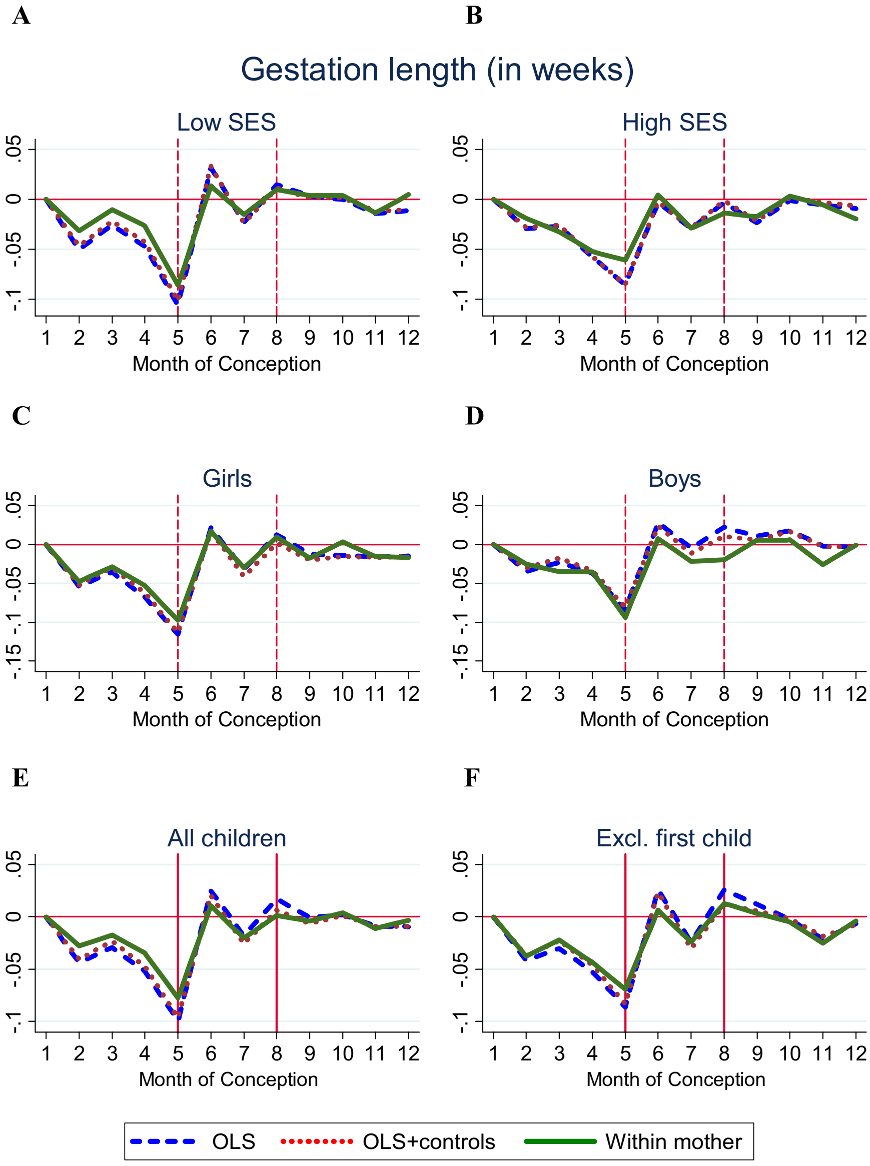

Fig. S2. Gestation length regressions including socioeconomic status (SES) and child sex and excluding first births. The dependent variable is gestation length in weeks. (*A* and *B*) A woman is high SES if she is white, has a college education, is married, and did not give birth below the age of 18 y, and a woman is low SES otherwise. (*C* and *D*) Girls/boys refers to the sex of the newborn. *E* displays the benchmark results. *F* excludes first births. Fig. 1 has additional notes.

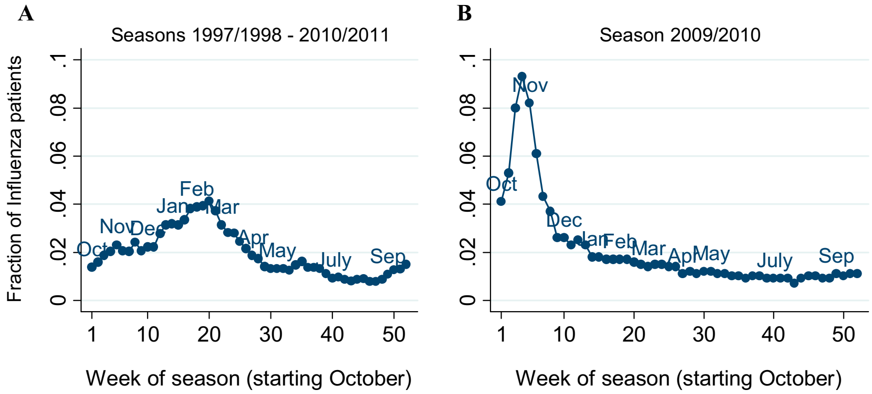

Fig. S3. Fraction of influenza patients by week of influenza season. The average fraction of patients with influenza-like illnesses is plotted over season weeks for the seasons 1997/1998-2010/2010 (*A*) and for the season 2009/2010 (*B*). The labels indicate the month and are placed at the first week that starts in each month (June and August omitted). The data come from the Center for Disease Control's US Outpatient Influenza-Like Illness Surveillance Network and cover the years 1997–2011. We restrict the data to US Department of Health and Human Services' regions 2 and 3, which include New Jersey, New York City, and Pennsylvania.

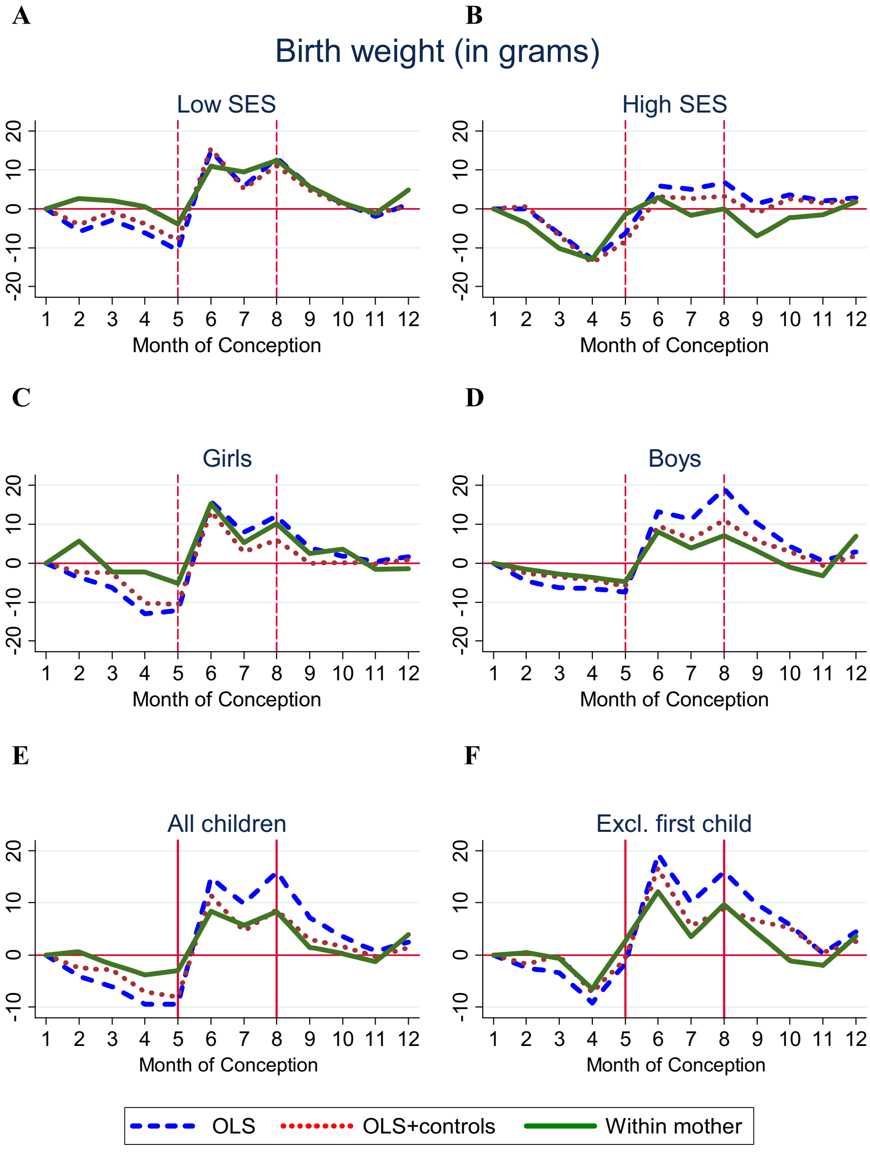

Fig. S4. Birth weight regressions including SES and child sex and excluding first births. The dependent variable is birth weight in grams. (*A* and *B*) A woman is high SES if she is white, has a college education, is married, and did not give birth below the age of 18 y, and a woman is low SES otherwise. (*C* and *D*) Girls/boys refers to the sex of the newborn. *E* displays the benchmark results. *F* excludes first births. Fig. 1 has additional notes.

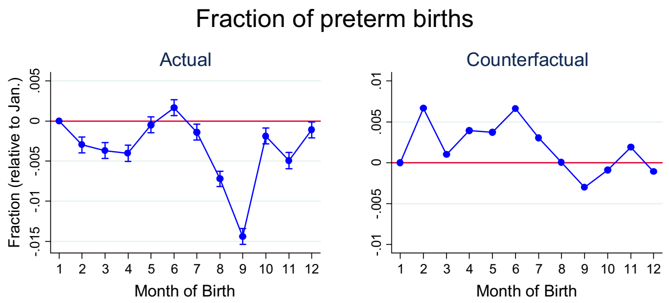

Fig. S5. Actual and counterfactual fractions of preterm births by months of birth. *Left* plots the coefficients of month zero/one indicator variables from an OLS regression of the observed fraction of preterm births (less than 37 wk of gestation) on month of birth zero/one indicator variables and year fixed effects; 95% confidence intervals are indicated. January is the reference group. *Right* plots the same regression coefficients as *Left* using a counterfactual dataset, in which prematurity rates are constant across conception months and only conception rates vary over time. This counterfactual dataset is constructed in the following way. First, we calculate the number of conceptions and the distribution of gestation lengths for each conception month in the sample. Then, we calculate the average distribution of gestation lengths for the overall sample and assign this average distribution to each month of conception. Hence, we eliminate any difference in gestation rates across conception months. Next, we multiply these (counterfactual) average gestation rates with the actual number of conceptions in each month to calculate how many babies would be born 7, 8, 9, and 10 mo after the respective month of conception. Finally, we sum up the number of babies with different gestation lengths who would be born in each month and calculate the counterfactual fraction of preterm births.

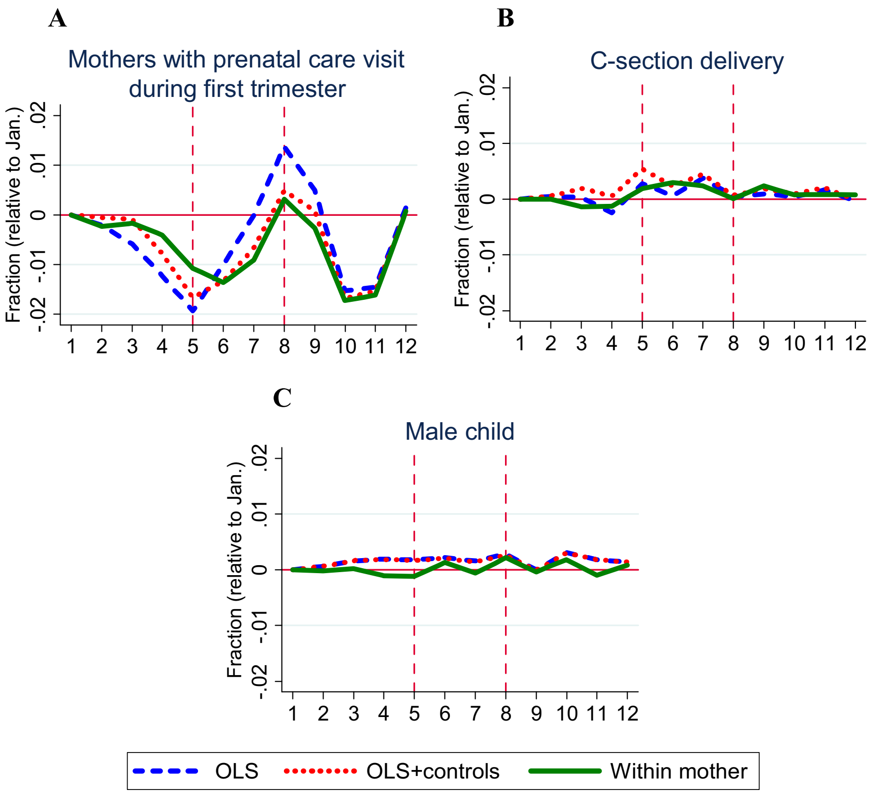

Fig. S6. Prenatal care, Cesarean sections (C-sections), and child sex by month of conception. The dependent variables are (*A*) the fraction of mothers with a prenatal care visit during the first trimester of pregnancy, (*B*) the fraction of newborns delivered by C-sections, and (*C*) the fraction of male children. None of the within-mother estimates in *C* are significantly different from zero. Fig. 1 has additional notes.

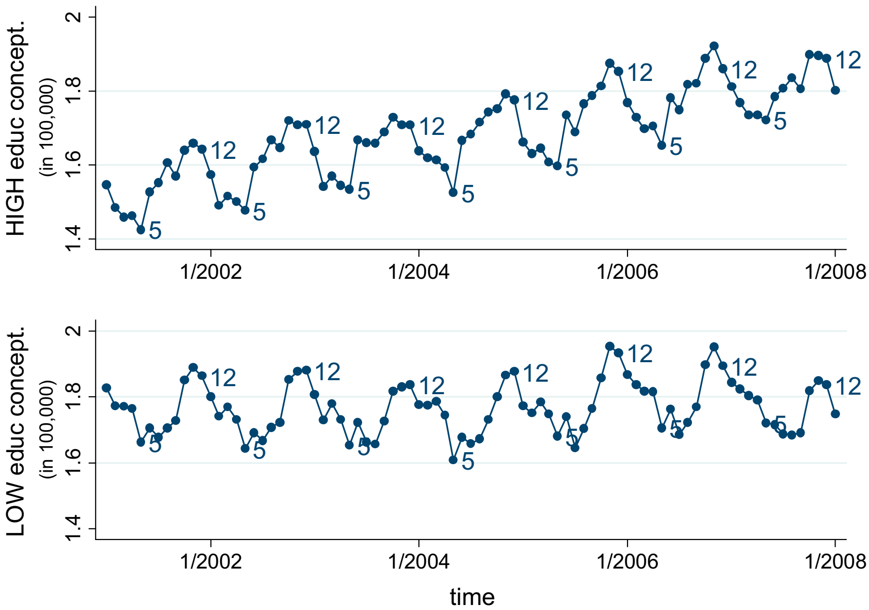

Fig. S7. Conceptions over time by maternal education (United States 2001–2008). The numbers of all conceptions that resulted in births in the United States between 2001 and 2008 are plotted by month of conception and maternal education. High education refers to mothers with more than 12 y of education. Low education refers to mothers with less than or equal to 12 y of education. The sample is the overall population of births in the United States, excluding twin births and births that do not report gestation length. Pre-2001 years are omitted to improve the visibility of seasonal patterns.

Table S1. Regressions of mother characteristics on month of conception indicators

	OLS		OLS + controls		Within mother	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Dependent variable: white (×100)						
January	Reference group		Reference group		Reference group	
February	−0.259	0.191	−0.057	0.171	−0.042	0.059
March	−0.901	0.193	−0.357	0.173	−0.009	0.060
April	−0.754	0.193	−0.523	0.173	−0.101	0.060
May	−0.588	0.196	−0.515	0.175	−0.067	0.061
June	0.829	0.187	0.235	0.167	−0.018	0.058
July	1.436	0.188	0.552	0.168	−0.069	0.059
August	2.024	0.186	0.878	0.166	−0.065	0.058
September	1.207	0.186	0.623	0.167	−0.044	0.058
October	0.406	0.184	0.233	0.165	−0.076	0.057
November	0.378	0.185	0.259	0.165	−0.004	0.058
December	0.302	0.185	0.235	0.166	−0.063	0.058
Dependent variable: >12 y education (×100)						
January	Reference group		Reference group		Reference group	
February	−0.140	0.202	0.079	0.172	0.034	0.125
March	−0.814	0.204	0.018	0.174	0.205	0.126
April	−0.704	0.204	0.121	0.174	−0.020	0.126
May	−0.119	0.207	0.488	0.176	0.232	0.128
June	1.317	0.197	1.019	0.169	0.085	0.122
July	1.945	0.199	1.134	0.169	−0.050	0.123
August	2.410	0.196	1.316	0.168	0.030	0.122
September	1.247	0.197	0.790	0.168	0.110	0.122
October	0.615	0.195	0.542	0.166	0.158	0.120
November	0.505	0.195	0.389	0.167	0.113	0.121
December	0.424	0.196	0.332	0.167	−0.016	0.121
Dependent variable: married (×100)						
January	Reference group		Reference group		Reference group	
February	-0.608	0.204	-0.237	0.161	-0.178	0.130
March	-1.566	0.206	-0.420	0.163	-0.104	0.132
April	-1.658	0.204	-0.364	0.161	-0.114	0.130
May	-1.425	0.207	-0.506	0.163	-0.121	0.132
June	0.177	0.198	-0.131	0.157	0.070	0.127
July	0.851	0.199	-0.078	0.157	0.184	0.127
August	1.436	0.197	0.034	0.156	0.051	0.126
September	0.606	0.198	-0.023	0.156	0.086	0.126
October	-0.278	0.196	-0.426	0.155	-0.001	0.125
November	-0.092	0.196	-0.202	0.155	0.145	0.125
December	-0.004	0.197	-0.111	0.155	-0.025	0.126
Dependent variable: smoking (×100)						
January	Reference group		Reference group		Reference group	
February	0.212	0.122	0.137	0.116	-0.109	0.102
March	0.438	0.123	0.187	0.117	-0.043	0.104
April	0.267	0.123	-0.052	0.117	-0.020	0.104
May	0.232	0.125	0.005	0.119	-0.069	0.105
June	-0.152	0.119	-0.127	0.114	-0.143	0.100
July	-0.364	0.120	-0.221	0.114	-0.156	0.101
August	-0.229	0.119	-0.012	0.113	-0.041	0.100
September	-0.193	0.119	-0.139	0.113	-0.128	0.100
October	0.127	0.118	0.087	0.112	-0.104	0.099
November	0.156	0.118	0.127	0.112	-0.067	0.099
December	0.127	0.118	0.095	0.113	0.014	0.099
Controls	—		✓		✓	
Mother indicators	—		—		✓	

The coefficients from regressions of zero/one variables indicating white mothers, mothers with more than 12 y of schooling, married mothers, and mothers smoking during pregnancy on month of conception zero/one indicator variables are displayed January serves as the reference month. OLS regressions control only for state-specific time trends. OLS + controls regressions further control—except if coinciding with the dependent variable—for maternal race, education, age, marital status, and newborn's parity and sex. Within-mother regressions further add mother indicators. Baseline sample: n = 1,435,213. Coefficients and SE are multiplied by 100 for better visualization.

Table S2. Regressions of birth outcomes on month of conception indicators

	OLS		OLS + controls		Within mother	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Dependent variable: gestation (×100)						
January	Reference group		Reference group		Reference group	
February	−4.402	0.830	−4.087	0.823	−2.769	0.952
March	−2.952	0.839	−2.327	0.832	−1.729	0.963
April	−5.218	0.838	−4.752	0.832	−3.482	0.963
May	−9.984	0.849	−9.669	0.842	−7.799	0.975
June	2.487	0.811	2.076	0.805	1.051	0.932
July	−1.781	0.815	−2.575	0.809	−2.013	0.938
August	1.722	0.807	0.642	0.800	0.148	0.929
September	−0.068	0.809	−0.650	0.803	−0.375	0.931
October	0.215	0.801	0.135	0.794	0.372	0.920
November	−0.883	0.802	−0.919	0.795	−1.091	0.921
December	−0.935	0.804	−0.894	0.798	−0.342	0.923
Dependent variable: birth weight						
January	Reference group		Reference group		Reference group	
February	−4.131	2.327	−2.496	2.262	0.637	2.312
March	−6.182	2.353	−2.943	2.288	−1.842	2.340
April	−9.460	2.351	−7.105	2.287	−3.832	2.340
May	−9.538	2.381	−8.145	2.316	−3.076	2.370
June	14.755	2.274	11.452	2.212	8.343	2.265
July	9.811	2.287	4.633	2.224	5.720	2.278
August	15.944	2.262	8.612	2.200	8.272	2.256
September	7.154	2.270	2.979	2.207	1.457	2.262
October	3.519	2.246	1.610	2.184	0.251	2.236
November	0.685	2.248	−0.298	2.186	−1.256	2.238
December	2.501	2.256	1.426	2.194	3.925	2.243
Dependent variable: birth weight conditional on gestation length						
January	Reference group		Reference group		Reference group	
February	4.237	1.768	3.297	1.823	4.449	1.829
March	−0.214	1.788	−2.363	1.844	−0.232	1.851
April	−0.328	1.787	−1.751	1.843	−0.423	1.850
May	7.504	1.810	6.888	1.866	7.656	1.874
June	6.780	1.729	9.132	1.782	7.023	1.791
July	8.440	1.738	12.107	1.792	8.910	1.802
August	6.762	1.719	11.910	1.773	8.952	1.785
September	3.502	1.725	6.482	1.779	2.336	1.789
October	0.860	1.706	2.512	1.760	0.096	1.769
November	0.693	1.708	1.563	1.762	−0.411	1.771
December	2.441	1.714	3.513	1.768	3.783	1.775
Dependent variable: Pregnancy weight gain (lb)						
January	Reference group		Reference group		Reference group	
February	0.234	0.059	0.239	0.058	0.243	0.064
March	0.345	0.060	0.382	0.059	0.457	0.065
April	0.476	0.059	0.503	0.059	0.517	0.065
May	0.662	0.060	0.674	0.059	0.681	0.065
June	0.989	0.058	0.959	0.057	0.909	0.063
July	0.988	0.058	0.933	0.057	0.785	0.063
August	0.926	0.057	0.866	0.056	0.870	0.062
September	0.652	0.057	0.639	0.057	0.651	0.062
October	0.420	0.057	0.415	0.056	0.314	0.062
November	0.047	0.057	0.036	0.056	−0.067	0.062
December	−0.051	0.057	−0.044	0.056	−0.096	0.062
Dependent variable: Prepregnancy weight (lb)						
January	Reference group		Reference group		Reference group	
February	−0.392	0.189	−0.442	0.184	−0.172	0.102
March	0.238	0.190	0.169	0.185	−0.123	0.103
April	−0.372	0.190	−0.493	0.185	−0.412	0.103
May	−0.241	0.192	−0.321	0.187	−0.288	0.104
June	−0.330	0.184	−0.323	0.179	−0.329	0.100
July	−0.461	0.185	−0.319	0.180	−0.170	0.100
August	−0.731	0.183	−0.605	0.179	−0.316	0.099

Table S2. Cont.

	OLS		OLS + controls		Within mother	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
September	−0.475	0.184	−0.391	0.179	−0.333	0.099
October	−0.412	0.182	−0.428	0.177	−0.316	0.098
November	−0.122	0.182	−0.169	0.177	−0.075	0.098
December	−0.053	0.182	−0.193	0.177	−0.027	0.098
Controls	—		✓		✓	
Mother indicators	—		—		✓	

The coefficients from regressions of gestation length, birth weight, birth weight conditional on gestation length, pregnancy weight gain, and prepregnancy weight on conception month indicators are displayed. Birth weight conditional on gestation length includes indicators for each week of gestation length. January serves as the reference month. OLS regressions control only for state-specific time trends. OLS + controls regressions further control—except if coinciding with the dependent variable—for maternal race, education, age, marital status, and newborn's parity and sex. Within-mother regressions further add mother indicators. Baseline sample: n = 1,435,213.