INTERGENERATIONAL BENEFITS OF CHILDHOOD HEALTH INTERVENTION

Evidence from Measles Vaccination

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ABSTRACT
Previous literature suggested that promoting childhood health could have intergenerational benefits. While several studies have pointed to the life-cycle benefits of mass vaccinations and disease elimination, fewer studies have explored their long-run intergenerational aspects. This paper joins the ongoing literature by exploring the intergenerational health benefits of mothers' childhood exposure to the measles vaccination for their infants' birth outcomes. Our identification strategy takes advantage of cross-cohort exposure to the introduction of the measles vaccine in 1963 and cross-state variations in pre-vaccine measles rates. Using the universe of birth records in the US over the years 1970–2004, we show that mothers who were exposed to the measles vaccine reveal improved birth outcomes. For mothers in states with an average pre-vaccine measles rate, full exposure to the vaccine during childhood is associated with roughly 5.4 and 5.7 percent reduction in the incidence of low-birth-weight and preterm-birth newborns. A series of event study analyses suggest that these findings are not driven by preexisting trends in outcomes. Further analyses suggest that improvements in educational outcomes, increases in prenatal care utilization, reductions in smoking, and increases in several measures of socioeconomic status are potential mechanisms.

KEYWORDS: intergenerational effects, birth outcomes, infant health, vaccination, measles, childhood health, public health, prenatal health utilization
JEL CLASSIFICATION: D62, H51, H75, I18

I. Introduction

The 20th century witnessed remarkable advancements in the field of vaccination that have had a significant impact on public health. Vaccines became widely available for diseases such as smallpox, polio, measles, mumps, rubella, and others. Vaccines have played a crucial role in preventing illness, hospitalization, and death, as well as reducing health-care costs and the spread of infectious diseases. While these benefits of vaccination are more immediate and easy to detect, there are spillovers and externalities in vaccination. The externalities lie in

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the fact that vaccination is not just a personal decision but also has broader implications for the entire population's health, non-health outcomes, longer-run outcomes, and spillover influences across generations.

An important achievement of such mass vaccination campaigns—with documented short-run and long-run benefits—is the case of the measles vaccine introduction in the United States. Measles is a highly contagious disease that could directly deteriorate childhood health capital. It could also indirectly compromise children's immune systems and make them more susceptible to other pathogens through an immunosuppression process that induces "immune amnesia" in immune memory cells (Mina et al. 2015). Measles disables immune memory, making individuals more susceptible to other diseases for several years (Mina et al. 2015; Sato and Haraguchi 2021). Prior to the vaccine, roughly 90 percent of children would have contracted the disease by age 12 (McLean and Anderson 1988). In 1963, the US Food and Drug Administration approved the license of the measles vaccine. The introduction of the measles vaccine was coupled with the Vaccination Assistance Act (VAA) of 1962, which initiated federal interventions in promoting vaccination campaigns by providing funds and grants to state and local health departments. The measles vaccine and joint federal-local efforts resulted in a relatively high take-up rate and immunity among children. By 1967–70, the annual measles case rates dropped by about 80 percent relative to the pre-vaccine case rates (Conis 2019). Since cohorts who do not contract measles because of vaccination are also less likely to contract other pathogens, one would expect them to accumulate higher health and human capital development. The health and human capital improvements can then be translated into better life-cycle outcomes with potential intergenerational effects.

This paper directly examines the externality of measles vaccination for the health of the next generation. We investigate whether higher exposure to the measles vaccine during childhood impacts the next generation's birth outcomes. The exposure variation comes from the 1963 introduction of measles vaccination coupled with pre-vaccine measles rates and the fact that different cohorts had differential exposure to the vaccine. We show that infants of mothers with higher exposure to measles vaccination during their (mothers') childhood reveal modest but significant increases in birth weight and reductions in low birth weight. We provide event study results to argue against the concerns over preexisting trends in birth outcomes. Moreover, the results suggest larger impacts among low-educated mothers. Finally, we find suggestive evidence of improvements in educational outcomes, increases in prenatal care, earlier utilization of prenatal care, reductions in smoking, increases in income, and improvements in socioeconomic measures as mechanisms.

The existing literature evaluates the link between childhood conditions and long-run intergenerational outcomes in various contexts and aspects (Smith 2009; Almond, Currie, and Duque 2018). For instance, several studies show that childhood economic, health, and emotional circumstances affect later-life maternal birth outcomes and can be detected in the health of the next generation of infants (Giallo et al. 2020; East et al. 2023; Noghanibehambari 2022). These studies provide a theoretical basis for the potential long-term and intergenerational benefits of measles vaccination. However, although several studies have pointed to the long-term benefits of measles vaccination for an array of health, economic, and educational outcomes, no study has explored its intergenerational benefits (Driessen et al. 2015; Atwood 2022). Specifically, no study has examined its impacts on later-life maternal birth outcomes. This study aimed to fill this gap in the literature.

Therefore, the contribution of this study to the literature is twofold. First, this is the first study to assess the impacts of childhood vaccination on later-life (maternal) birth outcomes. This aspect of the study contributes to the ongoing research on long-term later-life benefits of childhood health and well-being conditions (Almond, Currie, and Duque 2018; Hayward and Gorman 2004). Second, this study also adds to the literature on the benefits of vaccination. Specifically, we add to the limited empirical studies examining the intergenerational externalities of childhood immunity to diseases. We provide evidence of its benefits for the next generation's birth outcomes. The intergenerational effects of childhood measles vaccination are an understudied field with important potential policy implications.

The rest of the paper is organized as follows. Section II reviews the literature. Section III introduces data sources and discusses the sample selection strategy. Section IV discusses the empirical method and identification strategy assumptions. Sections V and VI review the results and their importance, and concluding remarks are in Section VII.

II. Pathways from a Healthier Childhood to the Next Generation's Health at Birth

Childhood measles vaccination could affect birth outcomes of the next generation through several channels. In this section, we review the relevant literature.

Measles may cause immune amnesia and expose individuals to other diseases for several years.[1] Therefore, one pathway of the impact of measles vaccination is through reductions in disease burden during childhood. One strand of the literature explores the influence of childhood exposure and contraction of infectious diseases and general disease burden on later-life outcomes (Case and Paxson 2010; Case, Fertig, and Paxson 2005).[2] For instance, Bleakley (2007) showed that cohorts exposed to hookworm eradication during childhood reveal higher literacy, school attendance, and income. Case and Paxson (2009) documented that exposure to a disease environment in early life was associated with lower cognitive scores during old age. Peracchi and Arcaleni (2011) used data from Italy and showed that early life disease burden negatively affects young men's height and body mass index. Bloom, Canning, and Shenoy (2011) employed data from the Philippines and showed that early childhood vaccination did not affect later-life height but significantly impacted cognitive test scores.

Another pathway through which measles vaccination may affect maternal birth outcomes is through improvement in later-life health, education, and labor market outcomes

1 This is in contrast to other infectious diseases such as polio, for which the vaccination campaign started in the 1950s.

2 Other studies have documented an association between health and human capital during childhood (not neceesarily related to disease burden) and later-life outcomes, including education, earnings, employment, diseases, disability, self-reported well-being, hospitalization, and old-age health (Almond and Currie 2011; Almond, Currie, and Duque 2018; Smith 2009).

(Mrozek-Budzyn et al. 2013; Anekwe et al. 2015; Nandi et al. 2019). For instance, Driessen et al. (2015) exploited the rollout of measles vaccination across districts of Bangladesh and found that age-appropriate vaccination was associated with a higher probability of school attendance among boys. Nandi et al. (2019) showed that measles vaccination in early life was associated with higher body mass index for age, height for age, and Picture Vocabulary Test scores in ages 7–12. Atwood (2022) exploited the introduction of the measles vaccine in 1964 in the US to examine its later-life labor market impacts. She found that cohorts in states with higher exposure to pre-vaccine measles rates revealed higher earnings as adults and were more likely to be employed. Chuard et al. (2022) showed that cohorts who were exposed to measles vaccination in the US revealed improvements in education, measures of socioeconomic status, and reductions in disability. Summan, Nandi, and Bloom (2023) investigated the effects of the Universal Immunization Program of India, a government-run program aimed at providing free and mandatory vaccination to all children and pregnant women against preventable diseases. They found that cohorts with a higher exposure to the program during early life reveal higher wages and household consumption expenditure during adulthood. Nandi et al. (2020) showed that vaccination under the Universal Immunization Program in early life is associated with about 0.2 more years of schooling later in life.

Therefore, the literature suggested that disease/vaccine exposure in early life may influence anthropometric outcomes, cognitive ability, test scores, educational outcomes, and health status during adulthood. The vaccine-induced health improvements and these later-life impacts can potentially contribute to the next generation's health capital at birth (Currie and Moretti 2003; Gage et al. 2013; Lindo 2011; Mocan, Raschke, and Unel 2015). For instance, Noghanibehambari, Salari, and Tavassoli (2022) examined the effects of maternal education on birth outcomes and found that an additional year of maternal schooling was associated with 34 grams higher birth weight. Lindo (2011) showed that parental job loss is associated with significant reductions in birth weight. Mocan, Raschke, and Unel (2015) documented a relatively small but significant impact of maternal earnings on birth weight of their infants.

III. Data and Sample Selection

The primary data source is public-use natality birth record data extracted from the National Center for Health Statistics (NCHS 2020). The data cover the years 1970–2004. We restrict the sample to mothers born between 1930 and 1980. Since birth outcomes of teenage mothers and older mothers could be largely driven by age-related factors, we restrict the sample to mothers between the ages of 19 and 40 (Letamo and Majelantle 2001; Ben-David et al. 2016).[3] Moreover, we limit the sample to singleton births since birth outcomes of multiple births are also primarily driven by factors unrelated to maternal exposures (Vohr et al. 2009). We also exclude observations with missing values on birth weight and gestational age.

3 In Online Appendix L, we show the robustness of the results to relaxing this age restriction.

We use the 12-year-average cross-state measles rate for the years prior to the vaccine, that is, the period 1952–63, extracted from Atwood (2022).[4] We merge these data with birth record data based on the mother's state of birth.[5] To control for other mothers' state of birth–level time-varying features, we use average state-level characteristics using decennial census data extracted from Ruggles et al. (2020) and interpolate them for inter-decennial years.[6]

The final sample includes 73,932,418 observations from 49 US states.[7] The outcomes that we examine are described below. Birth weight is the infant's weight at birth and is measured in grams. Low birth weight is a binary outcome that equals 1 if the birth weight is less than 2,500 grams. Very low birth weight is a binary outcome that turns on if the birth weight is less than 1,500 grams. Fetal growth is gain in weight per week of gestation, that is, birth weight divided by gestational weeks. Full-term birth weight is the birth weight of infants at maturity, that is, those with a gestational age of between 37 and 42 weeks. Gestational-age-adjusted birth weight is the predicted value of regressing birth weight on gestational age.

Table 1 provides summary statistics of the final sample. The first panel reports infants' characteristics, and the second panel reports mothers' sociodemographic features. The average birth weight in the sample is 3,364 grams. On average, 6 percent of births are categorized as low birth weight. About 49 percent of infants are female. Roughly 30 percent of births in the sample occur among first-time mothers. The average 12-year measles rate from 1952 to 1963 is 924 cases per 100,000, with a standard deviation of 538. The top panel of Figure 1 shows the geographic distribution of the 12-year pre-vaccine measles rate by mother's state of birth. The bottom panel shows infants' birth weight distribution by their mother's state of birth.

IV. Empirical Method

Our econometric method is built on cross-cohort variation in the share of exposure to the vaccine's introduction and cross-state variation in pre-vaccine concentration of measles rate.[8] Specifically, we implement the following difference-in-differences regressions:

4 In Online Appendix G, we show the robustness of the results to using the past three-year, six-year, and nine-year averages of measles rates as the benchmark intensity variation.

5 Between 1970 and 1979, roughly three million records do not contain birth state. In Online Appendix E, we use mother's state of residence as a proxy for birth state for this missing information. We then replicate the main results and find effects that are almost identical to the main results of the paper.

6 In Online Appendix D, we explore the robustness of the results to including covariates from the nearest censuses rather than using the linear cross-census interpolation of control variables. We observe quite comparable results to the main findings of the paper.

7 The measles data for Kansas and Alaska are not available.

8 This combination of cohort-level exposure and cross-region of variation by pre-event case rate has been used in many studies with a similar setting (Atwood 2022; Bleakley 2007; Cutler et al. 2010; Finkelstein 2007; Lucas 2010).

TABLE 1. Summary statistics

Variable	Mean	Std. dev.	Min.	Max.
Child characteristics				
Birth weight (grams)	3,364.393	284.155	942.588	3,572.004
Low birth weight	0.055	0.229	0	1
Very low birth weight	0.009	0.095	0	1
Fetal growth	86.046	13.67	4.904	352.778
Gestational age	38.069	7.218	0	52
Preterm birth	0.115	0.32	0	1
Child female	0.488	0.5	0	1
Child first born	0.29	0.454	0	1
12-year pre-vaccine measles rate	924.896	538.158	91.343	2,936.104
Share childhood exposure	0.715	0.372	0	1
Share childhood exposure × de-meaned pre-vaccine measles rate	0.72	0.598	0	3.196
Maternal characteristics				
Birth year	1961.832	9.211	1931	1980
Year of giving birth	1989.101	8.937	1970	2004
Mother White	0.841	0.366	0	1
Mother Black	0.143	0.35	0	1
Mother's age	27.269	4.762	20	39
Mother's age 20–24	0.331	0.471	0	1
Mother's age 25–29	0.351	0.477	0	1
Mother's age 30–34	0.231	0.422	0	1
Mother's age 35–39	0.086	0.281	0	1
Mother's education < high school	0.1	0.3	0	1
Mother's education high school	0.462	0.499	0	1
Mother's education some college	0.219	0.413	0	1
Mother's education bachelor's degree and above	0.219	0.414	0	1
Any prenatal visits	0.917	0.276	0	1
Observations		73,932,418		

Note: The data are extracted from NCHS (2020) and cover births between 1970 and 2004. Low birth weight is a dummy indicating birth weight of less than 2,500 grams. Very low birth weight is a dummy indicating birth weight of less than 1,500 grams. Preterm birth is a dummy indicating gestational age of less than 37 weeks. Fetal growth is calculated by dividing birth weight by gestational age.

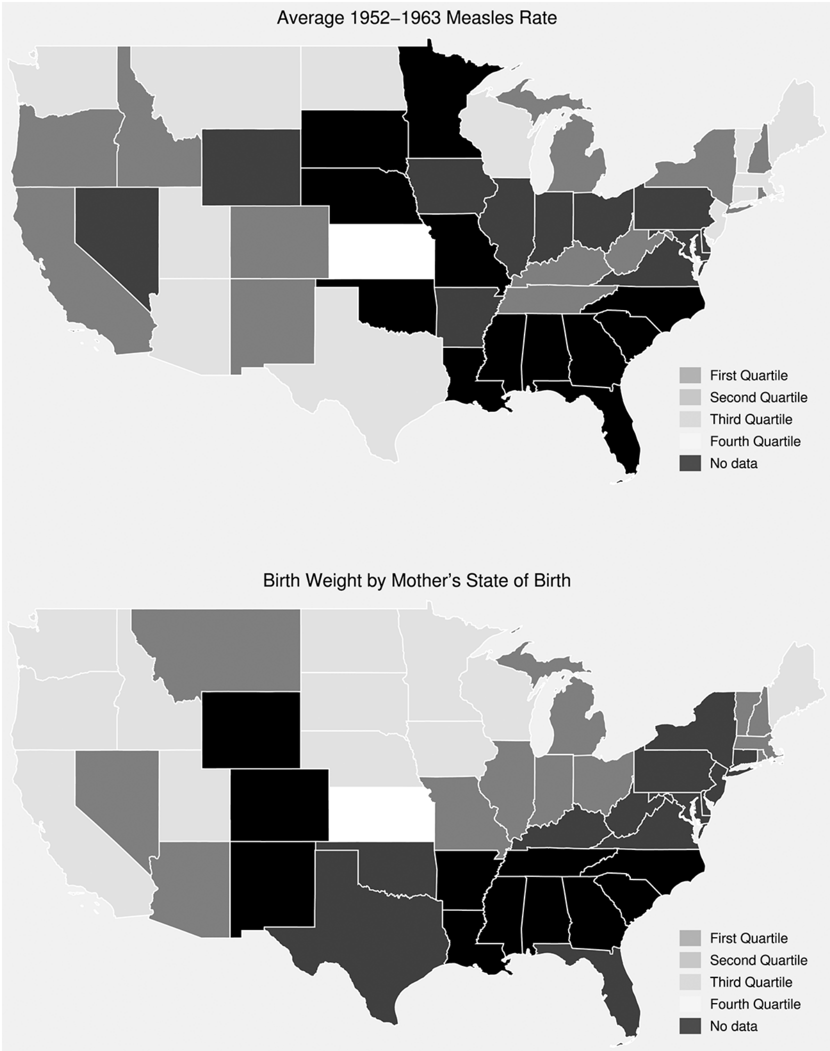

FIGURE 1. Geographic distribution of 12-year pre-vaccine measles rate and birth weight

$$y_{ibcst} = \alpha_0 + \alpha_1 ShareExp_c \times Measles_b^* + \alpha_2 X_i + \alpha_3 Z_{bc} + \theta_{st} + \xi_c + \zeta_b \times T_c + \varepsilon_{bcst} \quad (1),$$

where y is the birth outcome to mother i who was born in state b and year c, who is observed in state s and year t.[9] The variable *ShareExp* is the share of childhood up to

9 We refer to the current state, where the mother gives birth, as state of residence; we refer to the year of giving birth as simply the year. We should also note that state of birth and year of birth refer to the state and year in which the mother was born.

age 12 that the mother could have been exposed to the introduction of the vaccine.[10] It varies between 0 (unexposed cohorts) and 1 (fully exposed cohorts). The variable $Measles^{*}$ represents the state-of-birth-specific 12-year average measles rate prior to the vaccine.[11] To ease interpretation, we divide it by its mean across all states. Therefore, the parameter α_1 measures the effect of full exposure to vaccine introduction (versus no exposure) and a reduction in the state-specific measles rate from the average of pre-vaccine rates to zero on birth outcomes of the next generation. Note that the main effects of these variables are absorbed by fixed effects. In X, we include dummies for race, ethnicity, age, education, and prenatal visits. In Z, we include the mother's birth state by birth year covariates, including average socioeconomic index, female labor force participation rate, literacy rate, the share of married individuals, and the average number of children. State of birth and year of birth fixed effects are represented by ζ and ξ, respectively. We also include a birth-state-specific linear trend to account for the secular and linear evolution of time-varying characteristics of mothers' birth states. The parameter θ represents the current state of residence by current year fixed effects. The interaction of these two dimensions of fixed effects absorbs all time-varying unobserved characteristics of mothers' state of residence. Therefore, the model fully controls for all state-level policy changes or all state-specific economic and sociodemographic shocks that vary year by year. We cluster the standard errors at the mother's birth state level to account for serial correlation and at birth year level to account for spatial correlation in the error terms. In Online Appendix A, we show that the results are quite robust to alternative clustering levels.

V. Results

A. CONCERNS OVER PREEXISTING TRENDS: EVENT STUDY ANALYSIS

The 1950s–1970s are decades of rapid drug/vaccine innovations and improvements in public health. A concern in interpreting our results is that there are preexisting trends of public health promotion in states with higher/lower pre-measles-vaccine measles rates and that the effects are picking up on the unobserved trends. To address this concern, we implement an event study analysis in which the event is the introduction of the vaccine in 1963, and the event time is years relative to the year a mother turns 12.[12] We implement specifications similar to equation 1 and replace *ShareExp* with event dummies. Specifically, we implement the following regressions:

10 In Online Appendix F, we explore the effects across an alternative cutoff age as well as using a measure of age at exposure to flexibly account for differences in the intensity of the effects across various ages. We find much larger impacts among earlier childhood years, specifically ages 0–6.

11 One potentially useful alternative would be to use state-level per capita vaccine funding or the number of vaccine doses that were administered as the measure of intensity of treatment exposure. However, none of these measures are available.

12 Studies show that roughly 90 percent of children contract measles by age 12 (McLean and Anderson 1988).

$$y_{ibcst} = \alpha_0 + Measles_b^* \times \left\{ \sum_{i=\underline{T}}^{-2} \beta_i I(Year\ Turn\ 12 - 1963 = i) + \sum_{j=0}^{\bar{T}} \gamma_j I(Year\ Turn\ 12 - 1963 = j) \right\} + \alpha_2 X_i + \alpha_3 Z_{bc} + \theta_{st} + \xi_c + \zeta_b \times T_c + \varepsilon_{bcstt} \quad (2),$$

where $I(.)$ is an indicator function, and all other parameters are as in equation 1. The set of parameters β_i and γ_j are the event time coefficients of interest.

In Figure 2, we depict the event study results for birth weight and low birth weight in the top and bottom panels, respectively. The negative event time coefficients are virtually zero in magnitude and statistically insignificant. The effects start to rise (in magnitude) for cohorts who were partially exposed to the vaccine and become stable for fully exposed cohorts (i.e., those born post-vaccine). In Figure 3, we replicate the event study analysis for gestational age and preterm birth. We observe virtually similar patterns of effects. The negative event time coefficients (representing unexposed cohorts) do not reveal an economically and statistically significant association. This set of coefficients rules out the concerns over pre-trends for various measures of physical growth-related outcomes for infants. Positive event time coefficients start to rise in magnitude and become significant for partially exposed cohorts. For fully exposed cohorts, the effects become stable in magnitude and remain statistically significant.

Before moving on to the main results, we discuss another source of endogeneity. An issue that needs to be addressed when interpreting the main findings is the selection of mothers into the maternity ward, in other words, endogenous fertility. For example, it is possible that Black mothers exhibit higher fertility rates during adulthood and are more likely to enter the maternity ward (i.e., our sample) owing to improvements in health during their childhood because of vaccination. Since Black mothers generally experience poorer birth outcomes for unobservable reasons, the coefficients might underestimate the actual effects since the sample includes a higher proportion of Black mothers. To investigate this source of endogeneity, we conduct a regression analysis of several observable maternal characteristics on our exposure measures while controlling for fixed effects, trends, and birth state covariates. The results of this analysis can be found in Online Appendix K. The results do not point to a significant and consistent pattern of endogenous fertility effects.

B. MAIN RESULTS

The main results of the paper are reported in Table 2. The findings suggest significant improvements in birth outcomes for mothers with higher childhood exposure to the measles vaccine. For instance, among fully exposed mothers relative to unexposed mothers, a reduction in the measles rate from the average of pre-vaccine rates to zero (roughly equivalent to the reduction in measles after the vaccine was available) was associated with roughly 5.8 grams higher birth weight (column 1), 29 basis points lower probability of low birth weight (column 2), and 6.9 basis points lower likelihood of very low birth weight (column 3). In addition, the results suggest that the benefits are considerably larger for infants at the lower tail of the birth weight distribution, as the percentage changes from the

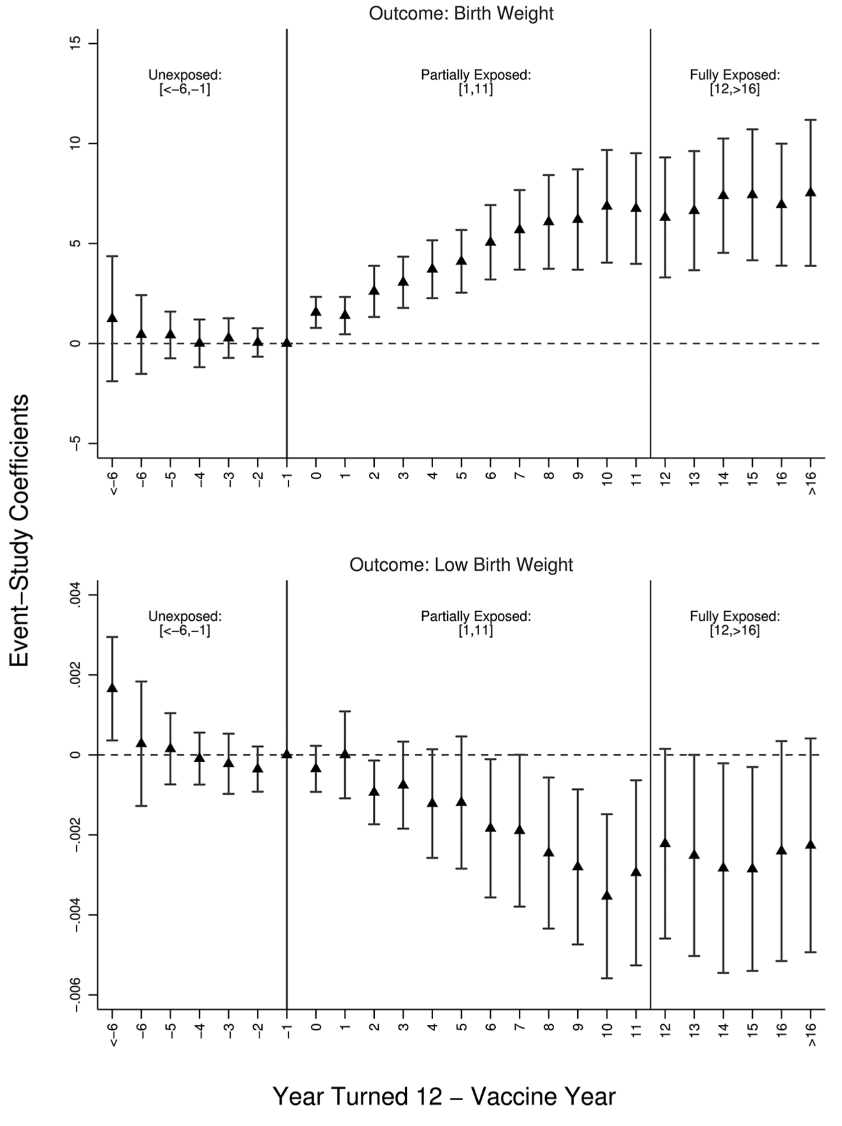

FIGURE 2. Event study results for birth weight and low birth weight

mean of the outcome (reported in the last row) imply. For instance, the implied percentage change for low birth weight and very low birth weight are 5 and 9 percent, respectively, versus 0.36 percent for mean birth weight. We further probe this heterogeneity by evaluating the effects across various birth weight thresholds. Specifically, we define a series of binary variables that indicate whether an infant's birth weight is above a specific threshold. We then use these indicators as the outcome in our fully parameterized regressions. We

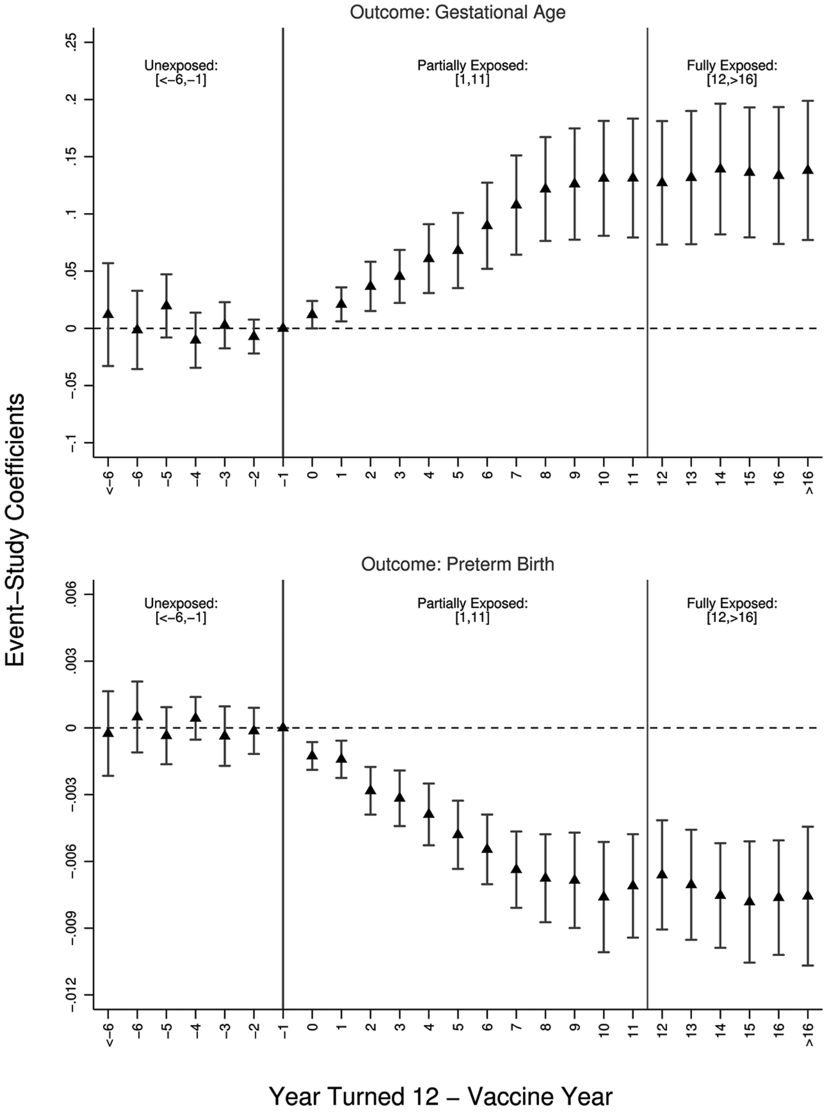

FIGURE 3. Event study results for gestational age and preterm birth

depict the results in the top panel of Figure 4. In this graph, the outcomes are on the vertical axis, and the horizontal axis refers to the coefficient of interest (α_1 in equation 1). Since the interpretation of effects requires a baseline value and these are the effects across various outcomes, we divide point estimates and confidence intervals by the mean of their respective outcomes and illustrate the results in the bottom panel of Figure 4. The implied effects (relative to the mean of the outcomes) suggest larger effects for lower thresholds of low

TABLE 2. Main results: The association between childhood exposure to measles vaccination and birth outcomes

	Outcomes					
	Birth weight (1)	Low birth weight (2)	Very low birth weight (3)	Fetal growth (4)	Gestational age (5)	Preterm birth (6)
Share childhood exposure × pre-vaccine measles rate	5.84403[a]	−0.00298[b]	−0.00069[b]	0.15271	0.13329[a]	−0.00655[a]
	(1.46155)	(0.00125)	(0.00029)	(0.12255)	(0.03185)	(0.00126)
Observations	73,932,418	73,932,418	73,932,418	71,672,945	73,932,418	73,932,418
R^2	0.03027	0.01667	0.00623	0.05512	0.84706	0.24521
Mean DV	3,364.393	0.055	0.009	86.046	38.069	0.115
Percentage change	0.174	−5.422	−7.661	0.177	0.350	−5.693

Note: Standard errors, two-way clustered at the mother's state of birth and year of birth, are in parentheses. All regressions include the mother's state of birth fixed effects, year of birth fixed effects, state of birth linear trend in year of birth, and state of residence by year fixed effects. The regressions also include controls for maternal age, maternal education, maternal race, maternal ethnicity, child's gender, birth parity, and prenatal visits. The regressions include birth-state-year controls extracted from decennial censuses and interpolated for inter-decennial years. These controls include average socioeconomic index, female labor force participation rate, literacy rate, share of married individuals, and the average number of children. *Birth weight* is the weight of infant at birth and measured in grams. *Low birth weight* is a binary outcome that turns on if birth weight is less than 2,500 grams. *Very low birth weight* is a binary outcome that turns on if birth weight is less than 1,500 grams. *Fetal growth* is gain in weight per each week of gestation, that is, birth weight divided by gestational weeks. *Gestational age is* the clinical estimation of the period between conception and birth. Preterm birth is a dummy that equals 1 if gestational age is less than 37 weeks. [a]$p < 0.01$, [b]$p < 0.05$.

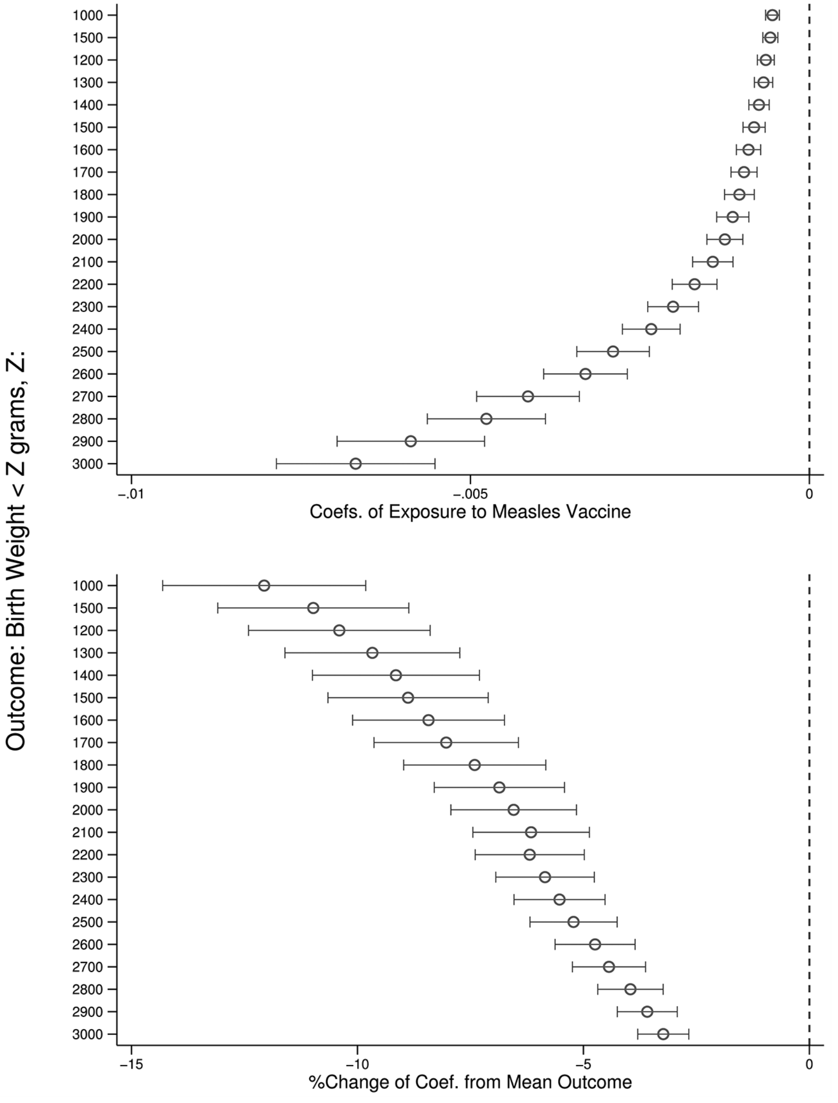

FIGURE 4. Effects across low birth weight thresholds

birth weight definition. There is a monotonous trend in the magnitude of implied percentage changes with respect to the thresholds; that is, at lower thresholds, we observe larger effects. This fact suggests that the effects are larger for infants at the lower tail of the birth weight distribution.

In column 4 of Table 2, we explore the effects on fetal growth, which measures infants' intrauterine weekly weight gain. The results suggest an increase in fetal growth of about 0.15 grams per week of gestation, although the coefficient is statistically insignificant. This effect is about a 0.17 percent rise from the mean of the outcome. Comparing the implied percentage change with that of birth weight in column 1 suggests that part of the increases in birth weight can be explained by variations in the gestational period. We also observe an increase of 0.13 weeks of gestation, roughly a 0.4 percent change from the mean (column 5). Similar to the outcomes related to birth weight, we observe larger effects on preterm birth, with a decrease of roughly 66 basis points, equivalent to a 5.7 percent reduction in the incidence of premature birth with respect to the mean of the outcome. This fact suggests that the impacts are primarily concentrated among infants at the lower tail of gestational age distribution.

C. ROBUSTNESS CHECKS

In this section, we explore the sensitivity of the main results to alternative specification checks. To control for cross-cohort convergence in birth outcomes across census regions, we include the mother's region of birth by birth year fixed effects in our fully parameterized regressions and replicate the results. The estimated effects are reported in panel A of Table 3. The effects reveal a slight drop in magnitude but remain significant in all cases. Moreover, the marginal effect of fetal growth is precisely estimated in this specification.

One concern in interpreting the main results is the endogeneity due to time-variant health improvements across states that could be correlated with our vaccine exposure measure. To address this potential omitted variable bias, we include in our regressions a series of (mothers') state–year of birth measures of infant mortality rate, all-age mortality rate, and general fertility rate. These variables are extracted from Bailey et al. (2016). The results, reported in panel B of Table 3, suggest similar effects compared with the main results.

Several studies suggest that health endowment during childhood generates a selective migration pattern (Halliday and Kimmitt 2008; Norman, Boyle, and Rees 2005). Moreover, the choice of residential location also influences health outcomes through many channels, such as local social programs, economic conditions, safety, access to health care, and air quality. To control for the potential confounding influence of migration, we interact state of birth by state of residence fixed effects. Therefore, the model compares the outcomes across mothers who were born and gave birth in the same set of birth state and residence state. The results are reported in panel C of Table 3. We observe effects that are very similar to the main results. To further explore this issue, we replicate the main results of Table 2 for mothers who give birth in their own birth state (i.e., non-movers) and mothers who give birth in a different state than their state of birth (i.e., movers). We report and discuss these results in Online Appendix C. The effects are very similar to the main results, suggesting little concern over the influence of endogenous migration.

As a next step to evaluate the robustness of the results, we implement alternative sample selections and replicate the regressions. Specifically, we drop partially exposed cohorts, that is, mothers born between 1952 and 1963, and focus on comparing fully exposed and unexposed mothers. The results are reported in panel D of Table 3. We observe slightly larger effects than the main results of Table 2. For instance, we observe a reduction in low birth weight by about 5.8 percent (versus 5.4 percent in Table 2). In Online Appendix I, we restrict the sample to narrower birth cohorts, mothers born between 1941 and 1970. The results become smaller than the main results because of limited variation in exposure but remain statistically and economically meaningful.

TABLE 3. Robustness checks: Alternative specifications

	Outcomes					
	Birth weight (1)	Low birth weight (2)	Very low birth weight (3)	Fetal growth (4)	Gestational age (5)	Preterm birth (6)
	A. Adding mother's region of birth by birth year fixed effects					
Share childhood exposure × pre-vaccine measles rate	4.87194[a]	−0.00244[a]	−0.00051[a]	0.12501[a]	0.13301[a]	−0.00581[a]
	(0.51723)	(0.00035)	(0.00012)	(0.02792)	(0.01226)	(0.00052)
Observations	73,932,418	73,932,418	73,932,418	71,672,945	73,932,418	73,932,418
R^2	0.03028	0.01668	0.00623	0.05515	0.84706	0.24521
Mean DV	3,364.393	0.055	0.009	86.046	38.069	0.115
Percentage change	0.145	−4.428	−5.684	0.145	0.349	−5.056
	B. Adding mortality rates in state–year of birth of mother					
Share childhood exposure × pre-vaccine measles rate	5.92649[a]	−0.00296[a]	−0.00067[a]	0.13712[a]	0.14146[a]	−0.00676[a]
	(0.56850)	(0.00040)	(0.00013)	(0.03254)	(0.01051)	(0.00054)
Observations	73,932,418	73,932,418	73,932,418	71,672,945	73,932,418	73,932,418
R^2	0.03043	0.01680	0.00627	0.05541	0.84734	0.24536
Mean DV	3,364.393	0.055	0.009	86.046	38.069	0.115
Percentage change	0.176	−5.377	−7.403	0.159	0.372	−5.883

	C. Adding mother's birth state by state of residence fixed effects					
Share childhood exposure × pre-vaccine measles rate	5.89036[a]	−0.00300[a]	−0.00068[a]	0.16236[a]	0.12978[a]	−0.00651[a]
	(0.56801)	(0.00040)	(0.00013)	(0.03233)	(0.01059)	(0.00053)
Observations	73,932,418	73,932,418	73,932,418	71,672,945	73,932,418	73,932,418
R^2	0.03055	0.01679	0.00629	0.05542	0.84717	0.24544
Mean DV	3,364.393	0.055	0.009	86.046	38.069	0.115
Percentage change	0.175	−5.461	−7.587	0.189	0.341	−5.662
	D. Excluding partially exposed cohorts					
Share childhood exposure × pre-vaccine measles rate	6.48372[a]	−0.00333[a]	−0.00095[a]	0.23701[a]	0.13895[a]	−0.00689[a]
	(0.67605)	(0.00048)	(0.00016)	(0.03910)	(0.01489)	(0.00063)
Observations	47,276,779	47,276,779	47,276,779	45,752,904	47,276,779	47,276,779
R^2	0.02852	0.01619	0.00639	0.05429	0.85316	0.24403
Mean DV	3,356.015	0.057	0.010	86.000	37.899	0.121
Percentage change	0.193	−5.850	−9.515	0.276	0.367	−5.690

Note: Standard errors, two-way clustered at the mother's state of birth and year of birth, are in parentheses. All regressions include the mother's state of birth fixed effects, year of birth fixed effects, state of birth linear trend in year of birth, and state of residence by year fixed effects. The regressions also include controls for maternal age, maternal education, maternal race, maternal ethnicity, child's gender, birth parity, and prenatal visits. The regressions include birth-state-year controls extracted from decennial censuses and interpolated for inter-decennial years. These controls include average socioeconomic index, female labor force participation rate, literacy rate, share of married individuals, and the average number of children. *Birth weight* is the weight of infant at birth and measured in grams. *Low birth weight* is a binary outcome that turns on if birth weight is less than 2,500 grams. *Very low birth weight* is a binary outcome that turns on if birth weight is less than 1,500 grams. *Fetal growth* is gain in weight per each week of gestation, that is, birth weight divided by gestational weeks. *Gestational age is* the clinical estimation of the period between conception and birth. Preterm birth is a dummy that equals 1 if gestational age is less than 37 weeks. [a]$p < 0.01$.

We further investigate the robustness of the results to alternative specifications in Online Appendix H. We allow time-invariant birth state features to vary across mothers of different sociodemographic groups by interacting birth state fixed effects with mothers' education, race, and age dummies. Moreover, we control for local policy, economic, and environmental influences in birth outcomes by including the county fixed effects interacted with year–month of birth fixed effects. In both models, the effects are almost identical to the main results.

D. HETEROGENEITY BY SOCIODEMOGRAPHIC CHARACTERISTICS

Several studies have documented the sociodemographic gap in birth outcomes and that the effects of maternal exposures on birth outcomes could be heterogenous based on maternal social class, human capital, and race (Noghanibehambari 2022; Florian, Ichou, and Panico 2021). Therefore, one would expect to observe the heterogeneous impacts of a healthier childhood on later-life health outcomes based on sociodemographic characteristics. For instance, low-educated mothers are more likely to reside in poorer neighborhoods and more polluted areas, less likely to have health insurance and health-care access, and less likely to be aware of the causes and consequences of diseases (Banzhaf, Ma, and Timmins 2019; Cutler and Lleras-Muney 2010). All these factors contribute to the prevalence and severity of measles disease and point to larger benefits of vaccination for this subpopulation.

We explore this potential source of heterogeneity by replicating the main results among subpopulations of low-educated mothers (education $\leq$ 12 years of schooling) and high-educated mothers (education > 12 years of schooling). The results are reported in panels A and B of Table 4, respectively. The marginal effects and implied percentage changes from the outcomes suggest larger impacts among low-educated mothers. For instance, the results suggest 7.6 grams of additional birth weight among low-educated mothers, roughly 30 percent larger than the marginal effect of birth weight in Table 2. This effect is also roughly twice the observed effect on birth weight among high-educated mothers. In Online Appendix Table J-1, we extend Table 4 by showing the effects on mothers with 0–8, 9–12, and more than 12 years of schooling. For most outcomes, we observe larger changes from the mean in lower-education groups. Moreover, we should note that adverse birth outcomes, such as preterm birth and low birth weight, are more prevalent among low-educated mothers. In both Table 4 and Online Appendix Table J-1, we find much larger effects on these adverse outcomes among low-educated mothers. In addition, we can rescale the observed effects based on pre-vaccine measles rates in high-measles states.[13] Full exposure to the vaccine among mothers with 0–8 and 9–12 years of schooling is associated with reductions in preterm birth by about 22.5 and 13.6 percent with respect to the mean of the outcome.

Another potential source of heterogeneity is based on the child's gender. While studies find that changes in maternal education and measures of socioeconomic status (as potential pathways in the current study, discussed in Section V.F) have differential impacts on

13 While the 12-year average pre-vaccine measles rate is roughly 924 per 100,000, the average of above-median states is approximately 1,450 per 100,000 population.

male versus female infants, the direction of the differential effects remains inconclusive. Some studies find larger effects among males (Clark, D'Ambrosio, and Rohde 2021), while others find the opposite (Chen et al. 2020). In Online Appendix B, we explore the heterogeneity in the results by infant gender. Although we find significantly larger effects on females, the differences in the marginal effects are very small.

E. EFFECTS ON MORTALITY AND FERTILITY

So far, we have observed the direct long-run effects of measles vaccine introduction. In this subsection, we explore the contemporaneous effects on mortality and fertility outcomes. In so doing, we construct a state by year panel between 1931 and 1980. The main independent variable of interest is the interaction between the pre-vaccine measles rate (as defined in equation 1) and a dummy indicating post-vaccine years. We implement regressions that include state and year fixed effects. The results are reported in Table 5. In column 1, we show the effect on the log of state-level measles rate (per 100,000). Post-vaccine and for a state at the average pre-vaccine measles rate, the marginal effect suggests an average drop of about 28 percent. In column 2, we investigate the effects on state-level log infant mortality rate. We observe a reduction of 4.6 percent, consistent with several studies that suggest the benefits of the measles vaccine for infant and children mortality outcomes (Breiman et al. 2004).

Women's choice of maternity could be a function of their health and human capital. If higher exposure to measles/vaccination is correlated with this decision, and if this correlation varies by other maternal sociodemographic characteristics that also influence birth outcomes, then regressions of equation 1 are biased. To search for these sources of selective behavior, we explore the effects of measles vaccine exposure on measures of fertility and share of birth to different demographic groups. The results are reported in columns 3–5 of Table 5. We do not find statistically significant evidence for the endogenous selection of births. Specifically, we do not observe any association with the log of birth or the log of birth rate. We also do not find a significant correlation between the measles vaccine measure and the share of births to White mothers. Moreover, the estimated effects suggest quite small sizes, about a 0.36 percent reduction in births to White mothers. Since White mothers have, on average, healthier infants, the negative effects on the share of White mothers in the sample suggest that the estimated effects probably underestimate the true effects and offer a lower bound.

We should also note that this selective fertility analysis is based on contemporary data around the years of measles vaccination. Another source of endogenous fertility arises because of future fertility decisions among those exposed to measles during childhood. In Online Appendix K, we explain the reasons for this concern and the implications of this source of bias and empirically explore this issue. We find no evidence that exposure to measles during childhood is statistically associated with observable maternal characteristics of mothers. Hence, we also do not expect to find an association with unobservables (Altonji, Elder, and Taber 2005; Fletcher et al. 2021).

F. POTENTIAL MECHANISMS

In Section II, we briefly reviewed the literature that has examined the effect of childhood health and later-life outcomes. Using these studies and pathway channels, we argued that

TABLE 4. Heterogeneity of the results across subsamples

	Outcomes					
	Birth weight (1)	Low birth weight (2)	Very low birth weight (3)	Fetal growth (4)	Gestational age (5)	Preterm birth (6)
	A. Low-educated mothers (education $\leq$ 12 years)					
Share childhood exposure × pre-vaccine measles rate	7.58801[a]	−0.00500[a]	−0.00097[a]	0.27127[a]	0.16996[a]	−0.00827[a]
	(0.78056)	(0.00058)	(0.00019)	(0.04199)	(0.01488)	(0.00076)
Observations	41,555,092	41,555,092	41,555,092	39,600,577	41,555,092	41,555,092
R^2	0.03254	0.01704	.00671	0.04724	0.87966	0.30866
Mean DV	3,357.162	0.064	0.010	85.038	37.435	0.139
Percentage change	0.226	−7.816	−9.722	0.319	0.454	−5.948
	B. High-educated mothers (education > 12 years)					
Share childhood exposure × pre-vaccine measles rate	3.81116[a]	−0.00122[a]	−0.00043[a]	0.04253	0.08217[a]	−0.00458[a]
	(0.55172)	(0.00039)	(0.00016)	(0.02951)	(0.00901)	(0.00055)
Observations	32,377,321	32,377,321	32,377,321	32,072,363	32,377,321	32,377,321

R^2	0.02534	0.01215	0.00524	0.05246	0.69103	0.10686
Mean DV	3,373.673	0.045	0.008	87.291	38.882	0.085
Percentage change	0.113	−2.719	−5.436	0.049	0.211	−5.385
	p-value of the difference between coefficients of panels A and B					
	0.000	0.000	0.000	0.000	0.000	0.000

Note: Standard errors, two-way clustered at the mother's state of birth and year of birth, are in parentheses. All regressions include the mother's state of birth fixed effects, year of birth fixed effects, state of birth linear trend in year of birth, and state of residence by year fixed effects. The regressions also include controls for maternal age, maternal education, maternal race, maternal ethnicity, child's gender, birth parity, and prenatal visits. The regressions include birth-state-year controls extracted from decennial censuses and interpolated for inter-decennial years. These controls include average socioeconomic index, female labor force participation rate, literacy rate, share of married individuals, and the average number of children. *Birth weight* is the weight of infant at birth and measured in grams. *Low birth weight* is a binary outcome that turns on if birth weight is less than 2,500 grams. *Very low birth weight* is a binary outcome that turns on if birth weight is less than 1,500 grams. *Fetal growth* is gain in weight per each week of gestation, that is, birth weight divided by gestational weeks. *Gestational age is* the clinical estimation of the period between conception and birth. Preterm birth is a dummy that equals 1 if gestational age is less than 37 weeks. [a]$p < 0.01$.

TABLE 5. Exploring the effects on measles rates, infant mortality, and selective fertility

	Outcomes				
	Log measles rate (1)	Log infant mortality rate (2)	Log birth counts (3)	Log birth rate (4)	Share of births to White mothers (5)
$I(\text{year} > 1963) \times$ pre-vaccine measles rate	-0.27568^{a}	-0.04608^{a}	−0.01219	−0.00863	−0.00304
	(0.08177)	(0.01576)	(0.04074)	(0.01356)	(0.00681)
Observations	1,163	1,850	2,417	2,084	2,417
R^2	0.87131	0.96611	0.99071	0.92273	0.97763
Mean DV	5.467	3.889	11.030	7.644	0.841
Percentage change	−5.043	−1.185	−0.111	−0.113	−0.362

Note: Standard errors, two-way clustered at the state and year, are in parentheses. All regressions are weighted using the total birth count in each state-year. All regressions include state and year fixed effects and a state linear trend. $^{a}p < 0.01$.

measles vaccination provides a healthier childhood, improves health capital, raises physical growth, affects cognitive and noncognitive outcomes, and improves educational attainment and labor market outcomes. We then built on these pathways to posit potential effects on maternal birth outcomes. In this section, we also add to this line of argument by empirically examining the impacts on a wide range of later-life socioeconomic outcomes, which have been shown to influence birth outcomes (Corman, Dave, and Reichman 2019; Thorsen, Thorsen, and McGarvey 2019; Currie and Moretti 2003; Noghanibehambari, Salari, and Tavassoli 2022). We start by exploiting limited information available in the NCHS data on education, prenatal care utilization, and smoking behavior. We regress these outcomes on the exposure measures, conditional on fixed effects, trends, and birth state covariates. The results are reported in Table 6. We observe a 2 percentage point decrease in the probability of having less than 12 years of schooling (off a mean of 0.46; column 1) and a similar increase in having education of college or more (column 2). Full exposure is associated with a rise of 11 basis points in the likelihood of having utilized any prenatal care, an increase of 0.11 percent (column 3). Exposed mothers are also more likely to start prenatal care utilization in earlier pregnancy months (column 4). Finally, they are less likely to smoke during pregnancy, a reduction equivalent to 23 percent from the mean of the outcome (column 5).

We continue to explore mechanisms using alternative data sets. We pool decennial censuses 1970–2000 and American Community Survey (2001–04) data files to cover a similar period as the main analysis sample. We restrict this sample to women aged 15–50 with a child under two years old in the household. We merge these pooled data with the measles rate database based on individuals' state of birth. We then implement regressions similar to equation 1, including birth year fixed effects, birth state fixed effects, birth state trend, and current state by year fixed effects. The results are reported in Table 7. We observe an

TABLE 6. Exploring mechanisms using information in NCHS data

	Outcomes				
	Education < 12 (1)	Education: College or more (2)	Any prenatal care during pregnancy (3)	Pregnancy month that prenatal care began (4)	Is mom smoker (5)
Share childhood exposure × pre-vaccine measles rate	−0.02053[a]	0.01991[a]	0.00112[a]	−0.03092[a]	−0.01748[a]
	(0.00562)	(0.00556)	(0.00020)	(0.00599)	(0.00212)
Observations	73,932,418	73,932,418	67,933,302	67,551,757	73,932,418
R^2	0.22466	0.21953	0.01867	0.10113	0.13849
Mean DV	0.464	0.438	0.994	2.546	0.077
Percentage change	−4.424	4.546	0.113	−1.215	−22.706

Note: Standard errors, two-way clustered at the mother's state of birth and year of birth, are in parentheses. All regressions include the mother's state of birth fixed effects, year of birth fixed effects, state of birth linear trend in year of birth, and state of residence by year fixed effects. The regressions include birth-state-year controls extracted from decennial censuses and interpolated for inter-decennial years. These controls include average socioeconomic index, female labor force participation rate, literacy rate, share of married individuals, and the average number of children. [a]$p < 0.01$.

TABLE 7. Exploring mechanisms using census and American Community Survey data

	Outcomes						
	Socioeconomic score (1)	Is employed (2)	Log total income (3)	Log house value (4)	House owner (5)	Food stamp recipient (6)	Education < high school (7)
Share childhood exposure × pre-vaccine measles rate	0.29099[c]	0.00756[b]	0.06689[a]	0.06068[a]	0.00105	−0.03559	−0.00859[a]
	(0.16086)	(0.00350)	(0.01174)	(0.00880)	(0.00380)	(0.05290)	(0.00204)
Observations	881,286	1,031,751	729,154	590,169	1,031,751	107,733	1,031,751
R^2	0.11746	0.09441	0.33784	0.61040	0.15313	0.12212	0.05197
Mean DV	45.857	0.461	8.888	11.364	0.615	0.140	0.032
Percentage change	0.635	1.640	0.753	0.534	0.171	−25.419	−26.845

Note: Standard errors, two-way clustered at the mother's state of birth and year of birth, are in parentheses. All regressions include the mother's state of birth fixed effects, year of birth fixed effects, state of birth linear trend in year of birth, and state of residence by year fixed effects. The regressions include birth-state-year controls extracted from decennial censuses and interpolated for inter-decennial years. These controls include average socioeconomic index, female labor force participation rate, literacy rate, share of married individuals, and the average number of children. [a]$p < 0.01$, [b]$p < 0.05$, [c]$p < 0.10$.

increase of 0.29 units in the socioeconomic score (column 1).[14] We find a 1.6 percent rise in employment (respective to the outcome mean, column 2). Further, we find a 6.7 percent increase in total personal income (column 3), an effect size larger than the findings of Atwood (2022). We also observe a 6 percent increase in house value and an insignificant 10 basis point rise in the probability of being a homeowner (off a mean of 0.6) (columns 4 and 5). These improvements in socioeconomic status and income measures could partly operate as the pathways between measles vaccination and the next generation's birth outcomes (Barr, Eggleston, and Smith 2022; Hoynes, Miller, and Simon 2015; Lindo 2011). These effects are in line with several studies that examine later-life education-income effects of measles contraction and vaccination during childhood (Summan, Nandi, and Bloom 2023; Atwood 2022). These effects are also comparable to the findings of Schwandt (2017) that the contraction of flu during pregnancy is associated with reductions in income and education during adulthood.

In column 6, we find a reduction in receipt of food stamps owing to measles vaccine exposure. The marginal effect, although statistically insignificant, implies a 25 percent drop from the mean of the outcome. This is also in line with the results of Schwandt (2017) that reveal an increase of 35 percent in welfare dependency due to maternal influenza exposure during pregnancy.

In column 7, we find a reduction of 86 basis points in the probability of having less than a high school education, a drop of 27 percent from the mean. This relatively large drop in low-educated mothers is informative of the potential pathways. Research has shown that the effects of education on such outcomes tend to be more significant for mothers with lower levels of education (Noghanibehambari, Salari, and Tavassoli 2022; Currie and Moretti 2003; Gage et al. 2013).

VI. A Discussion on the Magnitude of the Results

To put the magnitude of the results into perspective, we can compare them with other policy interventions. For instance, Almond, Hoynes, and Schanzenbach (2011) explored the effect of the introduction of the Food Stamp Program during the 1960s on birth outcomes. Their treatment-on-treated effects for participants suggested improvements in birth weight between 13 and 42 grams and reductions in low birth weight by 0.5–1.4 percentage points. Comparing these effects with coefficients of Table 2 and assuming a midpoint effect in their estimations, our findings on birth weight and low birth weight account for 13–44 percent and 20–58 percent of the treatment-on-treated effects of the Food Stamp Program, respectively. These impacts are large for two reasons. First, the effects of Table 2 are among the whole population and provide only intent-to-treat estimates. This aspect of our estimates can be better captured when we focus on the disadvantaged population (with potentially larger gains), as reported in Table 4. Moreover, we can use the estimated effect in column 1 of Table 5 as the benchmark first-stage effects to scale up the estimates. Therefore,

14 The socioeconomic score in column 1 of Table 7 refers to the Duncan Socioeconomic Index reported by Ruggles et al. (2020). This measure is constructed using other measures of occupational education and income scores reported by the census (Duncan 1961).

we can calculate reductions in low birth weight and preterm birth by 20 and 21 percent, respectively. Second, our effects are assessed in the long run and for the next generation, compared with the other contemporaneous policy-induced impacts on birth outcomes. Moreover, the measles vaccine was neither designed for nor targeted at pregnant women. The results of our study suggest spillovers and externalities rather than direct planned and targeted policy effects.

Noghanibehambari (2022) examined the impacts of childhood exposure to the introduction of Medicaid during the 1960s on later-life maternal birth outcomes. He found that among non-White mothers born in states with average Medicaid eligibility, their newborns' birth weight increased by about 36 grams. Therefore, the intent-to-treat effect of measles vaccination for the next generation's birth weight is roughly 16 percent of the introduction of Medicaid, the largest federally funded social program in the US.

We can also focus on the documented later-life consequences of birth outcomes to understand the economic significance of the results. For instance, Almond, Chay, and Lee (2005) evaluated the extra hospital discharge costs associated with low birth weight. Their calculations suggested an average discharge cost of $13,200 related to low birth weight in excess of discharge costs related to normal birth weight (in 2020 dollars). In the year 2000, there were about 307,000 infants categorized as low birth weight. Table 2 suggests a 5.4 percent reduction in low birth weight, equivalent to 16,578 incidences in the year 2000. Using Almond, Chay, and Lee (2005) estimations, we reach a reduction of $218.8 million in hospital discharge costs due to the intergenerational benefits of measles vaccination.

VII. Conclusion

This study joined the ongoing literature on intergenerational spillovers in health capital. We attempted to shed light on the intergenerational benefits of exposure to measles vaccination during childhood. We employed the universe of birth records in the US over the years 1970–2004. We implemented a difference-in-differences econometric method to explore the effect of mothers' childhood exposure to the measles vaccine on their future birth outcomes. We found that for mothers in states with an average pre-vaccine measles rate, fully exposed cohorts reveal roughly 6 grams of additional birth weight and 5 percent reductions in the incidence of low birth weight. These effects represented larger changes for adverse birth outcomes, suggesting higher intergenerational benefits for mothers at higher pregnancy risks. Moreover, we observed larger effects among low-educated mothers. Further analyses suggest that improvements in educational outcomes, increases in prenatal care utilization, reductions in smoking, and increases in several measures of socioeconomic status are potential mechanisms.

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