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 eliminations, 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 12 grams of additional birth weight and a 5 percent reduction in the incidence of low-birth-weight newborns. A series of event-study analyses suggest that these findings are not driven by preexisting trends in outcomes. Moreover, the effects are considerably larger among black mothers and low-educated mothers. Further analyses suggest that improvements in education and increases in prenatal care utilization are potential mechanism channels.

Keywords: Intergenerational Effects, Birth Outcomes, Infant Health, Vaccination, Measles, Childhood Health, Public Health, Prenatal Health Utilization

JEL Codes: H51, H75, I18, D62

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* The authors claim that they have no conflict of interest to report. The authors would like to acknowledge financial support from the Center for Demography of Health and Aging (CDHA) at the University of Wisconsin-Madison under NIA core grant P30 AG17266.

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1. Introduction

Studies in several settings have documented an association between health and human capital during childhood and later-life outcomes, including education, earnings, employment, diseases, disability, self-reported well-being, hospitalization, and old-age health (Almond et al., 2018; Almond & Currie, 2011; Ding & He, 2021; Huang et al., 2011; Lee & Ryff, 2016; Lei et al., 2020; Liu et al., 2022; Mersky et al., 2018; Skarda et al., 2022; Smith, 2009a; Steiber, 2019; Testa et al., 2022; Trinidad, 2021). One strand of this literature explores the influence of childhood exposure and contraction of infectious diseases on later-life outcomes (Blackwell et al., 2001; Crimmins & Finch, 2006; Finch & Crimmins, 2004; Moore et al., 2006; Venkataramani, 2012). For instance, Bleakley (2007) showed that cohorts exposed to Hookworm eradication during childhood reveal higher literacy, school attendance, and income. Case & Paxson (2009) showed that early-life exposure to infectious disease environments is associated with better cognitive scores in old ages.

Measles is a highly contagious disease that could directly deteriorate childhood health capital. It could also indirectly compromise children's immune system and make them more susceptible to other pathogens through a so-called *immunosuppression* process that induces "*immune amnesia"* to immune memory cells (Mina et al., 2015). Prior to the vaccine, roughly 90 percent of children would have contracted the disease by age 12 (Mclean & 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 1967-1970, 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 due to vaccination are also less likely to contract other pathogens, one would expect them to accumulate higher health and human capital development. A strand of literature documents that improvements in childhood health lead to better self-reported adulthood health, higher education-income, lower diseases, and higher longevity (East et al., 2020; Fletcher, 2009; Gisselmann, 2006; Kim & Fletcher, 2021; Smith, 2009b; Turner et al., 2022; Turner et al., 2016). The literature suggests that improvements in childhood health can also be translated into improved maternal birth outcomes (Giallo et al., 2020; Gisselmann, 2006; Harville et al., 2010; McDonnell & Valentino, 2016). Although several studies have pointed to the long-term benefits of measles vaccination, no study has explored its intergenerational benefits (Atwood, 2022; Bogler et al., 2019; Driessen et al., 2015; Nandi, Shet, et al., 2019). Specifically, no study has examined its impacts on later-life maternal birth outcomes. This study aimed to fill this gap in the literature.

We explored the effects of the 1963 introduction of measles vaccination and childhood exposure to vaccination on future maternal birth outcomes. We showed 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 provided event-study results to argue against the concerns over preexisting trends in birth outcomes. The results suggested larger impacts among black mothers and low-educated mothers. Finally, we found suggestive evidence of improvements in educational outcomes as mechanism channels.

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 birth outcomes. This aspect of the study contributes to the ongoing research on long-term later-life benefits of childhood health and wellbeing conditions (Almond et al., 2018; Hayward & Gorman, 2004; Montez et al., 2014). 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 2 reviews the literature. Section 3 introduces data sources and discusses the sample selection strategy. Section 4 discusses the empirical method. Section 5 reviews the results. We depart some concluding remarks in section 6.

2. Pathways between Healthier Childhood and Next Generations' Health at Birth

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

Several studies documented the association between disease in early-life and later-life health outcomes (Bozzoli et al., 2009; Lazuka, 2018; Öberg, 2015; Quaranta, 2013; Ronne, 1985; Rotstein & Levine, 2021; Voth & Leunig, 1996; Warren et al., 2012). For instance, Case & Paxson (2009) examined the effect of early-life exposure to a disease environment on old-age cognitive functioning. They used various measures of infectious disease mortality rates across US regions in the early twentieth century as proxies of disease environment. They found that individuals born in areas with higher mortality rates revealed lower cognitive scores during old ages. Quaranta (2014) used data from Sweden to examine early-life disease exposure and later-life mortality. She found that a higher exposure was associated with reductions in life expectancy by about 1.1-2.1 years, conditional on survival up to age 1. Warren et al. (2012) used US historic decennial censuses and implemented family fixed effects to examine the impact of sickness during childhood on outcomes during adulthood. They showed that, compared with their healthy brothers, individuals who experienced a sickness during childhood were more likely to be illiterate during adulthood. They were also more likely to be unemployed and are less likely to have been ever married. Borrescio-Higa et al. (2019) employed data from Chile and showed that improvements in early-life disease environment are associated with increased height during adulthood. Peracchi & Arcaleni (2011) used data from Italy and showed that early-life disease burden negatively affects young men's height and BMI. McEniry et al. (2008) employed data from Puerto Rico and documented that early-life exposure to infectious diseases was correlated with old-age heart disease and diabetes.

Childhood vaccination alleviates exposure to various diseases and contributes to a better accumulation of health capital, physical growth, and other developmental outcomes. A small strand of research has explored the later-life impacts of vaccination (Anekwe et al., 2015; Anekwe & Kumar, 2012; Bawankule et al., 2017; Breiman et al., 2004; Nandi & Shet, 2020; Rughini et al., 2022). For instance, Bloom et al. (2011) employed data from the Philippines and showed that early childhood vaccination did not affect later-life height but had a significant impact on cognitive test scores. Nandi et al. (2020) explored the impact of vaccination under the Universal Immunization Program in India on later-life education. They implemented family foxed effect models and showed that vaccinated siblings earn 0.18 years more schooling compared to their unvaccinated siblings. Anekwe & Kumar (2012) showed that Indian children who were exposed to the Universal Immunization Program had significantly higher height-for-age and weight-for-age scores. Nandi et al. (2019) examined the impacts of the Haemophilus influenzae type b (Hib) vaccine on anthropometric and educational outcomes. They documented a significant positive effect of vaccination on height-for-age and English and mathematics test scores.

Several studies have examined the short-term and long-term effects of measles vaccination (Anekwe et al., 2015; Mrozek-Budzyn et al., 2013; Nandi, Shet, et al., 2019). For instance, Driessen et al. (2015) exploited the roll-out of measles vaccination across districts of Bangladesh and found that age-appropriate vaccination was associated with a higher probability of school attendance among boys. Bogler et al. (2019) used survey data from 59 developing countries and showed that childhood measles vaccination significantly reduced the odds of stunting and being underweight. Nandi, Shet, et al. (2019) showed that measles vaccination in early-life was associated with higher BMI-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.

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 (Atmar et al., 1992; Azcorra & Mendez, 2018; Boney et al., 2005; Currie & Moretti, 2003; Elshibly & Schmalisch, 2008; Frederick et al., 2008; Gage et al., 2013; Han et al., 2012; Lindo, 2011; Löf et al., 2008; Mocan et al., 2015; Pickett et al., 2000; Tyrrell et al., 2016; Venkataramani, 2012; Yu et al., 2013; Zhang et al., 2015). For instance, Noghanibehambari et al. (2022) employed birth records data from the US and exploited the state-year variations in minimum dropout age policies as the exogenous influence in education to examine the effects of maternal education on birth outcomes. They found that an additional year of maternal schooling was associated with 34 grams higher birth weight. Zhang et al. (2015) used mother-infant-pair data from three Nordic countries and evaluated the effect of maternal height on birth outcomes. They found a significant association between mothers' height and infants' birth size. Yu et al. (2013) explored the impacts of pre-pregnancy maternal Body Mass Index on infants' health outcomes. They found that maternal underweight and overweight were associated with adverse birth outcomes.

3. Data and Sample Selection

The primary source of data is public-use Natality birth record data extracted from NCHS (2020). The data covers the years 1970-2004. We restrict the sample to mothers born between 1930-1980. 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 19-40 (Ben-David et al., 2016; Chen et al., 2007; Dennis, 2019; Gilbert et al., 2009; Hibbs et al., 2018; Letamo & Majelantle, 2001). Moreover, we limit the sample to singleton births since birth outcomes of multiple births are also primarily driven by factors unrelated to maternal exposures (Qin et al., 2015; Vohr et al., 2009). We also exclude observations with missing values on birth weight and gestational age.

We use the 12-year-average cross-state measles rate for the years prior to the vaccine, i.e., the period of 1952-1963, extracted from Atwood (2022). We merge this data with birth record data based on the mother's state-of-birth. 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.

The final sample includes 73,968,859 observations from 49 US states.[3] The outcomes that we examine are described below. Birth Weight is the weight of the infant at birth and measured in grams. Low birth weight is a binary outcome that equals one if birth weight is less than 2,500

[3] The measles data for Kansas and Alaska is not available.

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 week of gestation, i.e., birth weight divided by gestational weeks. Full-Term Birth Weight is the birth weight of infants at maturity, i.e., those with a gestational age of between 37-42 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, the second panel reports mothers' sociodemographic features, and the third panel summarizes mothers' state-year-of-birth controls that we used in our regressions. The average birth weight in the sample is 3,383 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. In the bottom panel, we show infants' birth weight distribution by their mother's state-of-birth.

4. Empirical Method

Our econometric method is built on cross-cohort variation in the share of exposure to the introduction of the vaccine and cross-state variation in pre-vaccine concentration of measles rate.[4] Specifically, we implement the following difference-in-difference regressions:

$$y_{ibt} = \alpha_0 + \alpha_1 ShareExp_t \times Measles_b^* + \alpha_2 X_{ibt} + \alpha_3 Z_{bt} + \zeta_b + \xi_t + \varepsilon_{bt} \qquad (1)$$

Where y is the birth outcome to mother i who was born in state b and year t. The variable $ShareExp$ is the share of childhood up to age 12 that the mother could have been exposed to the

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

introduction of the vaccine. It varies between zero (unexposed cohorts) and one (fully exposed cohorts). The variable $Measles^*$ represents the state-of-birth-specific 12-year average measles rate prior to the vaccine. To ease the interpretation, we divide it by its mean across all states. Therefore, the parameter α_1 measures the effect of full exposure to the vaccine introduction and a reduction in measles rate from the average of pre-vaccine rates to zero on next generations' birth outcomes. 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 cluster the standard errors at the mother's birth-state and birth-year level. In Appendix A, we show that the results are quite robust to alternative clustering levels.

5. Results

5.1. 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 measles rate from the average of pre-vaccine rates to zero (roughly equivalent to the reduction in measles after the vaccine is available) was associated with roughly 12.4 grams higher birth weight (column 1), 29 basis-points lower probability of low birth weight (column 2), and 8.2 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 tails of birth weight distribution as the percent changes from the mean of the outcome (reported in the last row) imply. For instance, the implied percent 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 parametrized regression. We depict the results in the top panel of **Error! Reference source not found.**. 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 require a baseline value and these are the effects across various outcomes, we divide point estimates and confidence intervals by the mean of their respective outcome and illustrate the results in the bottom panel of Figure 2. The implied effects (relative to the mean of the outcomes) suggest larger effects for lower thresholds of low-birth-weight definition. There is a monotonous trend in the magnitude of implied percentage changes with respect to the thresholds, i.e., at lower thresholds, we observe larger effects. This fact suggests that the effects are larger for infants at the lower tails of birth weight distribution.

One concern is that the increased physical growth of infants is due to overall increases in gestational age and reductions in preterm birth observed in recent decades (Dongarwar et al., 2021). To address this issue, we use three alternative measures of physical growth that partly account for variations in gestational age. The first outcome is fetal growth, which measures infants' intrauterine weekly weight gain. Column 4 suggests an increase in fetal growth of about 0.22 grams per week of gestation. This effect is about a 0.26 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 increases in birth weight can be explained by variations in the gestational period. When we restrict births to full-term births and eliminate premature and overmature births, we find an increase in birth weight of about 7 grams (column 5). Finally, in column 6, we look at gestational-age-adjusted birth weight to take advantage of a portion of birth weight that is explained by gestational age. We observe an effect size of 14.2 grams, equivalent to roughly a 0.42 percent rise from the mean of the outcome.

5.2. Concerns over Preexisting trends

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[5]. We implement specifications similar to equation 1 and replace $ShareExp$ with event dummies. Specifically, we implement the following regressions:

$$\begin{aligned} y_{ibt} = \alpha_0 + Measles_b^* \times \{ & \sum_{i=\underline{T}}^{-2} \beta_i I(Year\ Turn\ 12 - 1963 = i) \\ & + \sum_{j=0}^{\overline{T}} \gamma_j I(Year\ Turn\ 12 - 1963 = j)\} + \alpha_2 X_{ibt} + \alpha_3 Z_{bt} + \zeta_b + \xi_t \\ & + \varepsilon_{bt} \end{aligned} \tag{2}$$

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 3 through Figure 5, we depict the event-study results for all six outcomes studied in Table 2. For all outcomes, we observe virtually similar pattern of effects. The negative event-time coefficients (representing unexposed cohorts) do not reveal an economically and statistically significant association. This set

[5] Studies show that roughly 90 percent of children contract measles by age 12 (Mclean & Anderson, 1988).

of coefficients rules out the concerns over pre-trend for various physical growth-related infants' outcomes. 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.

5.3. 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 parametrized regressions and replicate the results. The estimated effects are reported in panel A of Table 3. The effects drop in magnitude but remain significant in most cases.

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 quite similar effects compared with the main results.

In addition, we control for time-invariant mother's state-of-residence characteristics and overall unobserved shocks across infants' birth years by including current state and year fixed effects. We report these results in panel C of Table 3. Again, the estimated effects are quite comparable with the main findings of the paper.

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, i.e., mothers born between 1952 and 1963, and focus on comparing fully exposed and unexposed mothers. The results are reported in panel A of Table 4. Moreover, in panel B of Table 4, we restrict the sample to birth cohorts of 1945-1970. The estimated effects and their statistical significance in both panels are quite comparable to the main findings of Table 2.

5.4. Selective Fertility

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. Moreover, changes in infant mortality due to immunization to measles could impose a selection based on different characteristics of the survived population. To search for these sources of selective behavior, we explore the effects of measles vaccine exposure on measures of fertility, infant mortality, and share of birth to different demographic groups. We collapse the final sample at the (mother's) state and year of birth and implement regressions similar to equation 1, including state and year fixed effects. The results, reported in Table 5, do not offer statistically significant evidence for endogenous selection of births and infant deaths. Specifically, we do not observe any association with the log of birth, log of birth rate, log of infant mortality rate, and share of births to white mothers, Hispanic mothers, and those delivered in a hospital. In addition, the estimated effects suggest quite small sizes. For instance, a difference equivalent to the average pre-vaccine measles rate is associated with a 0.7 percent increase in birth counts, 0.5 percent rise in birth rate, and about a 2.7 percent reduction in infant mortality rate.

5.5. 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 (Borrell et al., 2021; Florian et al., 2021; Mehra et al., 2017;

Noghanibehambari, 2022; Reagan & Salsberry, 2005; Rosenthal & Lobel, 2011; Slaughter-Acey et al., 2020). Therefore, one would expect to observe heterogeneous impacts of a healthier childhood on later-life health outcomes based on sociodemographic characteristics. We explore this potential source of heterogeneity by replicating the main results among subpopulations of blacks and low-educated mothers (education less than 12 years of schooling). The results are reported in panels A and B of Table 6. The marginal effects and implied percentage changes from the outcomes suggest larger impacts in these two groups. For instance, the results suggest 20.4 and 17.7 grams of additional birth weight among blacks and low-educated mothers, respectively, while Table 2 implied 12.4 grams for the full sample.

5.6. Potential Mechanisms

In section 2, 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 measles vaccination provides a healthier childhood, improves health capital, raises physical growth, affects cognitive and non-cognitive 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 maternal education and prenatal visits, both of which have been shown to influence birth outcomes (Corman et al., 2019; Currie & Moretti, 2003; Noghanibehambari et al., 2022; Thorsen et al., 2019). The results are reported in Table 7. We observe a 24 percent decline in the share of mothers with less than high school education (column 1). We also observe increases in the share of mothers with high school and college education of about 7 and 6 percent relative to the mean of the outcomes, respectively. In addition, we explore the effects on a dummy variable indicating having any prenatal visits during pregnancy. The estimated effect suggests a 14 basis-point increase in the likelihood of having any prenatal visits, equivalent to about a 0.15 percent rise from the mean of the outcome.

5.7. 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 et al. (2011) explore the effect of the introduction of the Food Stamp program during the 1960s on birth outcomes. Their treatment-on-treated effects for participants suggest improvements in birthweight between 13-42 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 35 percent and 30 percent of the treatment-on-treated effects of the Food Stamp program. Noghanibehambari (2022) examined the impacts of childhood exposure to the introduction of Medicaid during the 1960s on later-life maternal birth outcomes. He finds significant improvements in the next generation's health at birth. Among nonwhite mothers born in states with an average 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 one-third of the introduction of Medicaid, the largest federally funded social program.

6. 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-difference 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

12 grams 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 blacks and low-educated mothers. Further analyses suggested that improvements in education and prenatal care utilization are potential mechanism channels.

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Tables

Table 1 - Summary Statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Child Characteristics:					
Birth Weight	73,968,859	3382.502	575.707	227	8165
Low Birth Weight	73,968,859	0.056	0.229	0	1
Very Low Birth Weight	73,968,859	0.009	0.095	0	1
Fetal Growth	71,708,177	86.045	13.671	4.904	352.778
Full-Term Birth Weight	61,283,360	3450.34	490.674	227	8165
Gestational-Age-Adjusted Birth Weight	73,968,859	3364.374	284.201	942.588	3572.004
Child Female	73,968,859	0.488	0.5	0	1
Child First Born	73,968,859	0.29	0.454	0	1
Share Childhood Exposure × Pre-vaccine Measles Rate	73,968,859	0.71489	0.59369	0	3.17477
12-Year Pre-Vaccine Measles Rate	73,968,859	924.824	538.14	91.343	2936.104
Maternal Characteristics:					
Birth Year	73,968,859	1961.827	9.212	1931	1980
Mother White	73,968,859	0.841	0.366	0	1
Mother Black	73,968,859	0.143	0.351	0	1
Mother Age	73,968,859	27.269	4.762	20	39
Mother Age 20-24	73,968,859	0.331	0.471	0	1
Mother Age 25-29	73,968,859	0.351	0.477	0	1
Mother Age 30-34	73,968,859	0.231	0.422	0	1
Mother Age 35-39	73,968,859	0.086	0.281	0	1
Mother Education<High School	73,968,859	0.1	0.3	0	1
Mother Education High School	73,968,859	0.462	0.499	0	1
Mother Education Some College	73,968,859	0.219	0.413	0	1
Mother Education Bachelor-above	73,968,859	0.219	0.414	0	1
Any Prenatal Visits	73,968,859	0.917	0.276	0	1
State Controls:					
Average Socioeconomic Index	73,968,859	33.592	3.548	19.456	42.198
Average Number of Children	73,968,859	0.376	0.068	0.134	0.628
Female Labor Force Participation Rate	73,968,859	0.405	0.074	0.16	0.656
Average Married People	73,968,859	0.651	0.031	0.323	0.729
Literacy Rate	73,968,859	0.002	0.032	0	0.893

Notes: measles rate is measured as cases per 100,000 state population.

Table 2 - Main Results: The Association between Childhood Exposure to Measles Vaccination and Birth Outcomes

	Outcomes:					
	Birth Weight	Low Birth Weight	Very Low Birth Weight	Fetal Growth	Full-Term Birth Weight	Gestational-Age-Adjusted Birth Weight
	(1)	(2)	(3)	(4)	(5)	(6)
Share Childhood Exposure × Pre-vaccine Measles Rate	12.44558***	-0.00291***	-0.00082***	0.22443***	7.04996***	14.23283***
	(1.06457)	(.00027)	(0.00008)	(0.02647)	(0.99366)	(0.79784)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05484	0.01592	0.0054	0.05525	0.0571	0.02576
Mean DV	3382.502	0.056	0.009	86.045	3450.340	3364.374
%Change	0.368	-5.194	-9.139	0.261	0.204	0.423

Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth 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 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, i.e., birth weight divided by gestational weeks. ***Full-Term Birth Weight*** is birth weight of infants at maturity, i.e., those with gestational age of between 37-42 weeks. ***Gestational-Age-Adjusted Birth Weight*** is the predicted value of regressing birth weight on gestational age.

*** p<0.01, ** p<0.05, * p<0.1

Table 3 - Robustness Checks to Alternative Specifications

	Outcomes:					
	Birth Weight	Low Birth Weight	Very Low Birth Weight	Fetal Growth	Full-Term Birth Weight	Gestational-Age-Adjusted Birth Weight
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Adding Mother's Region-of-Birth-by-Birth-Year Fixed Effects						
Share Childhood Exposure × Pre-vaccine Measles Rate	6.92193***	-0.0022***	-0.00069***	0.08921***	1.07195	13.06941***
	(0.73681)	(0.00025)	(0.00009)	(0.02079)	(0.85032)	(0.96526)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05494	0.01594	0.00541	0.05531	0.05718	0.02588
Mean DV	3382.502	0.056	0.009	86.045	3450.340	3364.374
%Change	0.205	-3.926	-7.713	0.104	0.031	0.388
Panel B. Adding Mortality Rates in State-Year of Birth of Mother						
Share Childhood Exposure × Pre-vaccine Measles Rate	12.40467***	-0.00252***	-0.00077***	0.22914***	7.67516***	14.24733***
	(1.16328)	(0.00028)	(0.00009)	(0.02682)	(0.98045)	(0.80696)
Observations	72478749	72478749	72478749	70476430	60230200	72478749
R-squared	0.05537	0.01614	0.0055	0.05561	0.0574	0.02599
Mean DV	3382.595	0.055	0.009	86.050	3450.509	3364.325
%Change	0.367	-4.579	-8.523	0.266	0.222	0.423
Panel C. Adding Current State and Year Fixed Effects						
Share Childhood Exposure × Pre-vaccine Measles Rate	13.38629***	-0.00302***	-0.00084***	0.28693***	10.19048***	14.59448***
	(1.08304)	(0.00028)	(0.00009)	(0.02493)	(0.9431)	(0.77214)
Observations	73932418	73932418	73932418	71672945	61254736	73932418
R-squared	0.05747	0.01664	0.00583	0.05732	0.06001	0.02738
Mean DV	3382.571	0.055	0.009	86.046	3450.393	3364.393
%Change	0.396	-5.496	-9.354	0.333	0.295	0.434

Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth 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 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. Infant mortality rates in panel B include non-infant death rate, infant mortality rate (per 100,000), and total number of births per women aged 15-45.

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, i.e., birth weight divided by gestational weeks. ***Full-Term Birth Weight*** is birth weight of infants at maturity, i.e., those with gestational age of between 37-42 weeks. ***Gestational-Age-Adjusted Birth Weight*** is the predicted value of regressing birth weight on gestational age.

*** p<0.01, ** p<0.05, * p<0.1

Table 4 - Robustness of the Results across Alternative Subsamples

	Outcomes:					
	Birth Weight	Low Birth Weight	Very Low Birth Weight	Fetal Growth	Full-Term Birth Weight	Gestational-Age-Adjusted Birth Weight
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Excluding Partially Exposed Cohorts						
Share Childhood Exposure × Pre-vaccine Measles Rate	11.91594***	-0.00263***	-0.00071***	0.22909***	6.91397***	15.59865***
	(1.35305)	(0.00032)	(0.0001)	(0.03836)	(1.45882)	(0.98804)
Observations	47295137	47295137	47295137	45770541	39133541	47295137
R-squared	0.05331	0.01553	0.0056	0.05413	0.05529	0.02442
Mean DV	3372.635	0.057	0.010	85.999	3443.300	3356.005
%Change	0.353	-4.610	-7.050	0.266	0.201	0.465
Panel B. Excluding Mother Cohorts Born between 1945-1970						
Share Childhood Exposure × Pre-vaccine Measles Rate	9.82008***	-0.00266***	-0.00075***	0.16122***	4.36538***	13.27668***
	(1.07951)	(0.0003)	(0.00009)	(0.0247)	(0.91446)	(0.95474)
Observations	57285365	57285365	57285365	55539597	47470908	57285365
R-squared	0.05608	0.01686	0.00542	0.057	0.05812	0.02646
Mean DV	3394.076	0.054	0.009	86.195	3460.077	3370.593
%Change	0.289	-4.920	-8.287	0.187	0.126	0.394

Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth 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 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, i.e., birth weight divided by gestational weeks. ***Full-Term Birth Weight*** is birth weight of infants at maturity, i.e., those with gestational age of between 37-42 weeks. ***Gestational-Age-Adjusted Birth Weight*** is the predicted value of regressing birth weight on gestational age.

*** p<0.01, ** p<0.05, * p<0.1

Table 5 - Exploring Selective Fertility and Infants' Survival

	Outcomes:					
	Log Birth Counts	Log Birth Rate	Log Infant Mortality Rate	Share of Births to White Mothers	Share of Births to Hispanic Mothers	Share of Births Delivered in Hospital
	(1)	(2)	(3)	(4)	(5)	(6)
Share Childhood Exposure × Pre-vaccine Measles Rate	0.0071 (0.04327)	0.00531 (0.00839)	-0.02794 (0.02038)	-0.01013 (0.00806)	0.00093 (0.00461)	-0.00269 (0.00175)
Observations	2417	2084	1850	2417	2417	2033
R-squared	0.98064	0.88888	0.95106	0.95874	0.73547	0.90317
Mean DV	11.030	7.644	3.889	0.841	0.026	0.969
%Change	0.064	0.069	-0.718	-1.205	3.596	-0.278

Notes. 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.
*** p<0.01, ** p<0.05, * p<0.1

Table 6 - Heterogeneity of the Results across Subpopulations

	Outcomes:					
	Birth Weight	Low Birth Weight	Very Low Birth Weight	Fetal Growth	Full-Term Birth Weight	Gestational-Age-Adjusted Birth Weight
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Subsample of Black Mothers						
Share Childhood Exposure × Pre-vaccine Measles Rate	20.40765***	-0.00847***	-0.00204***	0.32413***	11.57441***	5.47929***
	(2.29663)	(0.00098)	(0.00043)	(0.0594)	(2.29423)	(1.25139)
Observations	10613674	10613674	10613674	10330650	8090695	10613674
R-squared	0.02265	0.01061	0.00497	0.02358	0.02917	0.0112
Mean DV	3145.273	0.113	0.023	81.290	3263.975	3276.767
%Change	0.649	-7.499	-8.863	0.399	0.355	0.167
Panel B. Subsample of Low Educated Mothers (Education≤ 12 years)						
Share Childhood Exposure × Pre-vaccine Measles Rate	17.71678***	-0.00361***	-0.00083***	0.40362***	13.67288***	16.52447***
	(1.46109)	(0.00035)	(0.00011)	(0.03888)	(1.41153)	(1.09522)
Observations	34321979	34321979	34321979	33786833	28189080	34321979
R-squared	0.05212	0.01687	0.00626	0.04621	0.05141	0.02998
Mean DV	3335.957	0.066	0.011	84.872	3407.056	3355.163
%Change	0.531	-5.470	-7.542	0.476	0.401	0.493

Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth 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 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, i.e., birth weight divided by gestational weeks. ***Full-Term Birth Weight*** is birth weight of infants at maturity, i.e., those with gestational age of between 37-42 weeks. ***Gestational-Age-Adjusted Birth Weight*** is the predicted value of regressing birth weight on gestational age.

*** p<0.01, ** p<0.05, * p<0.1

Table 7 - Exploring Mechanism Channels

	Outcomes:			
	Mother Education < High School	Mother Education = High School	Mother Education = College and More	Any Prenatal Visits
	(1)	(2)	(3)	(4)
Share Childhood Exposure × Pre-vaccine Measles Rate	-0.00049***	0.03238***	0.02687***	0.00146***
	(0.0001)	(0.0102)	(0.00491)	(0.00019)
Observations	73968859	73968859	73968859	67964937
R-squared	0.00889	0.0557	0.05204	0.01428
Mean DV	0.002	0.462	0.438	0.994
%Change	-24.535	7.008	6.135	0.147

Notes. Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth fixed effects. The regressions also include controls for maternal age, maternal race, maternal ethnicity, birth parity, and child's gender.
*** p<0.01, ** p<0.05, * p<0.1

Figures

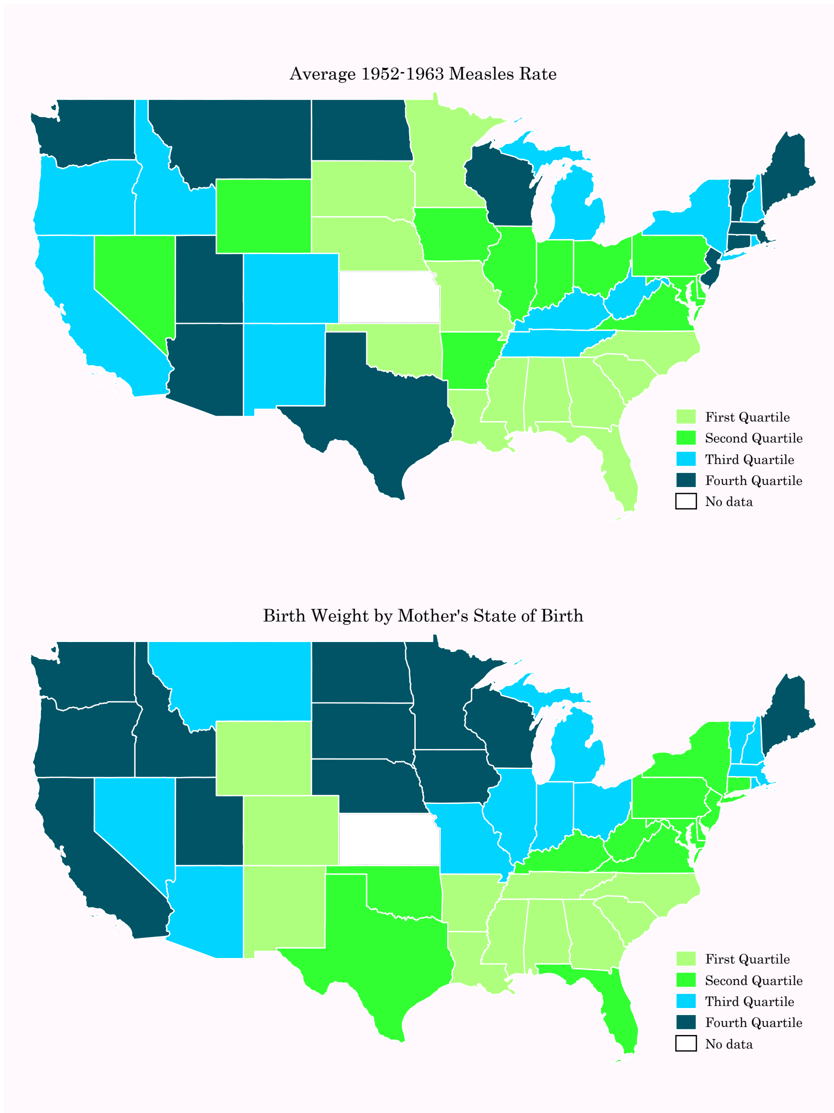

Figure 1 - Geographic Distribution of Mother's State-of-Birth Measles Case Rate and Birth Weight of Infants by their Mother's State-of-Birth

Figure 2 - Exploring the Effects of Exposure to Vaccination across Low-Birth-Weight Definition Thresholds

Notes. Point estimates and 90 percent confidence intervals are illustrated. Standard errors are clustered at the mother's state-year-of-birth. All regressions include mother's state-of-birth and year-of-birth 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 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 average number of children. N=73,968,859

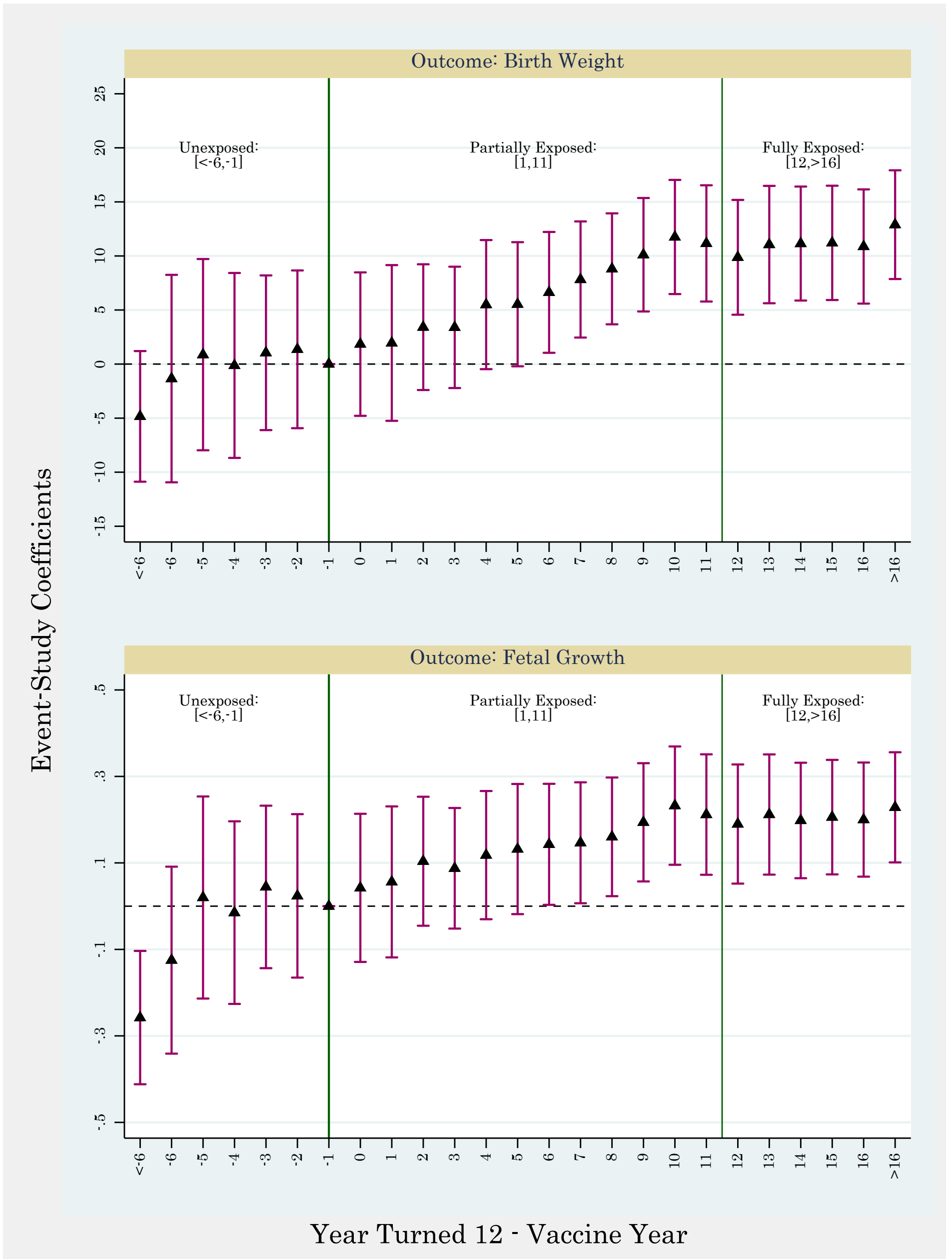

Figure 3 - Event Study Results of Childhood Exposure to Measles Vaccination and Birth Outcomes

Notes. Point estimates and 90 percent confidence intervals are illustrated. Standard errors are clustered at the mother's state-year-of-birth. All regressions include mother's state-of-birth and year-of-birth 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 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 average number of children.
N=73,968,859

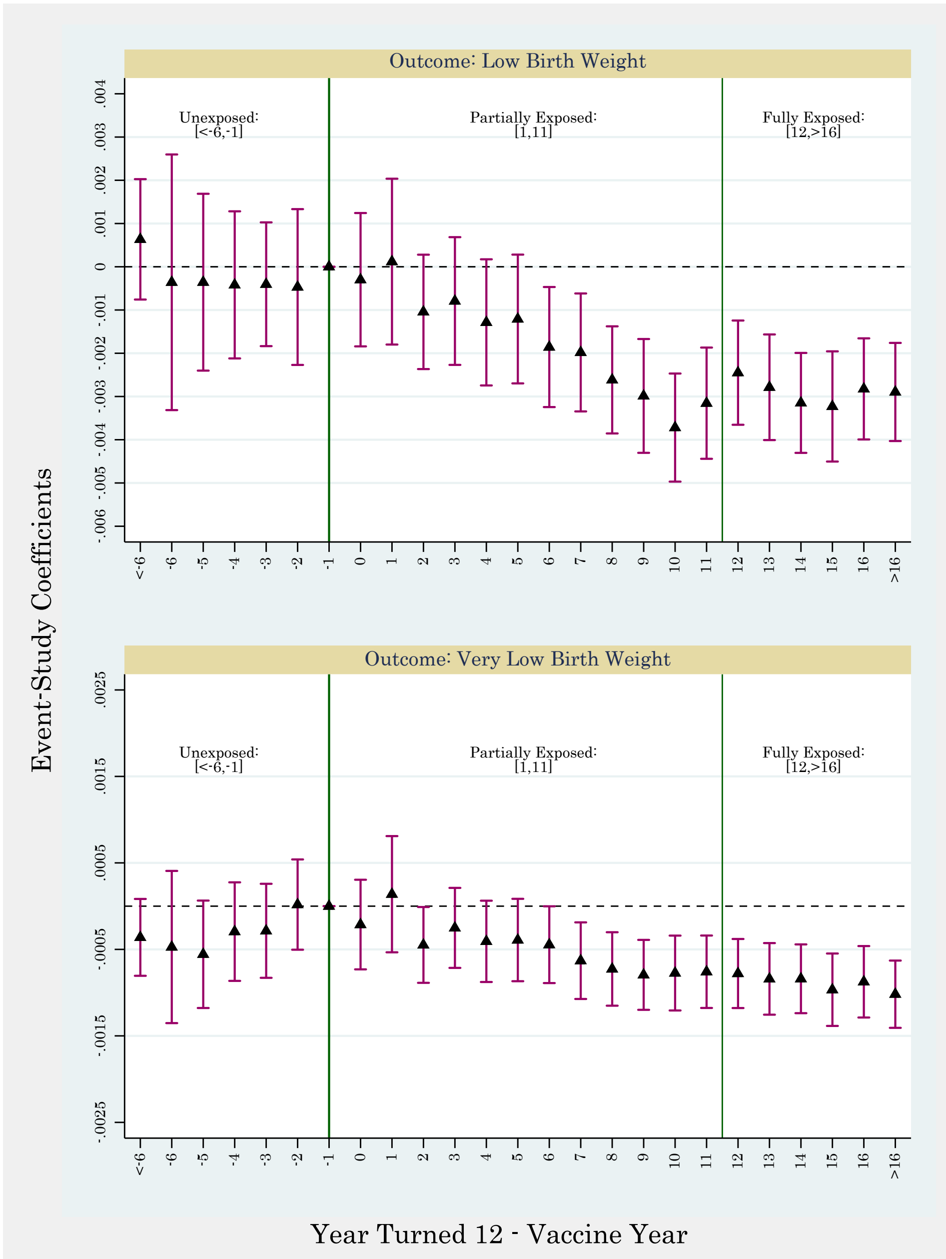

Figure 4 - Event Study Results of Childhood Exposure to Measles Vaccination and Birth Outcomes

Notes. Point estimates and 90 percent confidence intervals are illustrated. Standard errors are clustered at the mother's state-year-of-birth. All regressions include mother's state-of-birth and year-of-birth 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 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 average number of children.
N=73,968,859

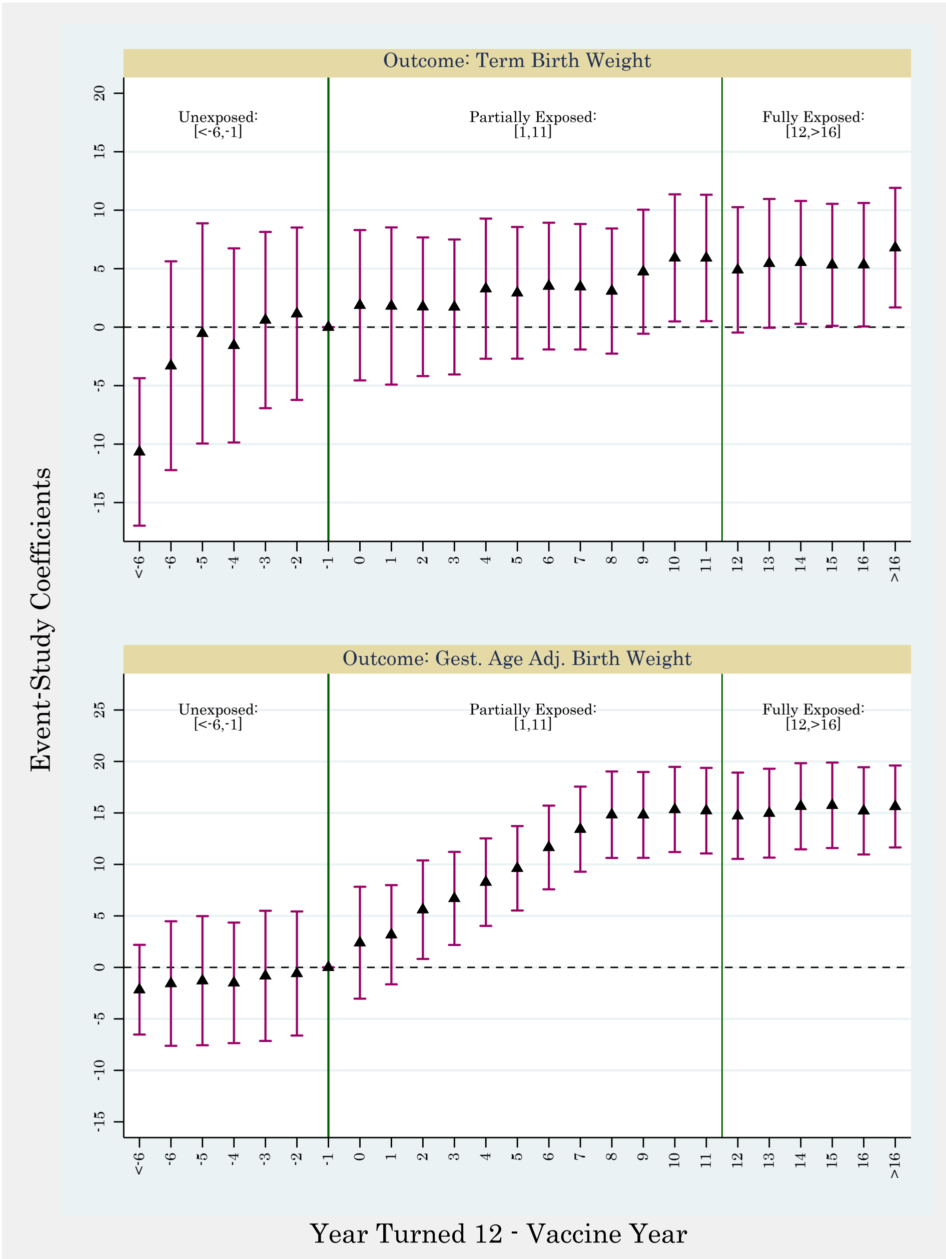

Figure 5 - Event Study Results of Childhood Exposure to Measles Vaccination and Birth Outcomes

Notes. Point estimates and 90 percent confidence intervals are illustrated. Standard errors are clustered at the mother's state-year-of-birth. All regressions include mother's state-of-birth and year-of-birth 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 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 average number of children.
N=73,968,859

Appendix A

In the main text, we use two-way clustering by mothers' birth state and birth year to adjust standard errors. In Appendix Table A-1, we explore the sensitivity of the results to alternative methods of fixing standard errors. We start by using Huber-White robust standard errors in panel A. We then implement alternative levels of clustering, including mothers' birth-state (panel B), mothers' birth-year (panel C), and two-way on mothers' birth-state and region-birth-year level (panel D). All the coefficients remain statistically significant at conventional levels.

Appendix Table A-1 - Robustness of Standard Errors to Alternative Clustering Levels

	Outcomes:					
	Birth Weight	Low Birth Weight	Very Low Birth Weight	Fetal Growth	Full-Term Birth Weight	Gestational-Age-Adjusted Birth Weight
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Using Huber-White Robust Standard Errors						
Share Childhood Exposure × Pre-vaccine Measles Rate	12.44558***	-0.00291***	-0.00082***	0.22443***	7.04996***	14.23283***
	(0.3128)	(0.00012)	(0.00005)	(0.00815)	(0.32044)	(0.14203)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05484	0.01592	0.0054	0.05525	0.0571	0.02576
Panel B. Clustering at Mother's State-of-Birth Level						
Share Childhood Exposure × Pre-vaccine Measles Rate	12.44558**	-0.00291**	-0.00082**	0.22443**	7.04996*	14.23283***
	(4.84865)	(0.00121)	(0.00034)	(0.10891)	(4.0796)	(3.27452)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05484	0.01592	0.0054	0.05525	0.0571	0.02576
Panel C. Clustering at Mother's Year-of-Birth Level						
Share Childhood Exposure × Pre-vaccine Measles Rate	12.44558***	-0.00291***	-0.00082***	0.22443***	7.04996***	14.23283***
	(0.70926)	(0.00018)	(0.00007)	(0.01685)	(0.73619)	(0.5622)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05484	0.01592	0.0054	0.05525	0.0571	0.02576
Panel D. Two-Way Clustering at Mother's State-of-Birth and Region-of-Birth-by-Year-of-Birth Level						
Share Childhood Exposure × Pre-vaccine Measles Rate	12.44558**	-0.00291**	-0.00082**	0.22443**	7.04996*	14.23283***
	(4.79634)	(0.00121)	(0.00034)	(0.10846)	(4.08491)	(3.24724)
Observations	73968859	73968859	73968859	71708177	61283360	73968859
R-squared	0.05484	0.01592	0.0054	0.05525	0.0571	0.02576

Notes. Standard errors, two-way clustered at the mother's state-of-birth-year-of-birth, are in parentheses. All regressions include the mother's state-of-birth and year-of-birth 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 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, i.e., birth weight divided by gestational weeks. ***Full-Term Birth Weight*** is birth weight of infants at maturity, i.e., those with gestational age of between 37-42 weeks. ***Gestational-Age-Adjusted Birth Weight*** is the predicted value of regressing birth weight on gestational age.

*** p<0.01, ** p<0.05, * p<0.1