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The Long-Term Effects of Measles Vaccination on Earnings and Employment†

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The measles vaccine was introduced in 1963. Take-up of the vaccine in the United States occurred quickly and universally, leading to reductions in morbidity and mortality. New biological evidence on how the measles virus interacts with our immune system indicates the impact of the measles vaccine may be underestimated. Using a difference-in-difference identification strategy, I find evidence the measles vaccine increased earnings and employment. Long-term follow-up of adults finds an increase in income of 1.1 percent and positive effects on employment. This increase in income is not from an increase in hours worked but rather from greater productivity. (*JEL* I12, I18, J22, J24, J31)

Since the late nineteenth century, the development of vaccines has provided a more cost-effective approach to treating infectious diseases, making for one of the most important advancements in public health (MMWR 1977; Institute of Medicine 2013). While vaccines provide direct disease-reduction effects upon the individual receiving the vaccine, they also work to reduce the burden of infectious disease through the creation of herd immunity within the community. Though several studies document the improvements in health resulting from the introduction of vaccines, particularly in developing countries, few have investigated the effects of these vaccines on long-run labor market outcomes. Vaccines prevent infectious disease the same way in rich and poor countries; however, the better health environment in wealthier countries may result in greater spillover effects from the vaccine. Clinical trials and observational studies (CDC 1996; Institute of Medicine 2013) have shown vaccines are effective, though future consequences due to the absence of early infections attributable to childhood vaccination remain unknown. This study aims to fill this gap by evaluating changes in adult earnings and employment, following the introduction of the measles vaccine in the United States. The introduction of the measles vaccine provides a plausibly exogenous intervention that both

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reduces childhood infection and provides an opportunity to study the consequences of measles on adult outcomes.

The measles vaccine was licensed in 1963. In 1962, the Vaccination Assistance Act (Pub L No 87-8688) was passed, which allowed the Centers for Disease Control and Prevention (CDC) to support mass vaccination campaigns and provided financial assistance to state and local health departments. In response, the United States' take-up of the vaccine was rapid and nearly universal, resulting in reductions in morbidity and mortality (Barkin 1975). Notably, the observed reductions in morbidity and mortality were larger than measles prevention alone would suggest (Koenig et al. 1990). Medical literature has shown that contracting the measles virus impacts the immune system and leads to increased susceptibility to other childhood infectious diseases for up to five years after the onset of measles (Mina et al. 2019; Petrova et al. 2019; Mina et al. 2015; Gadroen et al. 2018). It is hypothesized that since children no longer experience the weakened immune effects from measles, they are in better overall health throughout childhood post–vaccine introduction. Therefore, the impact of the measles vaccine has likely been significantly underestimated.

The research design exploits the exogenous change in the measles incidence rate that resulted from the licensing of the measles vaccine. I utilize a difference-in-difference identification strategy that takes advantage of cross-area differences in prevaccine measles incidence rates across states and differential exposure to the vaccine due to birth year to measure the long-run effects of measles vaccination on labor market outcomes. Areas across the country reported different prevaccine incidence rates of measles because of differences in susceptible population density. When the measles vaccine was introduced in the United States, there were mass vaccination initiatives resulting in high take-up and near complete reductions in incidence rates. Areas with higher prevaccine infection rates experienced greater reductions in measles than areas with lower prevaccine rates of measles. This identification strategy is similar to that used in studies assessing the impact of hookworm and malaria eradication (Bleakley 2007, 2010b; Cutler et al. 2010; Lucas 2010).

Differences across regions in prevaccine measles incidence rates and the resulting differences in the incidence of measles and other infectious diseases post–vaccine introduction will have subsequent effects on human capital accumulation. For example, if children who would otherwise have contracted measles do not get the measles and are healthier overall throughout childhood, then areas with comparatively high incidence of measles prior to vaccine introduction will experience larger gains as a result of the measles vaccine. My estimates suggest that those individuals born in a state with the average measles incidence rate prevaccine with lifetime exposure to the measles vaccine earn $447 more per year than those without exposure to the measles vaccine, representing a 1.1 percent increase in income as adults. Additionally, I find exposure to the measles vaccine leads to a decrease in the probability of living in poverty, increases the likelihood of being employed, and does not have an impact on the number of hours worked in a week, suggesting income gains are attained through increased productivity. Lastly, I provide a back-of-the-envelope calculation to illustrate the social benefit of the measles vaccine.

Understanding the potential long-run gains from disease eradication can shape future policy debates. In particular, my research can inform policymakers as to the value of attaining herd immunity, and ultimately eradication, for measles. Additionally, this paper contributes to the broader literature that investigates the long-run impacts on childhood health shocks and/or interventions.[1]

I. Measles Background: The Disease, the Vaccine, and Health Impacts

A. *Measles—The Disease*

Measles is a highly contagious virus transmitted through the air primarily by infected individuals coughing and sneezing. Measles is caused by a paramyxovirus and has an incubation period ranging from 7 to 23 days from exposure to symptom onset (Griffin 2013). Initial symptoms of infection are fever, runny nose, cough, red eyes, and sore throat, followed by a rash that spreads over the body, and in rare cases, death (Fitzgerald et al. 2012; Griffin 2013; Robbins 1962). Prior to the availability of a vaccine, there was no method of measles prevention: individuals were exposed, developed measles, and the virus ran its course (Conis 2019). Annual morbidity of measles in the US from 1912 to 1959 remained steady (Langmuir et al. 1962). In the decade before the vaccine was introduced, the death rate for measles was 0.1 percent in the United States[2] (Barkin 1975; Langmuir 1962; Wharton 2004).

Patients are typically contagious the four days preceding the rash and for the first four days after the rash's appearance (Griffin 2013; Robbins 1962). Because patients are typically infected by coming in contact with someone in the pre-rash stage of measles, the source of transmission is hard to identify and there is the opportunity for widespread infection of measles before the spreader develops the identifying measles rash. Medical advice for someone who contracts measles is to stay at home for at least four days after the rash appears and to rest.[3,4] Individuals with uncomplicated measles cases typically start to improve three days after the rash's appearance and fully recover in seven to ten days after the first appearance of the rash (Perry and Halsey 2004). Upon recovery from measles, lifelong immunity to the measles virus is obtained (Fox 1983).

Without an available vaccine, 50 percent of all children will have contracted the measles by age 6 and 95 percent by age 16 (Perry and Halsey 2004; Langmuir 1962; Strebel et al. 2018; Miller 1964). Additionally, adults born prior to 1957 are assumed to have contracted and had the measles.[5] Table 1, using the National Health Examination Survey (NHES) II and III, shows comparable values for the percent of the population having contracted measles by age 12 and 17, prior to the development of the vaccine (NHES 1963, 1966). In addition, the values in Table 1 illustrate that

[1] For example, Bhalotra and Venkataramani (2013); Case, Fertig, and Paxson (2005); Case and Paxson (2009); Almond (2006); Currie and Moretti (2007); Bleakley (2007; 2010b; 2010a); Cutler et al. (2010); Lucas (2010); Venkataramani (2012); Bhalotra and Venkataramani (2015); Almond and Currie (2011a, 2011b).

[2] Author calculations using NCHS—Vital Statistics of the United States: 1939–1964.

[3] National Health Service, England. https://www.nhs.uk/conditions/measles/treatment/.

[4] National Foundation for Infectious Diseases, USA. https://www.nfid.org/infectious-diseases/measles/.

[5] According to the CDC, all adults born in 1957 or later who have not been vaccinated or have not had measles should be vaccinated, but those born prior to 1957 do not. https://www.nfid.org/infectious-diseases/measles/.

Table 1—Measles Facts

	Yes	No	p-value	Years
NHES II—Native born school aged (6–12)				1963–1965
Measles	86.4%	13.6%		
Observations	5,708	899		
Black	13.6%	12.3%	0.295	
Female	49.1%	47.6%	0.387	
NHES III—Native born and school aged (12–17)				1966–1970
Measles	92.8%	7.3%		
Observations	5,665	443		
Black	14.0%	16.0%	0.230	
Female	47.5%	47.9%	0.891	
NHANES I—Native born and aged (1–5)				1971–1974
Measles vaccine	79.0%	21.0%		
Observations	2,070	550		
Black	24.0%	27.8%	0.066	
Female	49.7%	48.2%	0.524	
	Mean	SD		1952–1963
Measles prevaccine incidence rate average over 12 years (per 100,000)	964	591		
State-level measles vaccination rates	0.797	0.144		

Notes: The table includes data on only native-born children. State of birth is needed to understand their pre-vaccination exposure to measles. Four sources of data are included in the table. NHES II is from the years 1963 to 1965 and surveys children 6–12 years old. NHES III is from the years 1966 to 1970 and surveys children aged 12–17. All of the children included in the NHES II and NHES III were born before the measles vaccine was available and show rates consistent with expected levels of having contracted the measles: 50 percent by the age of 6 and 95 percent by the age of 16. The rows for Black and female indicate the fraction that group represents in either measles category. The associated p-value tests if there are differences between the contraction of measles or measles vaccination for Blacks versus Whites or females versus males. NHANES I is from years 1971 to 1974 for children aged 1–5 and were born after the introduction of the measles vaccine. The measles prevaccine incidence rate average for the 12 years prior to the measles vaccine is calculated using the MMWR for yearly state counts of measles cases and using the state population for those under the age of 18 to calculate the rate.

measles incidence does not differ across subgroups: measles is not associated with race or gender.

Measles is ubiquitous throughout the world and has both a global epidemic cycle and a local seasonal cycle. Prior to vaccine development, the world experienced major epidemic outbreaks of measles every two to three years. The local seasonal cycle of when measles cases peak is dependent upon climate, with incidence peaking late winter/early spring in temperate zones and during the dry season in tropical zones (Sencer, Dull, and Langmuir 1967; WHO 2017).

The most important factor for measles transmission is the density of the susceptible population. The susceptible population for measles is defined as those who do not have measles antibodies. Babies born to mothers with measles antibodies are protected for the first nine months of their lives through maternal antibodies. Therefore, individuals are at an increased risk to measles in settings where susceptible children—the segment of the population least likely to have measles antibodies—congregate, such as schools (Rota et al. 2016; Miller 1964; Fox 1983).

Schools are the primary site of measles transmission in the United States. From 1960 to 1964, 60 percent of measles cases were in school-aged children (MMWR 1977). The age distribution of measles cases holds in the time period immediately following approval of the vaccine and continues to hold decades after vaccine availability (Hinman et al. 1983; Rota et al. 2016). Explosive outbreaks immediately follow exposure to a contagious individual in the classroom. It is from these infected school-aged children that measles is brought home and infects their preschool-aged siblings (Sencer, Dull, and Langmuir 1967). Thus, illustrating incidence is a function of the proportion of the population that is susceptible.

Hedrich documented this relationship between the monthly susceptible population and measles cases from 1897 to 1927 in Baltimore, MD. The measles incidence in Baltimore fluctuated greatly over this time, coinciding with the two- to three-year cyclical nature of measles epidemics; however, there was very little fluctuation in the relationship between the susceptible and immune population (Hedrich 1930). Fine and Clarkson document the transmission pattern of measles cases in England and Wales, finding the measles transmission parameter peaks at three points during the year that coincide with the beginning of school terms and that the transmission parameter bottoms with term end and school holidays (Fine and Clarkson 1982). This reinforces Hedrich's findings in Baltimore that it is exposure to measles by a susceptible population that results in cases.

B. *Measles—The Vaccine*

The US Food and Drug Administration approved the measles vaccine in 1963. Prior to the measles vaccine, there was no medical prevention for the virus. In the United States, take-up of the vaccine occurred quickly and was universal. Table 1, using data from the National Health and Nutrition Examination Survey I (NHANES 1971), shows that 79 percent of children born between 1966 and 1973 had been vaccinated; take-up was not dependent on race or gender. Across all states take-up was high, with a mean state-level take-up rate of 0.8 and a standard deviation of 0.14.

There was a confluence of factors that led to rapid and universal uptake of the measles vaccine in the United States. First, there was a mass coordinated public media campaign for the launch of the vaccine. The US Public Health Service wanted a lot of publicity for the measles vaccine to educate the public about the risks of measles and the importance of getting vaccinated, as measles was regarded as trivial and a basic childhood disease (Conis 2019). This desire led to a highly publicized launch for the measles vaccine. The TV network CBS with the help of the Office of the Surgeon General produced the broadcast "The Taming of a Virus," which discussed the development of the two new measles vaccines and the toll of measles in West Africa. The broadcast aired the Sunday before the measles vaccine was licensed as part of the mass media campaign. Other aspects of the campaign included nightly news broadcasts, medical journals, front-page newspaper headlines, and CDC experts all hyping the vaccine and the goal of wiping out measles in the country (Conis 2019). For example, the front-page headline in the *New York Times* on March 21, 1963, read "2 Measles Vaccines Licensed; US sees End of Disease in 1965"[6].

[6] *New York Times*. 1963. "2 Measles Vaccines Licensed; U.S. Sees End of Disease in 1965; U.S. Authorizes 2 Measles Drugs—Vaccine Actions Differ." March 22, 1.

Second, the United States had been successful in fighting polio with mass vaccination efforts, and as a result, President Kennedy signed into law the Vaccination Act of 1962 (Pub L No 87-8688).[7] This was the first federal law that provided funds to states for immunization efforts—and these immunization efforts also were primarily targeted toward children. The program was then extended by President Johnson in 1965 (Pub L No 89-109),[8] making measles the first disease to have a federally supported eradication-through-vaccination campaign (Conis 2019). This Act coupled with the legislation of President Johnson's Great Society increased access to the measles vaccine. During 1967, between 7 and 8 million doses of measles vaccine were estimated to have been administered. Of these, 60 percent were purchased through federal project grants (Dull and Witte 1968). Further evidence of federal support is illustrated by President Johnson's endorsement of the CDC's elimination plan in 1967 (Conis 2019).

Third, school immunization laws played a role in the rapid uptake of the vaccine. School immunization laws require proof of antibodies for either enrollment or attendance in school. There is a long history of these laws in the United States. A smallpox vaccination compulsory law first appeared in 1809 in Massachusetts, which was soon followed by other states. At the time of the measles vaccine introduction, many states already had school immunization laws in place,[9] and these laws were amended to include measles when the vaccine became available (Jackson 1969).[10]

C. *Measles—The Health Impact*

The introduction of the measles vaccine created two effects: (1) a reduction in measles incidence and (2) a reduction in morbidity and mortality from other pathogens. The reduction in measles incidence was substantial, as illustrated by Figures 1 and 2. Figure 1 depicts how the national incidence fell from around 400,000 cases a year to almost 0 immediately following the vaccine's introduction to the market.[11] Figure 1 also shows a corresponding decrease in morbidity from other childhood infectious diseases.[12] Figure 2 plots the measles incidence rate in 1962 per 100,000 individuals against the change in incidence rate per 100,000 between 1962 and

[7] Vaccination Assistance Act. Pub L No 87-8688, 76 Stat (1962).

[8] Community Health Services and Facilities Act. Pub L. No 89-109 (1965).

[9] Twenty-six states and the District of Columbia had statewide laws for requiring immunization for a specific disease or diseases in 1968.

[10] Seventeen states amended immunization laws to include measles by 1968: Arkansas, California, Georgia, Hawaii, Illinois, Kansas, Kentucky, Louisiana, Massachusetts, Michigan, Minnesota, Mississippi, New Jersey, New York, Rhode Island, Tennessee, and West Virginia.

[11] To be included in the CDC incidence count for measles both pre– and post–vaccine availability, a patient must seek health care, the provider must diagnose the patient with measles, and the case must be reported to the health department. It is well documented that there was severe underreporting of measles in the prevaccine era. Given susceptible population levels in the decade preceding the vaccine, about 4 million cases would be expected annually. The consistent level of 400,000 reported cases a year represents 10 percent of cases. Prior to vaccine availability, health care–seeking behavior and reporting was consistently low due to the belief that measles was a universal childhood disease and there were no treatment or prevention options available (Harpaz 2004; Haward 1973; Hinman et al. 1980).

[12] Childhood infectious diseases in the figure include rubella, mumps, chicken pox, and pertussis. The case counts are from the Morbidity and Mortality Weekly Reports Annual Supplement. In 1964, there was a major epidemic of rubella in the United States, resulting in the largest epidemic for rubella since 1935, which accounts for the spike in the infectious disease category.

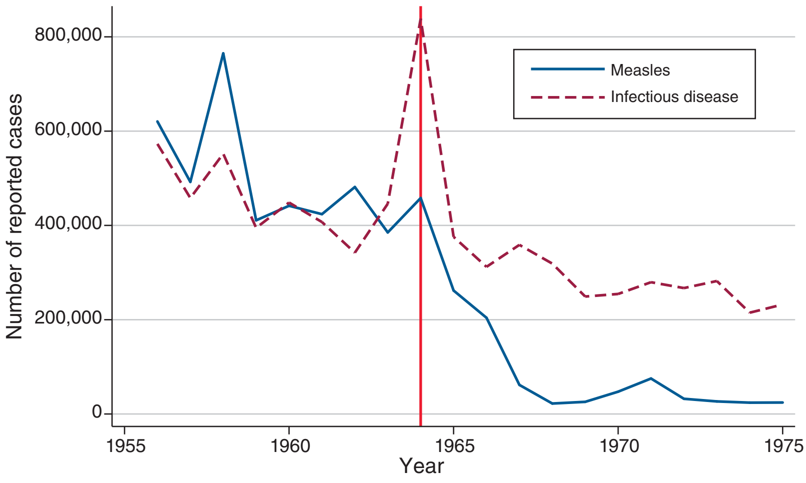

FIGURE 1. MEASLES AND OTHER INFECTIOUS DISEASE INCIDENCE COUNTS OVER TIME

Notes: Infectious disease category includes chicken pox, mumps, rubella, and pertussis. The lines show the national incidence rate for each category in a given year. The vertical line denotes 1964, the year after the measles vaccine was approved by the FDA and introduced in the United States. There is a sharp reduction in the measles incidence rate immediately following the vaccine's introduction and a lagged decline in the incidence rate of other infectious diseases. In 1964, there was a major epidemic of rubella in the United States, resulting in the largest epidemic for rubella since 1935, which accounts for the spike in the infectious disease category.

Source: Data are from the CDC's Morbidity and Mortality Weekly Reports.

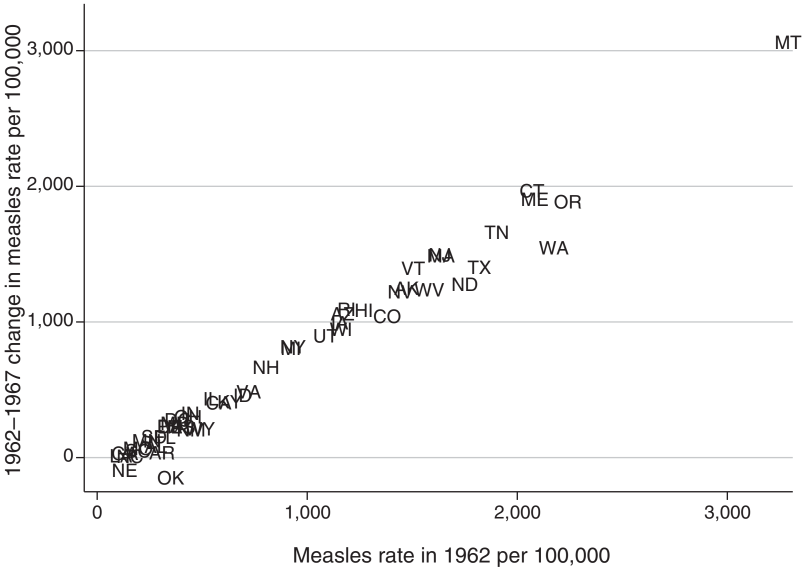

FIGURE 2. MEASLES INCIDENCE RATE PREVACCINE VERSUS THE CHANGE IN MEASLES INCIDENCE RATE PRE- AND POSTVACCINE

Notes: The horizontal axis represents measles incidence rate in 1962 per 100,000 individuals in a given state. This is plotted against the change in incidence rate per 100,000 for a given state between 1962 and 1967. The plot approximates a 45-degree line, indicating that measles was virtually eliminated after the introduction of the vaccine. Individual states have been indicated by their abbreviation.

Source: Data are from the CDC's Morbidity and Mortality Weekly Reports.

1967. The plot approximates a 45-degree line, indicating that measles was virtually eliminated after the introduction of the vaccine. Due to the striking reductions in child morbidity and mortality after the introduction of the vaccine (Moss and Griffin 2012; Simons et al. 2012), the measles vaccine has been recognized as one of the most successful public health interventions of all time (Perry et al. 2014).

Significantly, the observed reductions in morbidity and mortality are larger than primary measles prevention would suggest (Aaby et al. 1984; Aaby et al. 2003; Flanagan et al. 2013). Following measles virus infections, individuals experience profound immunosuppression, which increases their susceptibility to other pathogens (de Vries et al. 2012). Measles immune suppression was generally assumed to be transient, meaning postmeasles an individual's immune system will restock itself in the next few weeks to months using its immune memory cells (Karp et al. 1996; Hahm 2009; Schneider-Schaulies and Schneider-Schaulies 2009; de Vries et al. 2012). Therefore, it was expected that the introduction of the measles vaccine would result in only a contemporaneous decrease in nonmeasles mortality and morbidity.

However, reductions in infectious disease mortality after the introduction of the measles vaccine have been hypothesized to last longer, and there is evidence that improved immunity lasts for as much as five years (Koenig et al. 1990; Clemens et al. 1988; Desgrées du Loû, Pison, and Aaby 1995; Holt et al. 1990; Kabir et al. 2003; Mina et al. 2015; Schneider-Schaulies and Schneider-Schaulies 2009; de Vries et al. 2012). Recent studies have proposed "immune amnesia" to nonmeasles pathogens, meaning that when an individual contracts the measles virus, their immune system loses previously acquired immune memory cells, as the mechanism for increased morbidity and mortality from other infectious diseases in the absence of a measles vaccine. The process of reacquiring these immunities is prolonged; as a result, contracting measles results in prolonged susceptibility to other infectious diseases (de Vries et al. 2012; de Vries and de Swart 2014; Mina et al. 2015; Pirquet 1908; Pierson and Yewdell 2012; Lin et al. 2012).

Depression of the immune system is the natural response to any infection. After an infection passes, immune memory cells restock the immune system to provide future resistance to pathogens that were previously experienced and, therefore, for which an individual had previously developed antibodies. This process typically takes a few weeks to a few months (Perry et al. 2014; de Vries and de Swart 2014; Schneider-Schaulies and Schneider-Schaulies 2009). Although scientists have found that post–measles virus infection the body restocked memory cells within weeks, only measles-specific lymphocytes returned, leaving the body vulnerable to nonmeasles pathogens. Long-run measles-related immunosuppression was documented as early as 1908, with individuals showing negative tuberculin reaction after testing positive for them prior to having measles (Pirquet 1908). The body must reacquire immunity through contact with antigens, making an individual more susceptible to contracting other infectious diseases during this restocking period (Lin et al. 2012; Perry and Halsey 2004; de Vries et al. 2012; Selin et al. 1996; Peacock, Kim, and Welsh 2003; Griffin 2010; Kim and Welsh 2004; Kim et al. 2002).

Mina et al. (2015) showed nonmeasles infectious disease mortality is correlated with measles incidence over a two- to three-year lag period in developed countries. Another study using cohort analysis demonstrated that children up to five years post–measles infection were prescribed antimicrobial therapies at an increased rate due to more diagnosed infections attributed to measles-related immunosuppression (Gadroen et al. 2018). Two new studies provide evidence of "immune amnesia" using blood samples from children in the Netherlands who were unvaccinated for religious reasons. One study compares antibody samples from before and after a child contracts measles and finds 11 to 73 percent of the antibody repertoire is wiped out by the measles and antibody recovery only occurred after natural reexposure to the pathogens (Mina et al. 2019). The other study finds that previously formed memory cells (which had been formed to fight specific diseases) went missing after a child contracted measles. Thus, the immune system postmeasles is immunologically immature (Petrova et al. 2019).

A compromised immune system during childhood, as a result of measles, has the potential to adversely affect health and human capital development over the long run. For example, there is an extensive literature hypothesizing an association between infection in early life and its impacts in later life on height (Waaler 1984; Crimmins and Finch 2006), organ damage (Barker 2004; Fogel 2004), and adult mortality (Kermack, McKendrick, and Mckinlay 1934; Bengtsson and Lindström 2003; Costa 2000; Fridlizius 1989; Crimmins and Finch 2006). These later-life impacts from early childhood infection are attributed to a lifelong increase in chronic inflammation (Finch and Crimmins 2004; Crimmins and Finch 2006). Given an individual is more susceptible to disease for years after their measles infection as they are reexposed to pathogens and gradually rebuild their immunity back up to its premeasles level, those who do not contract measles will have healthier childhoods and in turn higher levels of earnings and employment in adulthood than those who did have measles.

III. Data

To estimate the effects of the measles vaccine introduction, I combine several data sources that contain information on infectious disease incidence and labor market outcomes.

A. *Infectious Diseases*

I construct annual state-level incidence rates for the population under the age of 18 using (i) population estimates from Current Population Reports (SEER 2019; CPS 1952–1968) and (ii) state-level case counts for nationally notifiable diseases published in the CDC's Morbidity and Mortality Weekly Reports Annual Supplement (MMWR) (CDC 1952–1975).[13] The MMWR begins in 1952. For the period of 1952 to 1975, childhood infectious diseases—measles, mumps, rubella, pertussis, and

[13] The incidence data are less well measured than the mortality data. There are numerous reports confirming the underreporting of childhood infectious diseases, specifically measles. However, there is no evidence that reporting changes over time within a state that is different from how reporting changes over time for the nation, so by including both state fixed effects and year fixed effects in my empirical models, I am able to control for underreporting and its variation by state.

chicken pox[14]—are reported, allowing me to collect case counts both pre– and post–measles vaccine availability. All five are common childhood diseases, and there is no treatment for any of them once contracted. The vaccines for mumps and rubella were licensed after the measles vaccine (1963) in 1967 and 1969, respectively. The three vaccines were then bundled into the MMR, which was licensed for use in 1971. The chicken pox vaccine was licensed in 1995 in the US and then combined with the MMR in 2005 to create the MMRV. The whole-cell pertussis vaccine was first licensed in 1914 and then combined with diphtheria and tetanus toxoids (as DTP) in 1948. However, for efficacy to be achieved with the DTP vaccine, a series of four doses was required, and protection decreased with time, resulting in little to no protection five to ten years following the last dose. The modern acellular pertussis vaccine contained in the DTaP vaccine was licensed in 1996.[15]

B. *Labor Market and Income Outcomes*

This paper focuses on labor market outcomes, specifically whether or not an individual is employed, their hours worked, whether they are below the poverty line, and income. I use IPUMS microeconomic data from the American Community Survey (ACS) for the years 2000–2017 for individuals aged 25 to 60 at the time of survey (Ruggles et al. 2021). I limit the sample to those born in the United States. I use the ACS because I need an individual's state of birth to assign their childhood measles incidence rate exposure rather than current state of residence. Matching individuals with measles incidence rates from the area where they currently reside as an adult instead of where they were children would make results difficult to interpret due to select migration. By assigning state of birth measles incidence rate to individuals, I am more accurately capturing their childhood exposure.[16] I include both males and females in my analysis, as both genders are equally susceptible to measles and its "immune amnesia" effects as well as the fact that female participation in the labor force is more robust over the time period of my study compared to other long-run human capital accumulation studies of other conditions in the United States.

IV. Empirical Strategy: Difference-in-Differences Using Childhood Exposure to Measles

The research design exploits the exogenous change in the measles incidence rate that resulted from the introduction of the measles vaccine. I use childhood exposure to measles in a difference-in-difference model that compares individual-level adult

[14] Mumps, rubella, chicken pox, and pertussis are used in the analysis for two main reasons: (i) they are childhood diseases whose vaccines status was unchanged or not available at the time the measles vaccine was introduced, and (ii) they are reportable diseases, so there are data available at the state year level for the time frame of interest. Ideally, I would be able to use other common childhood illnesses like ear infections, strep throat, or the flu. However, data for these types of illnesses are not collected or reported at the state-year-age level during the time period of interest.

[15] https://www.cdc.gov/vaccines/vpd/pertussis/index.html.

[16] Author calculations from the 1960 and 1970 census show that 83 percent of 0- to 16-year-olds reside in their state of birth, compared to 62 percent of adults when calculated using the 2000 census and 2012 and 2017 5-year ACS for 25- to 60-year-olds.

employment outcomes and earnings before and after the measles vaccine was available between states with higher and lower prevaccine measles incidence rates, measured by the average 12-year prevaccination infection rate for children per 100,000 in an individual's state of birth. The primary identifying assumption of this design is that in the absence of the measles vaccine, labor market outcomes would have evolved similarly in higher- and lower-measles-incidence-rate states. This is likely to hold for two main reasons.

First, as discussed in the background section, there is no treatment for measles. Once contracted, the virus must run its course, and all those who contract measles suffer "immune amnesia"—a depressed immune system for the next three to five years—making everyone who contracts measles less healthy for a prolonged period of time. Measles has a low death rate, and, in the decade preceding the vaccine, in the US the death rate remained constant at 1 per 1,000 (Barkin 1975; Langmuir 1962; Wharton 2004).[17] It is also of note that the current-era death rate for measles in the United States is 0.2 percent,[18] meaning that when the measles vaccine became available, it prevented measles infection and the likelihood of infection from other diseases, not death from measles.

Second, measles is a universal childhood disease. In the absence of a vaccine, 50 percent of the population will have contracted measles by the age of 6, and 95 percent of the population will have contracted measles by the age of 16. Susceptible population density is a contributing factor to measles incidence rate. To illustrate this relationship, I estimate a state-level regression of the prevaccine measles rate on a proxy for the susceptible population density in a state.[19] Ideally, I would be able to test this relationship with data that are smaller in geographic area than the state level and use susceptible population density rather than age group population density.[20] The national data available are at the state-year level and do not report measles cases by age at a level smaller than the national level. Therefore, I proxy for susceptible population density using the population of a state divided by the state's area in square miles. I aggregate up to the state level for the regressions because measles epidemics occur in a two- to three-year cycle, meaning that previous measles outbreaks influence the current year susceptible population.

The estimates are positive, precisely estimated, and are larger for the age ranges of the population that are more likely to be susceptible to measles infection, thus supporting the association between higher population density and higher incidence rates. Because this is a crude proxy for the susceptible population density, the R^2 values are low. Other factors like how people gather, busing for K–12 schools, and how

[17] CDC reports there were approximately 500 deaths for 500,000 reported measles cases before 1963, which yields a death rate of 0.001 or 1 in 1,000. https://www.cdc.gov/vaccines/pubs/pinkbook/meas.html#secular.

[18] https://www.cdc.gov/vaccines/pubs/pinkbook/meas.html and https://www.nfid.org/infectious-diseases/measles/.

[19] I aggregate up to the state level and capture the state's mean measles incidence rate and mean population density. I regress measles rates for the states on the population density of the states. I weight the regression by state population. Years 1953–1962 are included. The regression estimates are included in online Appendix Table 1.

[20] Previous work isolating the relationship between the susceptible population and measles incidence rates focused on small geographic areas, had monthly incidence counts by age, monthly birth counts, and monthly death counts by age (Hedrich 1930). Using these data for Baltimore from 1897 to 1927, Hedrich established that case counts for measles fluctuate with the susceptible (those who have never had the measles) population level in a community and that outbreaks are more likely in areas with higher susceptible population density.

closely people live together contribute to the variation in measles incidence across states prior to the vaccine and impact the susceptible population density. Measles is one of the most contagious diseases, so contagious that if infected, 90 percent of the individual's close contacts will become infected. Additionally, infected individuals spread measles before they exhibit symptoms, and a single cough or sneeze by someone infected with measles can live in the air space and infect others up to two hours later, making contact tracing extremely challenging.[21] The proxy I am able to derive for susceptible population density illustrates the relationship between those potentially susceptible and the measles incidence rate; but, due to the contagious nature of measles and the available data, there are unmeasurable factors that contribute to variation in incidence in states prior to the vaccine.

To test these primary identifying assumptions, I conduct the following event study analysis to present evidence that the parallel trends assumptions holds (Goodman-Bacon 2018). I begin with the standard event study model for state s in which pre/post treatment is defined by indicator variables that measure the time relative to measles vaccine availability and treatment/control groups are defined by the continuous value of the unweighted average 12-year prevaccine measles incidence rates, M^{pre}:

$$(1) \qquad Y_{ts} = M^{pre}_{1952-1963_s}\left[\sum_{y=-6}^{-2} \alpha_y \mathbf{1}\left\{t - t^* = y\right\} + \sum_{y=0}^{11} \lambda_y \mathbf{1}\left\{t - t^* = y\right\}\right] + \delta_s + \gamma_t + \theta X_{ts} + \varepsilon_{ts}.$$

The time period covered here is from 1958 to 1975. I include state fixed effects, which control for time-invariant state-level characteristics such as climate and unchanging public health infrastructure, and set the reference period to the year before the measles vaccine is available. The time-varying state-specific susceptible population is included as a covariate, and the standard errors are clustered at the state level.

The coefficients of interest, α_y and λ_y, measure the (covariate adjusted) relationship between the incidence rate of a disease and the unweighted average 12-year prevaccine measles incidence rate in the 6 years leading up to the introduction of the measles vaccine and the 11 years after. The indicator for the year the vaccine was licensed is omitted, which normalizes the estimates of α_y and λ_y to zero in that event year. The α_y are falsification tests that capture the relationship between initial categorical eligibility and outcomes before the measles vaccine existed. Their pattern and statistical significance are a direct test of the common trends assumption. The λ_y are intention-to-treat (ITT) effects of an additional 1 per 100,000 rate increase in the prevaccine measles rate on the postvaccine incidence rate of a disease. The estimates will equal zero if the measles vaccine affected morbidity equally across all states. If the pre–measles vaccine incidence rate is completely eliminated across states as suggested by Figure 2, then the estimates will equal negative one.

[21] https://www.cdc.gov/measles/transmission.html.

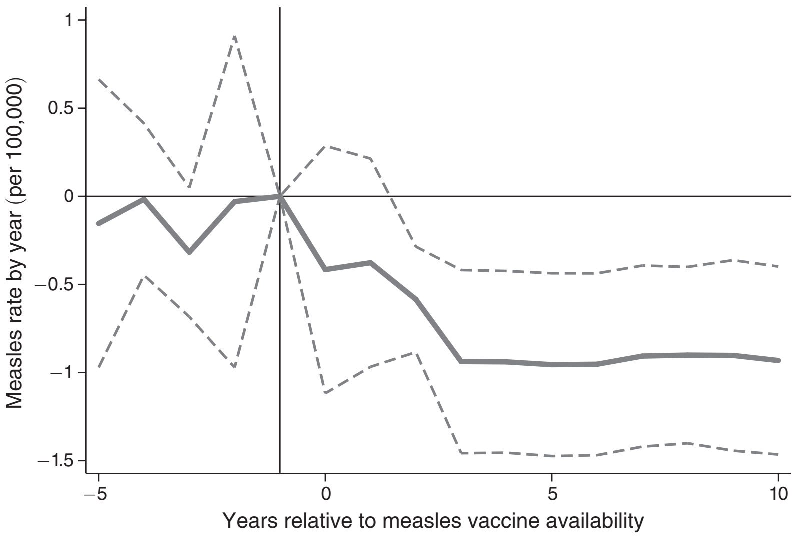

Figure 3. Event Study—Effect of Measles Vaccine on Measles Incidence

Notes: The figure shows regression-adjusted estimates of the measles vaccine's intention-to-treat effect on measles incidence. The dependent variable is the number of measles cases by year for a state per 100,000 of the population. The solid line plots the estimated coefficients on interactions between the time to measles vaccine dummies and the average 12-year pre–measles vaccine measles incidence from the regression model described in Section IV. The year the measles vaccine became available is omitted, so estimates are normalized to zero in that year. The model includes state fixed effects and controls for the susceptible population. The dashed lines are pointwise 95 percent confidence intervals based on standard errors clustered at the state level.

I start by illustrating that the incidence of measles was impacted by the arrival of the measles vaccine. Figure 3 plots the α_y and $\lambda_y$estimates of equation (1). This provides evidence that the common trends assumption holds, as there is no statistical difference in the pre-period for states' measles incidence rates. However, after the measles vaccine becomes available in 1963, as illustrated by the vertical line in the figure, there is a sharp and immediate decrease in the measles incidence rate. This decrease flattens four years after the measles vaccine is introduced, with a coefficient of negative one. The coefficient of negative one indicates a one-for-one negative effect of prevaccine incidence on subsequent measles cases. This decrease also indicates that states with larger incidence rates in the pre-period received a greater benefit from the measles vaccine than those in lower-incidence states.

The measles vaccine success story is not only in its prevention of measles but its prolonged protective effect for children from contracting other diseases. The primary mechanism through which measles vaccine availability should affect adult earnings and employment is by improving childhood health. Therefore, states with larger incidence rates in the prevaccine period received a greater benefit from the measles vaccine than those in lower-incidence states.

Using equation (1), I estimate the impact of the measles vaccine on other childhood infectious diseases. Figure 4 contains four panels; each panel presents the coefficients for the interaction terms, α_y and λ_y, from a separate regression for each

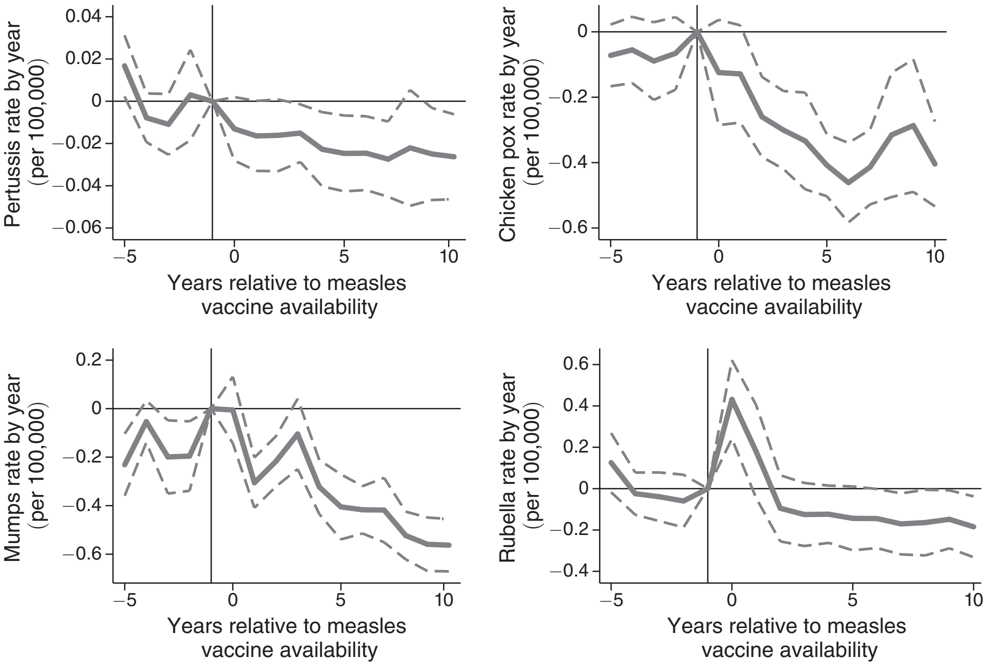

Figure 4. Event Study—Effect of Measles Vaccine on Infectious Disease Incidence

Notes: Each panel plots the regression-adjusted estimates of the measles vaccine's intention-to-treat effect on other childhood infectious disease incidence. Childhood infectious diseases that were reported to the CDC during the time period of interest include pertussis, chicken pox, mumps, and rubella. The dependent variable is the number of cases by year for a state per 100,000 population for childhood infectious diseases, as indicated in each panel. The solid line plots the estimated coefficients on interactions between the time to measles vaccine dummies and the average 12-year pre–measles vaccine measles incidence from the regression model described in Section IV. The year the measles vaccine became available is omitted, so estimates are normalized to zero in that year. The model includes state fixed effects, year fixed effects, and controls for the susceptible population. The data have been winsorized at 1 percent at each tail of the distribution. The dashed lines are pointwise 95 percent confidence intervals based on standard errors clustered at the state level. In 1964, there was a major epidemic of rubella in the United States resulting in the largest epidemic for rubella since 1935, which accounts for the spike in the infectious disease category.

of the four childhood diseases: pertussis, chicken pox, mumps, and rubella.[22] The lack of pre-trends in all four outcomes supports the common trends assumption needed for the difference-in-difference strategy to produce causal estimates. The top left panel presents the estimates for pertussis. The estimates decrease the first year the vaccine is available and show a statistically significant decrease in 1965, the second full year the measles vaccine is on the market. This decrease remains constant and persists through 1975. As with measles, chicken pox, mumps, and rubella, there is no treatment for pertussis, and it is only preventable via vaccine (which was licensed as a stand-alone vaccine in 1914 and as part of DTP in 1948; the modern DTaP vaccine was not licensed until 1996).[23] This presents additional evidence that

[22] The data for Figure 4 have been winsorized at the 1 percent tail of each distribution for the outcome variables pertussis, chicken pox, mumps, and rubella.

[23] https://www.cdc.gov/vaccines/vpd/pertussis/index.html.

the measles vaccine provided additional protective benefits to those vaccinated from losing immunity to viruses they had been inoculated against previously. The top right panel of Figure 4 presents the event study for chicken pox. There is a sharp statistically significant decrease immediately following the licensing of the measles vaccine that persists over time. At no time during the analysis period was a vaccine for chicken pox available (licensed in the United States in 1995). The bottom left panel of Figure 4 uses mumps as the outcome of interest. Again, there is an immediate decrease in cases after the measles vaccine becomes available, which predates the licensing of the mumps vaccine in 1967, and the effect persists over time. Finally, the bottom right panel of Figure 4 shows the impact of the measles vaccine on rubella. In 1964, there was a major epidemic of rubella in the United States, resulting in the largest epidemic for rubella since 1935, which accounts for the spike. The coefficients are not statistically different than zero post-epidemic until 1971, where they show a decrease in rubella. The rubella vaccine was licensed in the United States in 1969, and the combined vaccine for measles mumps and rubella (MMR) was licensed in 1971.

I now move on to the main model of the paper, to identify the long-run effects of the measles vaccine on labor market outcomes. A standard difference-in-difference specification effectively assumes that the measles vaccine effect is limited to the year of birth. Since individuals contract measles at different ages during childhood (with the majority of incidence recorded for children aged five to nine), my preferred specification allows for differential exposure to the measles vaccine. Following Bleakley 2007, I compare both across states, where variation is due to different prevaccine incidence rates, and across cohorts, with variation coming from different levels of exposure to the vaccine because of an individual's age at vaccine introduction using the specification

$$Y_{isct} = \beta\left(M^{pre}_{1952-1963} * Exposure\,to\,Vaccine\right)_{sc} + \delta_s + \gamma_c + \alpha_t + \theta X_{isct} + \varepsilon_{isct}, \tag{2}$$

where M^{pre} is the unweighted average 12-year prevaccination infection rate for children per 100,000 in an individual's state of birth.[24] As illustrated in Figure 2, the average incidence rate is equivalent to the change in incident rate, as measles infection drops to zero after the introduction of the vaccine, so using either the average incidence before or the change due to the vaccine will yield the same results. I match adult individuals to the prevaccine measles incidence rate of their state of birth.[25]

For cross-cohort comparisons, I use variation in the number of years exposed to the vaccine interacted with the unweighted 12-year average incidence rate of measles in a state prevaccine. Exposure to the vaccine is 0 for the older cohorts and rises linearly for children born in the 16 years prior to 1963 and is 16 for children born

[24] Online Appendix Table 2 presents the estimates for equation (2) using different numbers of years in M^{pre}.

[25] This assumption is important when looking at later life outcomes since migration is more likely over the longer term; only 60 percent of the sample reside as adults in the state of their birth.

after 1963. I use 16 as the maximum period of exposure because incidence rates of measles after age 16 are negligible.

X_{isct} are individual-level controls including indicators for race and gender; indicators for the interaction of age, race, and gender; as well as state of birth indicators interacted with race, gender, and race and gender. δ_s are state-of-birth fixed effects, which control for time-invariant state characteristics that can include climate and/or public health setup and infrastructure. γ_c are year-of-birth fixed effects that control for characteristics consistent across the birth year cohort. α_t are survey year fixed effects that control for national characteristics of the labor market in a given year. Standard errors are clustered at the state-of-birth by year-of-birth level.[26]

Equation (2) relies on two sources of variation. First, it relies on the differential exposure of cohorts to the timing of the vaccine's introduction. Second, as illustrated by Figures 1 and 2, states with higher prevaccine measles incidence benefited more from the introduction of the vaccine than states with lower levels of prevaccine measles incidence rates. Therefore, β provides the reduced-form estimate for the differences in gains based on prevaccine measles rates in outcome Y_{isct} for person i, born in state s, in cohort c, at year t. If measles adversely affects employment and earnings outcomes, then cohorts with more exposure to the vaccine in states with greater prevaccine measles incidence rates should have higher employment and earnings than those with less exposure to the vaccine in the same states.

V. Reduced-Form Estimates of the Measles Vaccine on Labor Market Outcomes

Table 2 presents evidence of the positive effect of the measles vaccine on adult earnings and employment. The estimates of equation (2) for the outcome variables appear in the top row of Table 2. The table also includes the outcome mean for the prevaccine cohorts (born prior to 1949), the unweighted average 12-year measles prevaccine incidence rate (0.00964), and the calculated impact of the coefficient for being born in a state with the average prevaccine measles incidence rate and full exposure (16 years) to the vaccine.

The measles vaccine has a positive and significant effect on earnings. I measure earnings three ways and find consistent impacts for the three measures. Column 1 uses income as the outcome variable and returns a coefficient of $2,901. Based on this point estimate, a reduction of the measles rate from 964 per 100,000 to 0 per 100,000 (equivalent to the average measles incidence reduction after the vaccine becomes available) and a full lifetime of exposure (16 years) would lead to an increase in income of $447. The average income for the prevaccine (exposure equals 0) cohorts is $40,971, and $447 represents a 1.1 percent increase to the prevaccine cohorts mean. In the United States, income increased from $42,088 (for those born between 1947 and 1948) to $48,358 (for those born between 1963 and 1964).[27] Thus, the measles vaccine roughly accounts for 7.1 percent of the increase in income

[26] Online Appendix Table 3 clusters the standard errors on different levels. If standard errors were clustered at the state of birth level, then individuals born in 1949 and 1975 would be clustered together. Therefore, my preferred model clusters standard errors on state of birth and year of birth.

[27] Using the 1963 and 1964 cohorts as the post group has the advantage that they experienced a lifetime of exposure to the measles vaccine and were born and able to be vaccinated before Medicaid was enacted.

Table 2—Effects on Adult Labor Market Outcomes

	Income (1)	Income (if > 0) (2)	ln Income (3)	Poverty (4)	Employed (5)	Hours worked (6)
$M^{pre}_{1952-1963}$ * *Exposure to Vaccine*	2,901	4,681	0.1101	−0.0326	0.0186	−1.2511
	(864)	(1,202)	(0.0233)	(0.0040)	(0.0032)	(0.3769)
R^2	0.0726	0.0880	0.0908	0.0301	0.0128	0.0827
Observations	15,710,435	12,126,516	12,126,516	15,429,840	12,593,724	15,710,435
Outcome mean for the prevaccine cohorts	$40,971	$60,538	10.5789	0.0688	0.9607	30.132
Average 12-year measles prevaccine incidence rate	0.00964 (964 incidences per 100,000)					
Impact to outcome of being born in a state with average prevaccine measles incidence rate and full exposure (16 years) to the vaccine	$447	$722	1.698%	−0.503 percentage points	0.287 percentage points	−0.193 hours

Notes: The table shows regression-adjusted estimates for the impact of the measles vaccine on adult labor market outcomes. Each column represents a separate outcome as listed in the column heading. The top two rows present the coefficient of interest from equation (2) and its standard error. A separate regression is run for each outcome variable. As described in Section IV, regression controls include gender, race, age*race*female indicators, state-of-birth*race indicators, state-of-birth*female indicators, state-of-birth*race*female indicators, state-of-birth fixed effects, year-of-birth fixed effects, and survey year fixed effects. Standard errors are clustered at the state-of-birth by year-of-birth level. Individual data come from the ACS for the years 2000–2017, with native-born individuals aged 25–60 included in the regressions. The rows below the estimates report the R^2 and observations for each regression. Measles prevaccine incidence rate is calculated using data from Current Population Reports and MMWR Annual Reports for the 12-year period from 1952 to 1963. The bottom row calculates the average impact of the measles vaccine for an individual with a full 16 years of exposure to the vaccine who was born in a location with the average measles incidence rate of 964 cases per 100,000 of the population. All dollar values are in 2018 dollars.

over that period. Columns 2 and 3 also use income as the outcome of interest but only include those individuals with an income greater than zero. Column 2 uses reported income dollar value as the outcome variable and finds being born in a state with the average prevaccine measles incidence rate and having full exposure to the vaccine is $722, which represents a 1.2 percent increase off the prevaccine cohort mean. Column 3 uses the natural log of income and finds a 1.7 percent increase in income. Estimates in columns 2 and 3 are statistically significant and are consistent with the impacts exhibited in column 1.

The last three columns of Table 2 examine poverty, employment, and hours worked per week. The estimate in column 4 shows that those born in states with higher incidence rates and with exposure to the measles vaccine are statistically significantly less likely to have a household income at or below the poverty line. Having full exposure to the measles vaccine and being born in the average incidence state decreases the probability of living in poverty by 0.50 percentage points, a decrease of 7.3 percent from the prevaccine cohorts mean. Exposure to the measles vaccine demonstrates a statistically significant increase in the likelihood of employment of 0.29 percentage points, an increase of 0.3 percent from the prevaccine cohort mean of 96 percent employment. It is of note that the share of households at or below the federal poverty line increased and the likelihood of employment decreased for the cohorts with exposure compared to the cohorts without exposure, so the coefficients for poverty and employment indicated that the measles vaccine contributed positively to labor market outcomes even though the overall trend was moving in the opposite direction. Column 6 examines hours worked per week. While statistically significantly different from zero, the coefficient is not economically significant. The calculated impact for full exposure from the average incidence state is 12 minutes less worked per week (a −0.64 percent change from the precohort mean).

VI. Robustness Checks

A. *Specification Checks*

Table 3 reports specification checks for long-run adult labor market outcomes using equation (2) and limits the sample by cohorts. Columns 1 through 6 represent the six outcomes of interest as discussed in the results section. The first row of Table 3 reports the "Main Results" from Table 2. In all specifications, the estimates are consistent with the "Main Results."

The first specification check limits the sample to only those with no exposure to the vaccine and those with a full lifetime of exposure to the vaccine. The point estimate magnitudes are within one standard deviation and statistically significant for all the income categories. The estimate for the poverty regression is smaller and statistically significant but still within two standard deviations from the main result. The estimates for employment are consistent both statistically and economically with the main results. The results for hours worked per week are not statistically significant, the sign is in the same direction, and the coefficient is within one standard deviation of the main results. Additionally, the economic impact of the coefficient for this subgroup is 6 minutes worked less per week, which is comparable to the 12 minutes less per week for the full analysis sample. In the second specification check, I limit the sample to cohorts from 1941 to 1971. This narrowed sample also produces coefficients of similar magnitude and statistical significance as the main results.

B. *Convergence*

Table 4 considers whether convergence could affect the results. If states had different trends in income and employment prior to the availability of the measles vaccine, then the gains in income and employment and the reductions in poverty could have happened even in the absence of the measles vaccine. I check for this in two ways. The first is by including census division by year-of-birth fixed effects in equation (2). This tests for the estimate sensitivity to the many other regional specific differences in trends across cohorts that are occurring during this historical period (Stephens and Yang 2014).[28] The second is by including the average level of the

[28] Table 4 presents the results for the nine US census divisions by year-of-birth fixed effects. Online Appendix Table 4 presents the results when this analysis is done in two alternative ways: (i) using the four census regions to add census region by year-of-birth fixed effects to equation (2) and (ii) interacting state-of-birth with year-of-birth to create state-of-birth-specific linear cohort trends to include in equation (2). The results for the census region by year-of-birth fixed effects model are consistent with the census division by year-of-birth fixed effects model, with larger impacts for the two dollar-based income outcomes and then consistent results for ln income, poverty, employment, and hours worked per week when compared to the main results. The estimates from the model including

Table 3—Specification Check, Adult Labor Market Outcomes

	Income (1)	Income (if > 0) (2)	ln Income (3)	Poverty (4)	Employed (5)	Hours worked (6)
Main results	2,901	4,681	0.1101	−0.0326	0.0186	−1.2511
	(864)	(1,202)	(0.0233)	(0.0040)	(0.0032)	(0.3769)
Observations	15,710,435	12,126,516	12,126,516	15,429,840	12,593,724	15,710,435
No and full exposure only	3,099	4,493	0.0972	−0.0172	0.0248	−0.6004
	(1,423)	(1,951)	(0.0436)	(0.0073)	(0.0069)	(0.7145)
Observations	9,175,509	7,273,935	7,273,935	8,961,155	7,487,614	9,175,509
Cohorts 1941–1971	5,205	7,071	0.1117	−0.0278	0.0134	−0.4522
	(855)	(1,071)	(0.0214)	(0.0038)	(0.0033)	(0.4019)
Observations	10,709,934	8,087,014	8,087,014	10,580,109	8,471,427	10,709,934

Notes: The table shows regression-adjusted estimates for the impact of the measles vaccine on adult labor market outcomes. Each column represents a separate outcome as listed in the column heading. Each row describes the sample used for the regression estimates displayed. The top row of estimates reports the main results (all native-born 25- to 60-year-olds), which are the same as in Table 2. The no and full exposure only sample includes only those from the full sample with 0 or 16 years of exposure to the measles vaccine. The cohorts 1941–1971 sample narrows the cohorts used in the analysis. A separate regression is run for every sample-outcome pair, and the coefficient of interest from equation (2), its standard error, and the sample size are presented. As described in Section IV, regression controls include gender, race, age*race*female indicators, state-of-birth*race indicators, state-of-birth*female indicators, state-of-birth*race*female indicators, state-of-birth fixed effects, year-of-birth fixed effects, and survey year fixed effects. Standard errors are clustered at the state-of-birth by year-of-birth level. Individual data come from the ACS for the years 2000–2017, with native-born individuals aged 25–60 included in the regressions. All dollar values are in 2018 dollars.

Table 4—Convergence Check, Adult Labor Market Outcomes

	Income (1)	Income (if > 0) (2)	ln Income (3)	Poverty (4)	Employed (5)	Hours worked (6)
Panel A. Main results						
$M^{pre}_{1952-1963} * Exposure\, to\, Vaccine$	2,901	4,681	0.1101	−0.0326	0.0186	−1.2511
	(864)	(1,202)	(0.0233)	(0.0040)	(0.0032)	(0.3769)
Panel B. Birth year effects vary by division						
$M^{pre}_{1952-1963} * Exposure\, to\, Vaccine$	7,581	9,633	0.2076	−0.0450	0.0229	0.7915
	(866)	(1,091)	(0.0206)	(0.0039)	(0.0032)	(0.3497)
Panel C. Mean reversion						
$M^{pre}_{1952-1963} * Exposure\, to\, Vaccine$	3,014	5,116	0.1164	−0.0314	0.0192	−1.0311
	(872)	(1,194)	(0.0231)	(0.0040)	(0.0032)	(0.3875)
Prevaccine Cohort * 1941–1949 *Dependent Variable*	0.0235	0.1061	0.1042	−0.0526	−0.2405	0.1804
	(0.0242)	(0.0230)	(0.0294)	(0.0293)	(0.0828)	(0.0322)
Observations	15,710,435	12,126,516	12,126,516	15,429,840	12,593,724	15,710,435

Notes: The table shows regression-adjusted estimates for the impact of the measles vaccine on adult labor market outcomes. Each column represents a separate outcome as listed in the column heading. Each panel describes the specification check for that section. A separate regression is run for every panel-outcome pair, and the coefficient of interest from equation (2) and its standard error are presented. As described in Section IV, regression controls include gender, race, age*race*female indicators, state-of-birth*race indicators, state-of-birth*female indicators, state-of-birth*race*female indicators, state-of-birth fixed effects, year-of-birth fixed effects, and survey year fixed effects. Standard errors are clustered at the state-of-birth by year-of-birth level. Individual data come from the ACS for the years 2000–2017, with native-born individuals aged 25–60 included in the regressions. Panel A reports the main results (all native-born 25- to 60-year-olds) estimates, which are the same as in Table 2. Panel B reports the estimates when census division by birth year fixed effects are added to equation (2). Panel C controls equation (2) for mean reversion and reports the estimates for the main coefficient of interest and its standard error in the top row and the coefficient and standard error for the additional mean reversion control variable in the second row. The last row shows the observations for the column. All dollar values are in 2018 dollars.

dependent variable by state for the prevaccine cohorts as an additional explanatory variable to check for mean reversion to equation (2). Table 4 is divided into three panels: panel A, main results as presented in Table 2; panel B, estimates allowing for cohort effects to vary regionally; and panel C, mean reversion estimates.

If the estimates hold when census division by year-of-birth fixed effects are included in the model, this provides support that the results are not being driven by differences between census divisions as opposed to variation within census divisions over time. Panel B shows that the income estimates increase but are still feasible gains that could be attributed to having a healthier childhood due to measles avoidance. The effects on poverty and employment remain statistically significant and consistent with the main results. Hours worked per week changes sign and has statistical significance; however, the economic significance of the coefficients tells the same story—no economically significant change to hours worked per week. The main results coefficient equates to a decrease of 12 minutes worked per week, and the positive coefficient in panel B equates to an increase of 7 minutes worked per week, neither of which is economically significant. My results hold in both sign and significance when allowing birth year effects to vary across census division, providing support that I have captured the causal impact of the measles vaccine. Panel C presents the mean reversion coefficients, which are all consistent in statistical significance, sign, and magnitude with the main results.

C. *The Contemporaneous Impact of the Vaccine's Introduction on Adult Labor Market Outcomes*

Adult employment, labor force participation, and years of education at the time of the introduction of the measles vaccine can be used as a falsification test. Measles is a childhood illness, and individuals who are adults in 1963 would not be eligible for the vaccine, as they already had measles in childhood. Therefore, there should be no impact on contemporaneous adult labor market outcomes from the measles vaccine introduction. I test for contemporaneous effect using adults aged 26 to 60 at the time of the 1960 and 1970 census for this analysis (Ruggles et al. 2021). I modify equation (2) by interacting $M^{pre}_{1952-1963}$ with an indicator variable if the observation occurs after the measles vaccine has been introduced. Regression estimates for adult employment, labor force participation, and years of education are displayed in Table 5. There is no statistically significant difference in the likelihood of being employed, the likelihood of participating in the labor force, or the number of years of education for adults in high-exposure states compared to low-exposure states. Additionally, the calculated impact of each of these coefficients is close to zero. These results further support the idea that the measles vaccine has short-run health impacts on the population it prevents from contracting measles, which in turn can lead to long-run impacts for those vaccinated.

the state of birth linear cohort trend show larger income effects than the main results, no impact on poverty and employment, and similar results for hours worked per week to the main results.

Table 5—Contemporaneous Outcomes Check, Adult Labor Market Outcomes

	Employed (1)	Labor force participation (2)	Education (3)
$M^{pre}_{1952-1963} * POST$	−0.0311	−0.0597	1.0009
	(0.1831)	(0.1897)	(6.0728)
R^2	0.30	0.32	0.24
Observations	1,345,220	1,345,220	1,345,220
Impact to outcome for an adult in state with average prevaccine measles incidence rate post–vaccine availability	−0.0300 percentage points	−0.0576 percentage points	0.0096 years

Notes: The table shows regression-adjusted estimates for the impact of the measles vaccine on contemporary adult outcomes. Each column represents a separate outcome as listed in the column heading. Data on native-born adults in the age range of 26–60 at the time of the 1960 or 1970 census were used in these regressions. A separate regression is run for each outcome variable. The top two rows present the coefficient of interest and its standard error. Regression controls include rural, gender, race, gender*race, rural*post, gender*post, race*post, gender*race*post, household income cubed, state fixed effects, and year fixed effects. Standard errors are robust and clustered at the state level. The rows below the estimates report the R^2 and Observations for each regression. Measles prevaccine incidence rate is calculated using data from Current Population Reports and MMWR Annual Reports for the 12-year period from 1952–1963. The bottom row calculates the average impact of the measles vaccine for an individual after the measles vaccine is available who resides in a location with the average measles incidence rate of 964 cases per 100,000 of the population.

VII. Discussion

This is the first study to examine the long-run earnings and employment effects of vaccination in the developed world. I evaluate the long-run impacts of the measles vaccine in the United States. The introduction of the measles vaccine provides a plausibly exogenous improvement in public health to estimate what happened to labor market outcomes when the United States gained herd immunity for measles. From improvements in childhood health due to avoiding the "immune amnesia" caused by the measles virus, I observe gains in adult labor market outcomes, with gains being greater for those born in areas with a higher initial measles incidence rate. An adult who was born after the licensing of the measles vaccine and thus had full exposure to the vaccine earns more, is less likely to live in poverty, and is more likely to be employed than an adult who did not have the opportunity to be vaccinated. I found a statistical but not economic difference in the hours worked per week. This indicates a higher wage rate is being earned and that individuals are more productive. The earnings for someone with a lifetime of exposure born in a state with the average prevaccine measles incidence rate are 1.1 percent greater than someone born in the same state but without exposure to the measles vaccine.

To place a dollar value on the social benefit gained from measles vaccination, I perform a back-of-the-envelope calculation. An individual with a full 16 years of exposure to the measles vaccine who was born in a state with the average prevaccine measles incidence rate (964 cases per 100,000) earns \$447 more a year as an adult. In 2019, there were 171 million adults aged 25–65 in the United States. If all adults experienced herd immunity from measles as a child, then \$76.4 billion of personal income in a year can be attributed to gains from the measles vaccine, which represents 0.4 percent of total personal income in 2019. In 1969, researchers at the

National Communicable Disease Center conducted a study to quantify the national impact of immunization against measles. In their study, they took into account not only direct medical costs and benefits, but also account for indirect costs and benefits in terms of loss of productivity associated with measles (workday and school day absences). They find the benefits are far greater than the costs associated with measles immunization, with the measles vaccine saving the nation $423 million between the years 1963 and 1968 ($3.1 billion in 2019), with 90 percent of the savings occurring from 1965 to 1968 (Axnick, Shavell, and Witte 1969). While it is clear there are short-run gains to measles immunization, if we do not think of the benefit to society in terms of both short-run and long-run gains, we underestimate the impact the measles vaccine has on society.

Measles specifically can be effectively controlled via herd immunity, as humans are the only natural hosts for the virus and lifelong immunity through antibodies is achieved after either being infected by or vaccinated for the measles virus (Fox 1983; Sencer, Dull, and Langmuir 1967). While measles has been considered eliminated (absence of continuous measles transmission for greater than 12 months) in the United States since 2000, it is not eradicated[29] (0 incidence in the world, with intervention no longer needed) and remains a threat for unvaccinated populations. For herd immunity to occur for measles, 90 to 95 percent of the population needs to have immunity (i.e., antibodies for the measles virus) to protect the rest of the population from the spread of measles (Fox 1983; Kwong and Ambizas 2019).

Current vaccination rates vary greatly across states (85.6 percent in Washington DC to 99.4 percent in Mississippi), with many geographic areas achieving rates below the 90–95 percent required for herd immunity, leaving the population susceptible to infections.[30] Additionally, measles immunity is not distributed homogenously across a state, and there are pockets of the population that are more vulnerable to the spread of measles. When these pockets of the population are exposed to measles, an outbreak will result. From January 1 to December 31, 2019, there have been 1,282 individual measles cases reported in the United States by the CDC.[31] This is the highest annual total since 1992 (Sun 2019). The two largest outbreaks have occurred in New York City and Rockland County, New York, where county officials recently declared a state of emergency and placed a ban on unvaccinated minors entering certain public places (Brum 2019).

Globally, the measles virus still poses a threat. Despite the availability of a cheap and effective vaccine with a proven track record of over 50 years (Bloch et al. 1985), measles remains one of the leading causes of death among young children (WHO 2017). Eradicating measles by 2020 is a major WHO initiative. Though predominantly occurring in developing countries, measles is a concern for the developed world, too. A majority of recent measles cases have been linked to unvaccinated travelers coming to the United States from Israel, Ukraine, and the Philippines, where large measles outbreaks are occurring.[32] Further, the decrease of vaccination

[29] Smallpox remains the only eradicated disease and was declared eradicated December 1979. https://www.who.int/csr/disease/smallpox/en/.

[30] https://www.cdc.gov/nchs/data/hus/2018/031.pdf.

[31] https://www.cdc.gov/measles/cases-outbreaks.html.

[32] https://www.cdc.gov/measles/cases-outbreaks.html.

rates and potential relaxing of vaccination requirements for school enrollment in developed countries has prompted heated debates and received considerable media coverage in recent years. In Rockland County, New York, over 80 percent of individuals with confirmed measles cases were completely unvaccinated, leading to the placement of noncompliance fines and potential jail sentences for the parents of unvaccinated minors (Brum 2019). This further illustrates how vaccination is not homogeneous and in small areas where the susceptible population rate is higher than that needed for herd immunity, outbreaks occur.

Vaccines reduce the burden of infectious disease in a population through both a direct effect for the individual receiving the vaccine and herd immunity in the community. Nationally, the vaccination rates among 19- to 35-month-olds declined from 93.1 percent in 2006 to 92.5 percent in 2013. While these overall rates do not fall below the herd immunity level for measles, entire states like Kentucky and Colorado are below the 90 percent level, and there are many other smaller geographic locations where vaccination levels have fallen below the 90 percent level. Recent measles outbreaks in the United States have occurred among those not vaccinated. Considering the average gains in adult earnings of 1.1 percent, there is a strong case to be made for prioritizing worldwide eradication of the measles virus.

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