Three Essays in Health Economics: Evidence from U.S. Vaccination Policy

By

Emily C. Lawler

Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Economics

August 10, 2018

Nashville, Tennessee

Approved:

Christopher S. Carpenter, Ph.D.

Andrew Goodman-Bacon, Ph.D.

Marie Griffin, M.D., M.P.H.

Michelle Marcus, Ph.D.

William Schaffner, M.D.

To my parents, who have supported me from day one

ACKNOWLEDGMENTS

I am thankful for a great number of people who have supported me through this journey and have helped shape me into the person I am today. First and foremost, I am grateful to my parents and my family, who fostered my love of learning early on and have never stopped believing in me, and to my husband, Benjamin Ward, who has been a constant source of love and strength. I am thankful for my friends here at Vanderbilt University, particularly Katie Yewell, Salama Freed, Danielle Drago Drory, Alper Arslan, Sebastian Tello-Trillo, James Harrison, Daniel Mangrum, Michael Mathes and Aaron Gamino, who have provided support, inspiration, and levity throughout this journey. I also would like to thank my undergraduate professors at the University of Kentucky for helping me to discover my passion for economics, and Jenny Minier for her continued support and advice.

This work would not have been possible without the guidance and support I received from my professors at Vanderbilt University. In particular I would like to thank my committee members, Andrew Goodman-Bacon, Marie Griffin, Michelle Marcus, and William Schaffner, as well as Andrew Dustan, Carolyn Heinrich, William Collins, Federico Gutierrez, and Kathryn Anderson. They have all been generous with their time, their advice, and their support through the past six years, and for that I am very grateful. I am especially indebted to my adviser, Kitt Carpenter, who has worked dedicatedly to help me become a better researcher and economist, and who has provided constant support and advice as I have pursued my career goals.

I also would like to acknowledge the generous financial support of the Vanderbilt Economics Department as well as research funding from the Walter M. Noel Dissertation Fellowship, the Kirk Dornbush Summer Research Grant, and the Vanderbilt Economics Department Faculty/Graduate Student Collaborative Research Grant. I am very grateful for the

opportunities that this support has afforded me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In the United States, achieving and maintaining high population immunization rates for a number of vaccines has become a public health priority, and this has resulted in the implementation of a broad set of vaccination policies. In this dissertation I rigorously examine several such policies that have been widely implemented in the United States in the past few decades. Through the application of established empirical methodologies, I am able to estimate the causal effects of these policies on a range of outcomes, and my results have clear policy implications.

The first chapter, *Effectiveness of Vaccination Recommendations versus Mandates: Evidence from the hepatitis A vaccine,* provides novel evidence on the effectiveness of two vaccination policies targeted at infants and very young children– simple non-binding recommendations to vaccinate versus mandates requiring vaccination prior to childcare or kindergarten attendance– in the context of one of the only diseases whose institutional features permit a credible examination of both: hepatitis A. Using a difference-in-differences strategy that allows me to take advantage of plausibly exogenous variation across states in the timing of the policy introductions, I find that recommendations significantly increased hepatitis A vaccination rates among young children by at least 20 percentage points, while mandates increased rates by another 8 percentage points. These policies also significantly reduced population hepatitis A incidence. My results further highlight important differences in the dynamics of the effects of the recommendations compared to the mandates, and show that while recommendations increase only the probability of initiating the hepatitis A series, mandates significantly increase the probability of both initiation *and* completion of the series.

In the second chapter, *Direct and Spillover Effects of Middle School Vaccination*

Requirements (joint work with Christopher S. Carpenter), we estimate the effects of state laws that mandate receipt of the tetanus, diphtheria, and pertussis (Tdap) vaccine prior to middle school attendance. A substantial literature has examined the effects of state laws requiring infants and children to be vaccinated against certain diseases prior to childcare and preschool entry, but there is far less work on the effects of similar requirements for middle school entry, despite the fact that 46 states have adopted such policies over the past decade. We fill this gap in the literature by examining the direct and indirect effects of such requirements in a quasi-experimental framework.

In this work we find that state laws requiring youths to obtain a Tdap booster prior to middle school entry increased the likelihood that an adolescent received a Tdap booster between 10 and 12 years of age by 13.5-13.7 percentage points. We also find substantial reductions in pertussis (whooping cough) disease incidence as a result of the mandates, with the largest reduction observed primarily for adolescents, who were targeted by the mandates, and among infants, who are particularly vulnerable to pertussis. We also document that these vaccination requirements had important spillover effects to the uptake of non-mandated vaccines. Specifically, we find that Tdap booster policies significantly increased meningococcal vaccination rates by 2.2-2.9 percentage points, increased human papillomavirus (HPV) vaccination series *initiation* by 4.2-4.9 percentage points and HPV vaccination series *completion* by 2.5-3.3 percentage points. Notably, these spillover effects are larger for youths from households with low socioeconomic status (SES).

Finally, in the third chapter, *Giving Teens a Boost? Effects of Meningococcal Disease Vaccination Policies,* I again examine the effects of non-binding vaccination recommendations and school entry mandates, but this time in the context of a population that is substantially less

connected to the health care system relative to infants and pre-teens: high school-aged adolescents. In the past decade, vaccination policies targeting this age group have become increasingly common; in this chapter I focus particularly on policies pertaining to the meningococcal vaccine, which was recommended for 16 year olds in 2011, and for which fourteen states have implemented 11^{th} or 12^{th} grade school entry mandates. My results show that both the recommendations and the mandates increased the probability that an individual receives a dose of the meningococcal vaccine at ages 16 or 17 by approximately 20 percentage points, and the evidence also suggests a resulting decrease in meningococcal disease incidence. Additional analyses show that the policy effects vary substantially across different demographic sub-groups, and in particular, the national recommendation appears to potentially exacerbate pre-existing disparities in receipt of the vaccine.

My results also suggest that the high school vaccination mandates significantly increased the probability of receiving additional preventive care: I find a robust 7 percentage point increase in the probability of having a check-up at age 16 or 17, as well as significant increases in the probability of receiving a dose of the HPV or Tdap vaccine at those same ages. These spillovers are larger than the spillovers documented in chapter 2, which is consistent with the fact that on average high school students have lower rates of contact with the health care system compared to middle school aged adolescents.

Overall, these three chapters provide important new empirical evidence on the effectiveness of vaccine recommendations and school entry mandates. My results document that these vaccination policies have substantially increased targeted vaccination rates, and have induced substantial improvements in child and population health. For middle and high school-aged adolescents, I also find large spillovers of vaccination mandates to the receipt of other non-

mandated preventive care. Additionally, my results suggest there is potentially large heterogeneity in the policy effects across different age groups, in a manner which is consistent with pre-existing differences in contact with the healthcare system.

CHAPTER 1

EFFECTIVENESS OF VACCINATION RECOMMENDATIONS VERSUS MANDATES: EVIDENCE FROM THE HEPATITIS A VACCINE[1]

1.1 Introduction

In the past century the widespread use of vaccines has resulted in dramatic decreases in the incidence of numerous diseases, and this achievement is lauded as one of the greatest successes in public health (CDC, 2014a). In the United States, however, childhood vaccination rates for a number of diseases remain persistently below the goals set by the U.S. Department of Health and Human Services[2] and outbreaks of vaccine-preventable diseases continue to occur due to undervaccination (see, for example, Gahr et al., 2014; CDC, 2009; or Parker et al., 2006). As a result, achieving and maintaining high population vaccination rates has become a public health priority, and a number of policies have been implemented at the state and national level. These policies include subsidized provision of vaccines, required insurance coverage, and mandates requiring that children receive certain immunizations prior to child care and/or school attendance.

In this article I provide new evidence on the effectiveness of two separate disease-specific vaccination policies: official recommendations for hepatitis A vaccination made by the Advisory Committee on Immunization Practices (ACIP) and hepatitis A child care/kindergarten

[1] A version of this chapter has been previously published as "Effectiveness of Vaccination Recommendations Versus Mandates: Evidence from the hepatitis A vaccine" in *Journal of Health Economics* 52, 45-62 (2017). It is reproduced here in accordance with the rights retained by the author.

[2] The current childhood immunization goals, which were established in 2010 as part of the "Healthy People 2020" initiative, along with their associated baseline vaccination rates, are given in Appendix Table 1. Among the recommended childhood vaccines, over half were below their goal rate in the baseline year, and in particular, the hepatitis A vaccination rate was nearly 45 percentage points below the goal of 85 percent (U.S. Dept. HHS, 2015). These vaccination targets are broadly based on the goal of achieving vaccination rates that are sufficient for maintaining herd immunity. In the case of hepatitis A, since the baseline coverage rate is low relative to other recommended childhood vaccines, the goal rate is simply justified as being "an achievable target."

mandates. I estimate the effects of these policies on both the vaccination rates of young children and on population disease incidence, using a difference-in-differences framework that allows me to take advantage of the considerable variation in the timing of the implementation of these policies across states. I supplement the standard difference-in-differences model with an event study style model, which allows me to test for dynamic policy effects.

Theoretically, there is a strong argument for government intervention in the market for the hepatitis A vaccine. When an individual decides to vaccinate, they reduce both their own susceptibility to the disease and also the probability of person-to person disease transmission in the community. Since in the United States person-to-person contact is the primary means of transmission of hepatitis A (CDC, 2006), vaccination against it generates a significant positive externality. Due to this externality, individuals value vaccination comparatively less than a centralized planner would, and so, in the absence of intervention, vaccination rates will be below the socially optimal level.[3]

Ex ante it is unclear the extent to which the particular interventions considered here, ACIP recommendations and child care/kindergarten mandates for hepatitis A vaccination, will increase vaccination rates and decrease disease incidence. The direct effect of the policies is straightforward: lowering a vaccine's effective price[4] or mandating its receipt should increase the demand for vaccination and decrease disease prevalence. If, however, vaccination demand is also a decreasing function of disease prevalence, then each of these policies further has the indirect

[3] Additionally, the difference between the private benefits and the public benefits of vaccinating young children against hepatitis A is potentially large, as children typically experience asymptomatic infections while serving as a significant source of infection for others.

[4] For simplicity in exposition, I consider the ACIP recommendation to lower the effective price of a vaccine. The justification for this is twofold: First, the recommendation reduces an individual's information cost regarding the safety and efficacy of a vaccine, and second, ACIP recommendations are closely tied to a number of other policies which directly subsidize the cost of vaccines, which is discussed in more detail in Section 2.2.

effect of *reducing* vaccination demand through the reduction in disease incidence (Philipson, 2000).[5] As a result, the net effect of these hepatitis A vaccination policies on vaccination rates and disease prevalence is an empirical question.

Presently, consideration of the ACIP recommendations has been confined to the medical and public health literature, and the effects of this policy have not yet been estimated within a rigorous causal framework. Using different policy settings, there are several articles in the economics literature that consider the effects of vaccine mandates (Abrevaya and Mulligan, 2011; Ward, 2011; Luca, 2014).[6] Due to data availability, however, those authors have been limited in their ability to simultaneously estimate the effects of vaccine mandates on both vaccination rates and disease incidence.

I am able to identify the effects of the ACIP recommendations and the mandates on both vaccination rates and population disease incidence due to two unique aspects of the hepatitis A policy variation and data availability. First, unlike other vaccines, the ACIP recommendations for hepatitis A vaccination were incrementally rolled out across states, instead of being implemented at the national level.[7] There is also significant variation in the timing of mandate implementation across states. Second, hepatitis A has the empirical advantage that much of the identifying variation in policies occurs during a period in which hepatitis A is covered in a state-representative immunization survey of young children, while also being a nationally notifiable disease. As a result, there is adequate data available to identify the effects on both vaccination

[5] The magnitude of the indirect effect depends on how "prevalence-elastic" individuals are, which likely varies across diseases.

[6] Other vaccination policies that have been empirically evaluated in the economics literature include insurance mandates (Chang, 2016; Lipton and Decker, 2015) and mass vaccination campaigns (Ward, 2014).

[7] It is noteworthy, however, that these recommendations were initially implemented based on historic state hepatitis A morbidity rates, and so are not exogenous with respect to morbidity. As a result, the estimated effects of the recommendations on morbidity rates should be interpreted cautiously.

rates among the targeted age group and disease incidence in the population.[8]

Overall, I find both of the vaccination policies to be highly effective. ACIP recommendations and hepatitis A mandates each significantly increase hepatitis A vaccination rates and decrease the population disease incidence. Together, the mandates and the ACIP recommendations explain approximately half of the change in both hepatitis A vaccination rates and disease incidence over my sample period. Analysis of policy dynamics indicates that individuals who are induced to vaccinate by the mandate respond immediately to the policy, while the ACIP recommendations have a more gradual effect that continues to increase for up to 4 years following implementation. This is consistent with the fact that the mandates are binding for children enrolled in child care or kindergarten, while the recommendations serve as a more general 'nudge' towards vaccination.

In my analyses I also consider the potential for heterogeneous policy effects across different subpopulations. I find that, among very young children, the effects of the mandates on vaccination are driven almost entirely by those enrolled in child care. I otherwise find no heterogeneity in the effects of the mandate by ethnicity, mother's education, or family income. I do, however, find some heterogeneity in the effects of the ACIP recommendations on vaccination. In particular, the policy effects are smallest for whites and for children whose households fall in the middle of the income and education distributions.

The rest of the article will proceed as follows. In Section 1.2 I provide background information on hepatitis A and the relevant vaccination policies. I present my data sources and descriptive statistics in Section 1.3, and I outline my empirical strategy and baseline results in Section 1.4. Section 1.5 provides results for different subpopulations of interest and estimates of

[8] A limitation, however, is that since I observe vaccination rates only for young children, I am unable to capture the effects of the policies on overall population vaccination rates.

the effects of the policies on other vaccines and diseases. Finally, Section 1.6 concludes.

1.2. Background

To provide context to the analysis, in this section I present background information on hepatitis A and both of the vaccination policies I am analyzing - hepatitis A vaccination recommendations and kindergarten/child care vaccination mandates. I first discuss the characteristics of hepatitis A infection and vaccination, and the implications this has for the expected degree of market failure. I next turn to the vaccination policies of interest, and present their relevant institutional and historical context. Additionally, I briefly discuss the mechanisms through which these policies could feasibly affect an individual's decision to vaccinate.

1.2.1 Hepatitis A

Hepatitis A is a liver disease characterized by flu-like symptoms and jaundice. Illness typically lasts 2 months, with symptoms persisting for up to 6 months in approximately 15 percent of cases (CDC, 2012). It is transmitted through the fecal-oral route, and is generally spread through person-to-person contact or by consumption of contaminated food or water. A defining characteristic of hepatitis A, and one that is particularly relevant in this context, is that both the probability and the severity of symptoms are increasing in age. Adults experience symptoms in over 70 percent of cases, and when they do experience symptoms, the consequences are significant: on average, they miss 27 work days per illness and are hospitalized in up to 22 percent of cases (CDC, 2012). Children under the age of 6, on the other hand, are typically asymptomatic.

The first hepatitis A vaccines were approved by the Food and Drug Administration (FDA) in 1995. Initially approved for use only in individuals 2 years of age or older, in 2005

they were further approved for children as young as 12 months of age. Each vaccine requires two doses, to be given 6 to 18 months apart, and they have been shown to be highly effective in clinical testing.[9] Since the development of these vaccines there has been a steady decline in the hepatitis A incidence in the United States, and as of 2013, the national rate reached a historic low of 0.6 cases per 100,000 people (CDC, 2013). Prior to the development of the vaccine, acute hepatitis A cases occurred at an annual rate of between 9.0 and 14.5 per 100,000 people (CDC, 2006). In some areas, however, this rate was much higher, as hepatitis A infection is characterized by community wide epidemics and has historically varied significantly between regions and across races/ethnicities.

Although adults experience the most significant morbidity effects from hepatitis A, routine hepatitis A vaccination has been targeted towards young children. This is motivated by the fact that, because children infected with hepatitis A are usually asymptomatic, they serve as particularly good transmitters of hepatitis A (CDC, 2012). Consequently, vaccinating children is an efficient way from the epidemiological perspective to reduce disease transmission in the community, and therefore reduce incidence among individuals of all ages. [10] However, since the receipt of the vaccine is potentially costly in terms of money and time, and the potential infection that it is preventing would likely have been asymptomatic, the incentives for children to be vaccinated against hepatitis A are small. As a result, in the case of hepatitis A, we may expect particularly low vaccination rates in the absence of intervention and also relatively low responsiveness to policies that 'nudge' individuals towards vaccination. Policies that require

[9] In clinical trials, over 95 percent of adults developed the protective antibody after one dose, and approximately 100 percent develop it after 2 doses. The rates are slightly higher for children, with over 97 percent of children developing the antibody after 1 dose, and 100 percent after two (CDC, 2012).

[10] Official recommendations explicitly argue that hepatitis A vaccination is important for young children because, in addition to reducing disease incidence among the targeted age group, it will also "indirectly protect older persons" (CDC, 1996) by "eliminating a major source of infection for others" (CDC, 2006).

vaccination, such as child care and school mandates, may then have room to induce a greater number of individuals to vaccinate.

1.2.2 Vaccination Policies

ACIP Recommendations

In the United States, official immunization recommendations are made by the Advisory Committee on Immunization Practices (ACIP) and are then reviewed and approved by the CDC Director. The ACIP was established under the Public Health Service Act, and consists of 15 voting members who are experts in medicine and public health. The initial ACIP statement on hepatitis A vaccination, released in 1996, generally recommended routine vaccination for particular high risk populations, such as children over the age of two in areas with high rates of hepatitis A infection, travelers to high-risk areas, men who have sex with men, and illegal-drug users (CDC, 1996). Over the subsequent decade ACIP issued two updates to this initial recommendation in which they incrementally increased the target population for routine hepatitis A vaccination.

The first update occurred in 1999. At this time ACIP recommended that routine vaccination of children 2 years of age and older *be implemented* in states with an average annual incidence of hepatitis A of more than 20 cases per 100,000 people between 1987-97 (i.e. over twice the national average for that time period) and that it *be considered* in states with between 10 and 20 cases per 100,000 people (CDC, 1999). Eleven states – Alaska, Arizona, California, Idaho, Nevada, New Mexico, Oklahoma, Oregon, South Dakota, Utah, and Washington – fall into the first 'high incidence' category ($\geq$20 cases per 100,000 people) and received the 'strong' ACIP recommendation, and six states – Arkansas, Colorado, Missouri, Montana, Texas, and

Wyoming– are in the second 'medium incidence' category (between 10 and 20 cases per 100,000 people) and received the 'weak' ACIP recommendation (CDC, 2006). For notational simplicity, I refer to the states at or below average incidence ($\leq$ 10 cases per 100,000 people), which received no ACIP recommendation for vaccination in 1999, as 'low incidence' states.

In 2006, following the approval of the vaccines for children as young as 12 months, a second update was issued which extended the strong ACIP recommendation for routine hepatitis A vaccination to children in *all states* and recommended the first dose be given between 12 and 23 months of age .The recommendation stipulates that all children that have not been vaccinated by the age of 2 should be vaccinated at their next doctor's visit (CDC, 2006). As of 2016, this remains the current ACIP recommendation. In Figure 1 I graphically present the timing of the vaccine approval and the ACIP vaccination recommendations, and how they vary across age groups and incidence categories.

There are a number of potential mechanisms through which the ACIP recommendations may affect an individual's decision to vaccinate. This is because, in addition to providing information regarding best immunization practices, the recommendations of the ACIP play an important role in determining the relevant set of vaccines for a number of policies that subsidize their provision. A primary example of this is the federally-funded Vaccines for Children (VFC) program, which provides all ACIP-recommended vaccines to eligible children for free (CDC, 2014b).[11] Similarly, insurance mandates that require coverage of vaccines generally use ACIP

[11] Individuals are eligible if they are 18 years of age or younger, and are Medicaid- eligible, uninsured, American Indian or Alaskan Native, or are underinsured. Children can receive vaccines through the VFC program at any enrolled provider, which includes private doctors and hospitals, and public health clinics. In general, underinsured children are able to receive vaccines through VFC only at Federally Qualified Health Centers or Rural Health Clinics. Notably, although VFC is a federal program, some states choose to supplement the program with state funds and thus the generosity of the program varies substantially at the state level.

recommendations to determine the set of vaccines that must be covered.[12] As a result of their role in these various policies, ACIP recommendations can affect an individual's decision to vaccinate both by increasing their information regarding vaccination and by decreasing the monetary cost. A limitation of my results is that I am unable to disentangle the extent to which the effect of the policy is being driven by each of these channels.

Within the medical and public health literature, there have been a number of studies that consider the effects of the ACIP recommendations. These studies find that the ACIP hepatitis A recommendations are associated with both increased vaccination rates (Bialek et al., 2004; Dorell et al., 2012) and decreased disease incidence (Bialek et al., 2004; Singleton et al., 2010; Wasley, Samandari, and Bell, 2005). Zhou et al. (2007) additionally find the recommendations to be associated with decreased hepatitis A-related ambulatory visits. These papers are limited, however, in that the research designs implemented do not allow for a causal interpretation of their results. Several of the studies rely on a single cross-section of data (Bialek et al., 2004; Dorell et al., 2012) or compare mean outcomes among a single group before and after they received an ACIP recommendation (Bialek et al., 2004). These designs are respectively unable to disentangle the effects of the ACIP recommendations from time-invariant differences across states or from pre-existing trends in the outcome variable. Singleton et al. (2010), Wasley, Samandari, and Bell (2005), and Zhou et al. (2007) each obtain their primary results on the effects of the ACIP recommendations by comparing mean outcomes between groups that did and did not receive the recommendations, before and after the recommendation was issued. This design is similar to a standard difference-in-differences model, although since it is not

[12] Particularly, the Affordable Care Act (ACA) preventative care provision requires that, as of September 23, 2010, all new insurance plans must provide all ACIP-recommended vaccines without cost-sharing (NCSL, 2015a). Under the ACA provision, newly recommended vaccines must be covered within one year of the recommendation.

implemented in a regression framework the authors are unable to control for time-varying observable differences across groups that may affect the outcomes of interest.[13] To the best of my knowledge, I am the first to provide a rigorous empirical estimate of the effects of the ACIP vaccination recommendations on vaccination rates and disease incidence.

Vaccination Mandates

There is a long history in the U.S. of using school and child care mandatory vaccination laws as a tool to increase vaccination rates, with the first mandate being implemented in Massachusetts in 1853 (Luca, 2014). Mandates are an appealing policy tool, as compulsory schooling laws provide an effective means for enforcement. An important limitation to the effectiveness of mandates, however, is the availability of individual exemptions. In all but two states exemptions may be obtained for individuals whose religious beliefs oppose vaccination, and 20 states additionally allow exemptions for personal/philosophical beliefs (NCSL, 2015a). All states grant exemptions for children who cannot be vaccinated due to medical reasons.

The decision to legislate vaccination has been left to state governments, and so although all states presently mandate the receipt of some vaccines, there is considerable variation in the set required for school or child care attendance in each state (Malone and Hinman, 2003).[14] In several states, such as Pennsylvania and West Virginia, child care and school mandates are automatically implemented for all ACIP recommended vaccinations, while most other states separately regulate each individual vaccine. Since the approval of the hepatitis A vaccine, 20

[13] Zhou et al. (2007) do estimate a regression model that includes a state group fixed effect (received ACIP recommendation in 1999 versus did not) and a [state group × year] interaction term, although they do not include year fixed effects. As a result, it would be difficult to interpret the coefficient on the interaction term as the effect of the ACIP recommendation. Their study is also limited in that the sample consists only of individuals with employer-provided insurance.

[14] There have been school vaccine mandates implemented in all 50 states and Washington D.C. since 1980, and by 1998 all states had requirements for child care centers as well.

states have implemented mandates requiring children to be vaccinated against hepatitis A prior to their enrollment in child care and/or kindergarten.

Within the economics literature, there are several papers that examine the effects of vaccine mandates. Abrevaya and Mulligan (2011) consider the implementation of state varicella mandates and find significant effects on varicella vaccination rates, but they do not study morbidity effects. Ward (2011) and Luca (2014) both consider the implementation of the first modern school vaccination laws, which took place between 1963 and 1980 and mandated the receipt of several vaccines, including the measles, mumps, and rubella (MMR) vaccine, prior to school attendance. They find reductions in morbidity and mortality for the vaccine-targeted diseases but are unable to estimate the effects on vaccination rates due to lack of available data. They are able, however, to consider long-run effects of the mandates, and they find significant increases in educational attainment, labor force participation, and income, as well as improvements in later life health.

1.3. Data

Data on my primary outcomes are from two main sources. Individual-level vaccination data are from the National Immunization Survey (NIS), 2003-2013, and all data on state disease incidence rates are from the CDC's National Notifiable Diseases Surveillance System (NNDSS), 1997-2013.

The NIS is an annual state-representative survey conducted by the CDC that targets children aged 19-35 months. These data are well-suited for this application, as they contain household socio-demographic information as well as reliable provider-verified immunization

histories.[15] A limitation, however, is that the survey does not begin covering hepatitis A vaccination until 2003, and so my analyses of policy effects on vaccination rates are restricted to 2003-2013. Due to the fact that the hepatitis A vaccine was not approved for 12-23 month olds until late 2005, I perform my analyses on two separate subsamples of the NIS survey population for this time period: 24-35 month olds for 2003 to 2013 and 19-35 month olds for 2007-2013.

The CDC's NNDSS data contain counts of cases of nationally notifiable diseases by state and year as voluntarily reported to the CDC by state health departments. I use morbidity data from 1997 to 2013, as the hepatitis A morbidity data are not subject to the same availability constraints as the NIS data. This allows me to take full advantage of all variation in the timing of ACIP recommendations and state mandates. Due to underreporting and asymptomatic infections, NNDSS data, while being the most comprehensive information available on U.S. national disease incidence, likely captures only a fraction of actual cases.

Information on the dates of mandate introduction were obtained from the Immunization Action Coalition (IAC) and from the CDC's 'SchoolVaxView School Vaccination Requirements and Exemptions' database. In cases of discrepancy between these two sources, I examined primary sources, such as state Department of Health websites or state statutes, to identify the correct date.[16] As of January 2015, 20 states have a hepatitis A vaccination mandate in place for either childcare, kindergarten, or both. The Arizona mandate, however, only applies to residents

[15] Unfortunately, the NIS does not contain information on the child's current or previous enrollment in child care. Since for children this young the mandates are binding only if they are enrolled in child care, child care enrollment status would provide an additional dimension across which treatment status would vary. These data are also limited in that they do not include information indicating whether patients received provider recommendations for different immunizations. As a result, I am unable to disentangle the effect of the ACIP recommendations on patient versus provider behavior.

[16] There were three cases of discrepancy between the IAC and CDC documents: Connecticut, Pennsylvania, and Wyoming. I verify that Connecticut and Pennsylvania do have hepatitis A mandates and Wyoming does not.

of Maricopa County, and so I exclude Arizona from my analyses.[17] Of the remaining 19 states, 11 implemented their first mandate during the years for which NIS hepatitis A vaccination data are available.

The specific years of implementation are given in Table 1. As is evident from this table, the implementation of a child care mandate is highly correlated with the implementation of a kindergarten mandate, and at present all states with kindergarten mandates also have childcare mandates in effect. Consequently I do not distinguish between the two types of mandates in my main analyses; I consider a state to have a hepatitis A mandate in effect if it has either a child care or kindergarten mandate.[18] In Figure 2 I graphically present the timing of the mandate implementations, grouped by incidence category. I find that, of the high incidence states that mandated, the majority did so prior to 2003. On the other hand, no low incidence state implemented a mandate prior to 2006, which coincides with the year ACIP extended their vaccination recommendation to include children in low incidence states.

To account for broad state differences in vaccine policy and childhood access to healthcare, I supplement my main data sources with annual state-level data on other child care and school vaccine mandates,[19] Vaccines For Children (VFC) provision policies, state Section

[17] As a robustness check I estimate the baseline model with Arizona included in the sample. Since Maricopa County contains over 60 percent of the residents of Arizona, I treat Arizona as if the mandate applied to the entire state. I find that my results are not sensitive to this inclusion.

[18] Although this may appear to be a strong assumption given that the NIS sample population is between 19 and 35 months of age, and therefore a child care mandate should bind more strongly than a kindergarten mandate, only in one state, Utah, was the kindergarten mandate enacted first. To test the sensitivity of my results to this assumption, I estimate the baseline model using the year the child care mandate was implemented as the treatment year. I find that the estimated mandate effect is smaller but remains marginally significant at the 10% level.

[19] Specifically, I include controls for childcare and school mandates for the hepatitis B, pneumococcal conjugate, varicella, influenza, Haemophilus Influenzae Type B, and rotavirus vaccines. To the best of my knowledge, these are the only other child care and school vaccine mandates that were implemented during my sample period.

317 funds,[20] mandated insurance coverage of childhood vaccines and well-child visits, non-medical exemption regulations, and Medicaid/SCHIP income eligibility thresholds, gathered from numerous sources.[21] I additionally use CPS data to control for differences in state economic and demographic characteristics (King et al., 2015). Included in my analysis are variables that capture the state unemployment rate, poverty rate, ethnic composition, population education attainment rates, and insurance coverage rates.

Descriptive statistics for the NIS sample are given in Tables 2a and 2b, and are presented separately by analysis subsample. For each subsample I further present the descriptive statistics both for the subset of individuals that had received at least one dose of the hepatitis A vaccine at the time of the survey and for those that had not. Individuals living in states with child care or kindergarten mandates are more likely to have initiated the hepatitis A vaccination series, as are those individuals living in states with historically higher incidence rates (and also therefore earlier ACIP recommendations for routine vaccination). The rate of initiation of hepatitis A vaccination is significantly higher in the 12-35 month old, 2007-2013 sample (73.7%) than in the 24-35 month old, 2003-2013 sample (55.0%), as is expected given that hepatitis A was

[20] Section 317 is a federal program that provides grant money to states to be used for purchasing of vaccines and implementing vaccine-related programs.

[21] Information on date of insurance mandate implementation comes from Chang (2016) and independent review of state statutes. I gather data on state VFC provision policies from the annual VFC Program Management Survey 2001-2010, which is collected by the CDC's National Center for Immunization and Respiratory Diseases. These data contain self-reports of the state VFC supply policy, provided by each state VFC Program coordinator. Section 317 funding data are available only for 1995-2003 and 2007-2013, and were graciously provided by Lenisa Chang and supplemented by data from IOM (2000) and CDC Congressional Justification Budget Request documents (retrieved from http://www.cdc.gov/budget/index.html). Historical information on non-medical exemption policies were gathered from Omer et al. (2006) and CDC and IAC publications. During my sample period, only two states, Arkansas and Texas, had substantive changes to their non-medical exemption policies. Both states added a personal belief exemption to their pre-existing religious exemption at the start of the 2003-2004 school year. Medicaid/SCHIP income eligibility thresholds are from the Kaiser Family Foundation (2015), Rosenbach et al. (2003) and Rosenbach et al. (2007).

universally recommended for the entire span of 2007-2013, and given that a larger fraction of the sample live in states with mandates during that period. For both subsamples I find that Hispanics vaccinate at a higher rate than other ethnicities, and that vaccination is increasing in mother's age. Interestingly, there is no monotonicity in vaccination rates for mother's education or household income.

1.4. Empirical Strategy & Results

In this section I describe each of the primary model specifications I estimate, and I present my main results. To estimate the effects of hepatitis A vaccine recommendations and mandates on vaccination rates and population disease incidence, I implement a difference-in-differences strategy that allows me to take advantage of the variation in the timing of policy implementations across states. I supplement the standard difference-in-differences model with an event study style model to test for dynamic policy effects.

1.4.1 Vaccination Baseline Results

First, using the individual-level vaccination data from the NIS, I estimate the effects of the ACIP recommendations and vaccine mandates on the probability of hepatitis A vaccination. In order to take advantage of the available household level socio-demographic information, the unit of analysis for this estimation is an individual. I estimate the following linear probability specification as my main equation:

$$(1) \quad \Pr(V_{ist} = 1 | X_{ist}, s, t) = \alpha Mandate_{st} + \gamma_1 strongACIP_{st} + \gamma_2 weakACIP_{st} + \beta X_{ist} + Z_{st} + \delta_s + \delta_t + \varepsilon_{ist},$$

where V_{ist} is an indicator for whether individual i living in state s at time t has been vaccinated against hepatitis A, and the variables $Mandate_{st}$, $strongACIP_{st}$, and $weakACIP_{st}$ are the

treatment variables of interest.[22] $Mandate_{st}$is a binary variable equal to one if the child lives in a state with a hepatitis A vaccination mandate in effect at time t, and $strongACIP_{st}$, and $weakACIP_{st}$ are each indicator variables describing whether the respective strong or weak ACIP recommendation is in effect at time t, with no ACIP recommendation as the omitted category. For all treatment variables the relevant policy changes are said to be in effect at the start of the calendar year following implementation.[23] The vector Z_{st} contains state-level controls,[24] and individual-level controls are captured by X_{ist}; the complete set of individual controls consists of the child's gender, age group, first-born status and race/ethnicity; mother's age group, marital status, and education level; and the number of children in the household as well as an indicator for whether the household ever received WIC. Finally, δ_s and δ_t are state and year fixed effects, respectively, and ε_{ist} is a random error term. All specifications are estimated using NIS provider-sample weights,[25] and standard errors are clustered at the state level to correct for within-state

[22]My primary outcome of interest is receipt of at least one dose of the hepatitis A vaccine (i.e. initiation of the hepatitis A vaccine series), although I also consider the effects of the policies on the receipt of two or more doses of the vaccine.

[23] To test the sensitivity of the results to this timing assumption, I additionally consider the following policy timing assumptions: (1) treat policy variables in effect for the entire calendar year in which they were implemented, (2) assign fractional treatment values in year of implementation, based on the number of months the policy was effective, and (3) omit observations from state-years that experienced a policy change. Given that there are two policies of interest - mandates and ACIP recommendations - I allow the timing assumption to differ across policy type and estimate the model for all combination of these timing assumptions. I find that the sign and significance of the policy variables are robust to these timing assumptions for the baseline model. The magnitudes also remain comparable, although estimated effect sizes are consistently smallest when policies are considered in effect for the entirety of their implementation year, and are largest when policies are considered in effect at the start of the calendar year following implementation.

[24] Included in all specifications are controls for state unemployment rate, poverty rate, ethnic composition, population education attainment rates, and insurance coverage rates. I additionally include a set of variables pertaining to state vaccine- and healthcare-related policies, which are discussed in more detail in what follows.

[25]In 2011 the NIS switched from exclusively using land-line telephones to including both land-line and cell phones in their sample. The 2011 dataset includes both 'dual weights,' which include both land lines

correlation in outcomes (Bertrand et al., 2004).

The inclusion of state fixed effects allows me to control for time-invariant unobservable state characteristics which may affect outcomes, while year fixed effects absorb the effects of unobservable shocks that are common across states. Therefore, as is standard in difference-in-differences models, identification relies on the 'common trend assumption' that in the absence of the policy, outcomes in the treated states would have evolved as in the untreated states. More precisely, to achieve identification I am assuming any unobserved *time-varying* state characteristics that affect outcomes are uncorrelated with treatment.

I do a number of things to provide support to this identification assumption. First, I control for a broad number of state vaccine- and healthcare-related policies that could feasibly affect vaccination rates and/or population disease incidence. Specifically, I control for other child care and school vaccine mandates, VFC provision policies, state Section 317 funding, childhood vaccine and well-child visit insurance coverage mandates, non-medical exemption laws, and Medicaid/SCHIP income eligibility thresholds.[26] Second, I augment some specifications with state-specific linear time trends, as this allows me to additionally control for state-specific unobservables that vary linearly over time. Third, in the event study model, I include a full set of

---

and cell phones, and land-line only weights, designed to make the 2011 estimates more directly comparable to previous survey waves. All data sets from subsequent years include only dual weights. For all reported estimates I use dual weights for 2012 and 2013, and land-line weights for all other years, although I verify that my baseline results are robust to using dual weights for 2011-2013 and land-line weights for 2003-2010 and also to not using weights.

[26] Since data on state VFC policies are available for only a restricted time period (2001-2010), I do not control for these policies in my baseline model. To ensure my results are not sensitive to this omission, I additionally estimate the baseline model for the restricted time period of 2003 to 2010 and include a set of dummy variables controlling for VFC policies. I find that my results are robust to the inclusion of controls for state VFC policies. Similarly, state Section 317 funds, which are available only for 1995-2003, 2007-2013, are not controlled for in my baseline specification. As a robustness check, I separately estimate the baseline model for the restricted years and include a 1-year lagged measure of total state Section 317 funds. My results are unaffected by the inclusion of this control.

policy leads, as this provides a test for potential policy endogeneity. Finally, as an additional test to see if my results are being driven by unobserved state differences that led to general increased uptake of vaccines or disease reduction, in Section 5.2 I estimate the effects of these policies on the vaccination rates and disease incidence of other diseases.

Results for the estimation of equation (1) are given in Table 3 and show the primary result that implementation of hepatitis A mandates and vaccine recommendations causes large and significant increases in the probability that young children are vaccinated against hepatitis A. The results from my preferred specification, presented in Panel A, Column 2, indicate that the strong and weak ACIP recommendations increase the probability of initiating the hepatitis A vaccine series by 27.3 and 19.3 percentage points, respectively, for the 24-35 month old, 2003-2013 subsample. Subsequent implementation of a state child care or kindergarten mandate significantly increases the probability of vaccination by an additional 8.18 percentage points. In Panel A, Column 1, I exclude individual and state-level controls, and these results suggest that although the sign and significance of the effects are unchanged when these controls are omitted, doing so may lead to the effects of the strong ACIP recommendation being overstated by nearly 26 percent. Finally, in Panel A, Column 3, I augment the full model with state-specific linear time trends; the sign and significance of the estimated effects are robust to this inclusion.[27]

Estimated effects of the hepatitis A mandate for the second subsample are given in Panel A, Columns 4 through 6,[28] and are slightly smaller than the effects for the first subsample. Given that these mandates are only binding if the child attends child care or kindergarten, and the

[27] Although not presented here, these results are also robust to the inclusion of higher order state-specific time trends.

[28] ACIP recommendation effects are estimated only for the 24-35 month old, 2003-2013 sample, as there were no changes in the recommendation for the other subsample's restricted time period (2007-2013), and thus the effects cannot be identified.

probability of ever having attended is likely increasing in age, then smaller effect sizes are expected for the sample that includes younger children, if all else is equal.

Overall, the magnitudes of these policy effects on the probability of initiation of the hepatitis A series are large in both absolute and relative terms. Between 2003 and 2013, the fraction of the population of children aged 24 to 35 months that had initiated the hepatitis A vaccination series increased by 73.4 percentage points, from 9.5 percent to 82.9 percent. Since my results indicate the receipt of a strong ACIP recommendation together with the implementation of a mandate increases the probability of vaccination by 35.5 percentage points, I estimate that the implementation of these policies explains approximately half of the increase in initiation of the hepatitis A vaccine series over this time period.

I next estimate the effects of the policies on the receipt of at least two doses of the hepatitis A vaccine. These results are presented in Table 3, Panel B. Given that two doses are the recommended number for the hepatitis A vaccine, using the receipt of at least two doses as the outcome variable may be a better measure of "full compliance" with vaccination recommendations and mandates.[29] The baseline estimates for the first subsample, given in Panel B, column 8, indicates that implementation of the hepatitis A mandate increases the probability of having received at least two hepatitis A shots by 8.11 percentage points. This effect size is nearly identical to the estimated effect on initiation of the hepatitis A vaccine series, and indicates that mandates are effective at inducing both initiation and completion of the vaccine series.

Unlike the estimates of the mandate effects, the estimates of the effects of the ACIP

[29] Ideally, my outcome variable would be a constructed measure of being up-to-date for the hepatitis A vaccine. This measure of vaccination would appropriately measure compliance to recommendations and mandates by taking into account that the 2nd dose of hepatitis A should be administered 6-18 months after receipt of the first dose, and therefore some individuals who presently only had one dose may still be "fully compliant." Unfortunately, the NIS does not include an up-to-date measure for hepatitis A.

recommendations on receipt of at least two hepatitis A shots vary significantly from the estimated effects on initiation of the vaccine series. Specifically, the ACIP recommendation effect estimates presented in Panel B, column 8 are negative, though insignificant; the addition of linear state time trends yields negative and significant estimates of the effects (column 9).
It is important to note that since the second dose of the hepatitis A vaccine is to be administered between 6 and 18 months after the first, the lagged policy dummy variable specification implemented here is potentially inappropriate to capture the effects of these policies on receipt of two doses of the vaccine. To address this, I supplement this analysis with a more flexible event study style model, the results of which are presented graphically in Appendix Figure 2.[30] The results from this estimation support the causal interpretation that the mandate significantly increases the probability of having received two doses of the vaccine, while the ACIP recommendations have no significant effects.

The lack of significant effects of the ACIP recommendation in the main specification could be indicative that policy 'nudges' towards vaccination, such as the recommendations, are effective only at increasing initiation of a vaccination series, and do not increase the probability of completing the series. Importantly, in the case of the hepatitis A vaccine, which results in 95 to 97 percent of individuals developing the protective antibody after the first dose, we should still expect large morbidity effects from a policy that induces initiation but not completion of the vaccine series.

1.4.2 Morbidity Baseline Results

Next, using surveillance data from the CDC National Notifiable Disease Surveillance

[30] Specifically, I estimate the model given in equation (3), which allows the effect of the policies to vary over time, with 'receipt of 2+ doses' as the outcome variable.

System, I estimate the effects of the hepatitis A vaccine policies on the rate of hepatitis A disease incidence in the population. As in the previous analysis, I implement a difference-in-difference strategy. Since all morbidity data are aggregated by state, however, these analyses are done at the state level. Specifically, I estimate the following equation:

$$(2) \quad R_{st} = \alpha Mandate_{st} + \gamma_1 strongACIP_{st} + \gamma_2 weakACIP_{st} + Z_{st} + \delta_s + \delta_t + \varepsilon_{st},$$

where R_{st} is the rate of hepatitis A per 100,000 people in state s at time t, and all other variables are defined as in equation (1). Specifications are estimated using relevant population weights, and standard errors are clustered at the state level. As with the individual-level regression, I include state-specific linear time trends in some specifications to increase the flexibility of the model.

Results from the estimation of equation (2) are presented in Table 4, and show that the ACIP hepatitis A recommendations and vaccine mandates had large and statistically significant effects on the incidence of hepatitis A in the entire population. These estimates suggest that omitting time-varying state-level controls (column 1) results in a substantial understatement of the effects of the strong ACIP recommendation, although the sign and significance of the result is unaffected and the estimated magnitudes of the other policy effects are largely unchanged. I also find that, as with the vaccination results, the estimated policy effects are generally robust to the addition of state-specific linear time trends (column 3). Given the large gains in explanatory power from the inclusion of state-specific linear time trends (R^2 increases from 0.73 in column 2, to 0.85 in column 3), column 3 is my preferred specification. The estimates from this specification imply that the implementation of a hepatitis A child care or kindergarten mandate in a state reduced hepatitis A incidence in that state by approximately 1.5 cases per 100,000 people, while the strong and weak ACIP recommendations reduced incidence by 4.3 and 3.3

cases per 100,000 people, respectively.[31]

The effects of these policies on hepatitis A incidence are large in both absolute and relative magnitudes. Over this time period, the average annual incidence of acute hepatitis A per 100,000 people declined from 10.5 cases in 1997 to .558 cases in 2013. Implementation of both a strong ACIP recommendation and a vaccination mandate is estimated to have reduced disease incidence by 5.8 cases per 100,000 people, which accounts for nearly 60 percent of the decline in the incidence of hepatitis A over this time period.[32] When interpreting these results, it is important to note that although the timing and strength of the ACIP recommendations were determined at the federal level and relative to somewhat arbitrary thresholds, an endogeneity concern persists since implementation was based on historic state morbidity rates. As such, the estimated effects of the recommendations on morbidity should be interpreted with caution.

1.4.3 Dynamic Policy Effects Model

Having shown that the ACIP recommendations and vaccine mandates have large and significant contemporaneous effects on both vaccination rates and disease incidence, I now explore the potential for dynamic policy effects. For this analysis, I estimate an event study type model, in which I replace each single policy indicator variable with a series of indicator variables

[31] To aid in comparison between the estimated vaccination effects and the morbidity effects, I estimate a model where the outcome variable is ln(*HepA cases)*, the results of which are presented in Appendix Table 2. The results of this estimation imply that the implementation of both a mandate and a strong recommendation decrease disease incidence by between 30 and 36 percent, though the mandate effect is sensitive to the inclusion of linear time trends. I additionally re-estimate the baseline morbidity model for the years 2003-2013, to match the time period of the vaccination results. The hepatitis A mandate effect remains negative and significant, and, when scaled by the change in disease incidence over the relevant time period, the relative magnitude of the coefficient is nearly identical. The effects of the ACIP recommendations, however, are statistically indistinguishable from zero for this restricted time period, although they are identified from very different sources of variation than in the full sample.

[32] This result is broadly consistent with the effect size in Zhou et al. (2007), who find that an ACIP recommendation explains 72 percent of the decline in hepatitis A-related ambulatory care visits among an insured population between 1996 and 2004 (with an implied difference-in-difference coefficient of -8.8 cases per 100,000 individuals),

representing the number of periods relative to policy implementation. I additionally include in the specification a full set of policy leads, as this allows me to test whether the policies were endogenously implemented in response to previous trends in vaccination rates or disease incidence.

Dynamic Policy Vaccination Results

For the analysis of the policy effects on vaccination rates, in which the individual is the unit of analysis, I estimate the following linear probability model:

$$(3) \qquad \Pr(V_i = 1 | X_{ist}, s, t) = \sum_{k \in K} \alpha_k \, Mandate_{st}^{k} + \sum_{k \in K} \gamma_{1k} \, strongACIP_{st}{}^{k} + \sum_{k \in K} \gamma_{2k} \, weakACIP_{st}{}^{k} + \beta X_{ist} + Z_{st} + \delta_s + \delta_t + \varepsilon_{ist},$$

in which $Mandate_{st}^{k}$ is a dummy variable equal to 1 if the mandate has been implemented for k periods, $K = \{< -5, -5, \ldots, -1, 1, \ldots 7, > 7\}$, and is zero otherwise, with the year of mandate implementation ($k = 0$) as the omitted category. Similarly, $strongACIP_{st}{}^{k}$ and $weakACIP_{st}{}^{k}$ are dummy variables equal to 1 if the recommendation has been effective for k periods, and are zero otherwise.[33] For all estimations of the dynamic policy model, I include the state vaccine-related policy controls; all other variables are as defined in equation (1).

The estimated dynamic policy effects of the ACIP recommendations and of the vaccine mandate on the probability of initiating the hepatitis A vaccine series are presented graphically in Figures 3a and 3b, respectively.[34] In this model, each of the event study coefficients captures the

[33] Because vaccination data are not available prior to 2003, the strong ACIP recommendation coefficients are identified only for *k* = -3, -2, -1,1, …7, >7, while the weak ACIP recommendation coefficients are identified only for *k*= 4, 5, 6, 7.

[34] For the dynamic policy model, I provide estimation results only for the 2003-2013 sample of 24-35 month olds, as it is unclear how to appropriately adjust the event study dummies for the 19-23 month old

effect of the policy relative to the year of implementation, and therefore should not to be interpreted as the per-period effects of the policy, but rather as the cumulative effect. Specifically, these coefficient estimates imply that the vaccination mandate increases the probability of initiating the vaccine series by 7.96 percentage points in the first year following implementation, and an additional year of the policy further increases the probability of initiating vaccination by 1.26 percentage points. Overall, however, the estimated mandate effects indicate that there are no additional sizable gains in the probability of initiating the vaccine series after the first period, and the total effect size is comparable in magnitude to the estimated effect from the baseline difference-in-differences model. Essentially, I find that the individuals who are induced by the mandate to initiate vaccination respond quickly to the policy.

In contrast, this model indicates that the effects of the strong ACIP recommendation steadily increase for up to four years following implementation, and thus the baseline difference-in-differences model understates the total effect of the strong recommendation. I find that there are additional gains to the probability of initiating the hepatitis A series of between 5.5 and 13.8 percentage points per year in the first four years following implementation, after which the cumulative effect levels out at approximately 39 to 46 percentage points. For the weak ACIP recommendation, it is difficult to accurately assess the extent to which dynamic policy effects are present as the coefficients are identified for only 4 to 7 years post implementation due to data limitations. These coefficients do indicate, however, that the total effect size is approximately 20 percentage points, which is comparable in magnitude to the difference-in-difference estimate.

Endogenous policy implementation – As a test for endogenous implementation of

---

age group to account for mandates that were implemented prior to or shortly after the time the vaccine was approved for that age group. Additionally, since the weak ACIP recommendation coefficients are only identified for periods 4 through 7 after implementation, I do not present these graphically in the main text of the paper, but I do present them in Appendix Figure 1.

hepatitis A vaccine mandates or strong ACIP recommendations, I consider the coefficients on the policy leads in Figure 3. Significant coefficients on the policy leads would indicate that the policies were implemented in response to pre-existing trends in vaccination rates, and this would limit the causal interpretation of my results. I find that, relative to the coefficients on the policy lags, the coefficients on the leads are much smaller in magnitude and are generally insignificant. This serves as strong evidence that the hepatitis A vaccine mandates and strong ACIP recommendations were not endogenously implemented in response to particularly low (or high) vaccination rates, and this supports the causal interpretation of my vaccination results.

Dynamic Policy Morbidity Results

To estimate the dynamic policy effects of vaccination mandates and ACIP recommendations on disease incidence, I modify equation (3) to account for the higher level of aggregation in the NNDSS data. Specifically, I estimate the following:

$$(4) \quad R_{st} = \sum_{k \in K} \alpha_k \, Mandate_{st}^{k} + \sum_{k \in K} \gamma_{1k} \, strongACIP_{st}{}^{k} + \sum_{k \in K} \gamma_{2k} \, weakACIP_{st}{}^{k} + Z_{st} + \delta_s + \delta_t + \varepsilon_{st},$$

where, as defined previously, R_{st} is the rate of hepatitis A per 100,000 people in state s at time t, and $Mandate_{st}^{k}$, $strongACIP_{st}{}^{k}$, and $weakACIP_{st}{}^{k}$ are indicator variables equal to 1 if the policy has been implemented for k periods, $K = \{< -5, -5, \dots, -1, 1, \dots 7, > 7\}$, and are zero otherwise, with the year of implementation ($k = 0$) as the omitted category. All other variables are as in equation (3).

Results from the estimation of the event study model specified in equation (4) are presented graphically in Figure 4. The point estimates for the mandate effects indicate that the mandates reduce population hepatitis A incidence by 0.76 cases per 100,000 people after year one of implementation; after two years the cumulative effect increases in absolute magnitude to a

reduction of 1.62 cases per 100,000 people, and after 4 years mandates are estimated to reduce hepatitis A incidence by 1.93 cases per 100,000 people. Unfortunately, limited precision in the estimated mandate effects make it difficult to identify the extent to which the effects vary over time.

For the ACIP recommendations, the event study coefficients indicate dynamic policy effects on disease incidence. The effect of the strong recommendation is large and immediate, and generally increasing over time. Specifically, the strong ACIP recommendation reduces hepatitis A incidence by 2.37 cases per 100,000 people within one year of implementation, and by 7 years following implementation the estimated effect is a reduction of approximately 4.40 cases per 100,000 people. On the other hand, the weak recommendation has a large effect within two years of implementation, but the effect size rapidly declines and is statistically not different from zero by 5 years following implementation.

Endogenous policy implementation - As in the previous section, I consider the coefficients on the policy leads as a test determine whether the mandates or ACIP recommendations were implemented in response to pre-existing trends in the outcome variable. For the mandates, coefficients on the policy leads are relatively small in magnitude and are insignificant, providing evidence that states did not implement the mandates in response to particularly high (or low) hepatitis A morbidity rates. For both the strong and weak ACIP recommendations, however, the coefficients for the pre-implementation dummies are large and positive, indicating the policies were implemented in states with particularly high morbidity rates. This result is not unexpected, as the 1999 ACIP recommendations were implemented based on the average state morbidity rate for 1987-1997, but it suggests that the magnitude of the ACIP recommendation effects on morbidity should be interpreted cautiously.

1.5. Additional Results

In this section I explore potential heterogeneity in policy response across different subpopulations and estimate the effects of the hepatitis A-targeted policies on the vaccination and disease incidence rates of other diseases. I also introduce an additional data source that allows me to directly estimate how the effect of the vaccination mandate varies by child care enrollment status. These additional analyses allow for a more complete understanding of the effects of the policies, and also provide insight into the mechanism through which child care mandates increase vaccination rates in young children.

1.5.1 Heterogeneous policy effects by subpopulation

Up to this point, my analysis has focused on identifying the average effects of the policies across the entire population of interest. While this is a useful metric for the overall effectiveness of a policy, it also has the potential to conceal substantial heterogeneity in the policy effects across different subpopulations. In the case of public health policies, heterogeneous policy responses can have important implications for the extent to which a policy affects the magnitude of existing health disparities across socioeconomic groups. This is a particularly relevant consideration for hepatitis A, as the disease has historically been endemic among otherwise disadvantaged populations, such as Hispanics, Native Americans, and Alaskan natives.

To test for heterogeneous policy effects across subpopulations, I estimate the effects of the policies on the probability of initiating the hepatitis A vaccine series separately by race/ethnicity, mother's education, and household income, using the baseline model given in

equation (1).[35] I present the results from these estimations in Table 5, and, to aid in interpretation, I scale the estimates by the within-group change in hepatitis A vaccination rates over the sample period. Overall, the results indicate that there is very little difference in the magnitude of the mandate effect across different races/ethnicities, levels of education, or family income groups. Across these subpopulations, the mandate consistently explains between 9.5 and 13.1 percent of the total change in hepatitis A vaccination initiation rates that took place between 2003 and 2013.

For the ACIP recommendations, however, there is some evidence of a heterogeneous policy response. Across ethnic groups, the strong ACIP recommendation increased the probability of initiating hepatitis A vaccination by 26 percentage points for whites, as compared to increases of approximately 30 to 33 percentage points for the other ethnic groups. This policy also explains a much smaller fraction of the total increase in vaccination for whites than for the other groups. The analysis by mother's education and family income indicates that the strong ACIP recommendation was most effective at increasing vaccination at the tails of these distributions. The estimates by education level show that the smallest effect is for children whose mothers have only a high school degree; the estimates by family income level show that the smallest effects are for households making between $30,000 and $50,000 a year. The effects of the weak ACIP recommendation follow a pattern similar to the strong ACIP recommendation for the estimations done separately by ethnicity and family income. For mother's education level, however, the effect of the weak ACIP recommendation is monotonically decreasing as education increases. Unfortunately, given the number of mechanisms through which the ACIP

[35] For simplicity, I include the estimation results by subpopulation for only one of the NIS subsamples (2003-2013 subsample of 24-35 month olds). Results for the 2007-2013 sample of 19-35 month olds are qualitatively similar, but suffer from a lack of precision.

recommendations potentially affect the individual's decision to vaccinate, without finer data it is difficult to determine what is driving the differential response to the ACIP recommendations.

1.5.2 Effects on other vaccines and diseases

I next estimate the effects of hepatitis A vaccination recommendations and mandates on receipt of other vaccines and the incidence of other diseases, as this allows me to identify the existence of spillover effects of hepatitis A vaccination policy, and also serves as a falsification test. First, I estimate the baseline model given in equation (1) with receipt of other recommended childhood vaccines as the dependent variable. The results for this estimation are presented in Appendix Table 3; they indicate that there are no substantial spillovers of the hepatitis A vaccine policy on vaccination rates for other childhood vaccines.[36] Second, as a falsification test for my morbidity results, I estimate the baseline model given in equation (2) with incidence rates for a number of other diseases as the dependent variable.[37] These results are presented in Appendix Table 4 and suggest that the hepatitis A vaccine policies were not associated with significant reductions in the incidence of other diseases. Overall, these results provide strong evidence that the reductions in hepatitis A morbidity were driven by the hepatitis A-targeted vaccine policies and not by unobserved state characteristics that generally increased vaccination or reduced disease incidence.

[36] This result is expected, as all states had child care and school vaccination mandates implemented for at least some subset of the recommended childhood vaccines prior to the development of the hepatitis A vaccine.

[37] Specifically, I consider the effects of the hepatitis A vaccine policies on the incidence of three diseases for which childhood vaccination is routinely recommended (hepatitis B, measles, and pertussis, selected from the full set of diseases with recommended childhood vaccines based on the fact that they were nationally notifiable diseases for the duration of my sample period), as well as the effects on several other diseases which are either not vaccine-preventable but have similar modes of transmission and risk factors as hepatitis A (giardia and salmonella), or are vaccine-preventable but not routinely recommended for young children (meningococcal disease and tuberculosis).

1.5.3. Mandate effects by child care attendance

Since the hepatitis A vaccination mandates are binding for very young children only if they are enrolled in child care, my *ex ante* expectation is that the mandates are effective at inducing vaccination primarily among enrolled children. Since child care enrollment status is not available in the NIS data, to test this hypothesis I analyze a cross-section of data from the National Survey of Children's Health (NSCH) which in 2003 contained questions on both child care attendance and hepatitis A vaccine receipt.[38] Using these data, I estimate a difference-in-differences model in which treatment varies by child care enrollment and state mandate status. Specifically, I estimate the following linear probability model:

$$(5) \quad \Pr(V_{is} = 1 | X_{is}, s) = \alpha_1 Mandate_s + \alpha_2 attendChildcare_i + \delta[Mandate_s \times attendChildcare_i] + \beta X_{is} + Z_s + \varepsilon_{is}.$$

Here, V_{is} is an indicator specifying whether individual i in state s has been vaccinated against hepatitis A, $Mandate_s$ is an indicator specifying if the state had a child care mandate implemented as of 2003, and $attendChildcare_i$ is an indicator variable equal to 1 if the child is enrolled in child care and is zero otherwise;[39] the interaction term $Mandate_s \times attendChildcare_i$ is the treatment variable of interest in this specification. I also

[38] This survey is conducted by the CDC and makes use of the NIS sampling frame to create state- and nationally-representative estimates of health measures for children aged 0-17 years. Hepatitis A questions were asked only in states that, at the time, had received an ACIP recommendation (i.e. high and medium hepatitis A incidence states), and were asked only to children over the age of 2, as the vaccine was not yet approved for younger children.

[39] Based on the survey questions in these data, I define child care enrollment as "regular attendance in the past month at a child care center outside the home or at an early head start program."

include a vector of household controls,X_{is},[40] and a vector of state controls, Z_s. I restrict my analysis to children between the ages of 2 and 4 years old, to ensure they are both old enough to receive the vaccine and too young to be enrolled in kindergarten.

Results from the estimation of equation (5) are presented in Table 6, and show that children enrolled in child care in mandating states are between 7 and 8 percentage points more likely to have initiated or completed the hepatitis A vaccine series relative to both (a) children in mandating states who are not enrolled in child care, and (b) children in non-mandating states who are enrolled in child care. These mandate-child care interaction effects are consistent with the mandate estimates obtained using NIS data and time-series variation, which suggested mandates causally increased the probability of vaccination by approximately 8 percentage points. A limitation of these results is that they cannot be interpreted as the causal effect of the mandate on vaccination rates, as this design and the cross-sectional nature of these data do not allow me to control for unobserved time-invariant differences across states. However, taken in context of the previous findings, these results are highly supportive of the hypothesis that mandates serve to primarily induce vaccination among individuals for whom the mandate is binding.

1.6. Conclusion

In the United States, immunization rates are persistently low for numerous vaccines, and recently there have been multiple outbreaks of vaccine-preventable diseases resulting from undervaccination. In response, a number of policies have been implemented in an attempt to achieve and maintain high population vaccination rates and reduce disease incidence. In this

[40] These controls were chosen to be generally comparable to the individuals controls included in earlier specifications, and include measures of the number of adults in the household, highest education level in household, total number of children in household, whether the child is the first born, as well as child's gender, ethnicity, age, and insurance status.

paper I showed that the implementation of ACIP recommendations and vaccination mandates has large and significant effects on both vaccination rates of young children and population disease incidence. Using variation across states in the timing of the policy introductions, I find that the strong ACIP recommendation and the hepatitis A vaccination mandate together explain approximately half of the change in vaccination rates and hepatitis A incidence over the sample periods. These results are robust to the inclusion of both a number of controls for state vaccine- and healthcare-related policies, and state-specific linear time trends. I also demonstrate that these results are not present for other vaccines and diseases, which is strong evidence that my findings are not being driven by unobserved state policies that generally increased vaccination or decreased disease incidence.

This paper further provides evidence that the effects of the ACIP recommendations and the mandates differ along several important dimensions. First, my results indicate that the mandates are effective at inducing individuals to complete the vaccine series, while the ACIP recommendations only significantly increase the probability that individuals initiate the series. Second, when I allow policy effects to vary over time, I find that individuals who are induced to vaccinate by the mandate respond rapidly to the policy, whereas the ACIP recommendations have a more gradual effect that continues to increase for several years following implementation. Finally, for the mandates I find no significant heterogeneity in the effects with respect to ethnicity, mother's education, or family income, although there is some evidence of a heterogeneous policy response for the recommendations.

This study has several limitations. Notably, the data sources I use do not allow me to disentangle the specific channels through which mandates and recommendations affect the decision to vaccinate. In order to better inform policy and understand the individual's

vaccination decision, future research is needed to identify these mechanisms. A further limitation of this paper is that the results are specific to hepatitis A. If individuals make vaccination decisions based on disease-specific characteristics such as severity, prevalence, or vaccination cost, then it is difficult to extrapolate these results to other vaccines and diseases. In particular, we should expect the responsiveness of individuals to these policies to be different in the case of hepatitis A, where the population that is targeted for routine vaccination (young children) typically experiences asymptomatic infections, as compared to diseases such as measles and pertussis where there are more severe morbidity consequences for the targeted group.

1.7. References

Abrevaya, Jason, and Mulligan, Karen, 2011. Effectiveness of state-level vaccination mandates: Evidence from the varicella vaccine. Journal of Health Economics 30, 966-976.

Bertrand, Marianne, Duflo, Esther, and Mullainathan, Sendhil, 2004. How Much Should We Trust Differences-in-Differences Estimates? The Quarterly Journal of Economics 19(1), 249-275.

Bialek, Stephanie R., Thoroughman, Douglas A., Hu, Diana, Simard, Edgar P., Chattin, Jody, Cheek, Jim, and Bell, Beth P., 2004. Hepatitis A Incidence and Hepatitis A Vaccination Among American Indians and Alaska Natives, 1990-2001. American Journal of Public Health 94(6), 996-1001.

Centers for Disease Control and Prevention, 1996. Prevention of Hepatitis A Through Active or Passive Immunization: Recommendations of the Advisory Committee on Immunization Practices. *Morbidity and Mortality Weekly Report* **45**: 1-30.

Centers for Disease Control and Prevention, 1999. Prevention of Hepatitis A Through Active or Passive Immunization: Recommendations of the Advisory Committee on Immunization Practices. *Morbidity and Mortality Weekly Report* **48**: 1-38.

Centers for Disease Control and Prevention, 2006. Prevention of Hepatitis A Through Active or Passive Immunization: Recommendations of the Advisory Committee on Immunization Practices. *Morbidity and Mortality Weekly Report* **55**: 1-23.

Centers for Disease Control and Prevention, 2009. Invasive *Haemophilus influenza* type b

disease in five young children – Minnesota, 2008. *Morbidity and Mortality Weekly Report* **58**: 58-60.

Centers for Disease Control and Prevention, 2012. "Hepatitis A." In Atkinson, W., Wolfe, S., and Hamborsky, J. (Eds.), *Epidemiology and Prevention of Vaccine-Preventable Diseases* 12th ed., 101-114. Washington DC: Public Health Foundation.

Centers for Disease Control and Prevention, 2013. Surveillance for Viral Hepatitis – United States, 2013. http://www.cdc.gov/hepatitis/statistics/2013surveillance/index.htm. [20 June 2015].

Centers for Disease Control and Prevention, 2014a. History of Vaccine Safety. http://www.cdc.gov/vaccinesafety/Vaccine_Monitoring/history.html. [20 June 2015].

Centers for Disease Control and Prevention, 2014b. Vaccines for Children Program. http://www.cdc.gov/vaccines/programs/vfc/about/index.html. [20 June 2015].

Chang, Lenisa V., 2016. The Effect of State Insurance Mandates on Infant Immunization Rates. Health Economics 25(3): 372-386.

Dorell, Christina G., Yankey, David, Byrd, Kathy K., and Murphy, Trudy V., 2012. Hepatitis A vaccination coverage among adolescents in the United States. Pediatrics, peds-2011

Gahr, Pamala, DeVries, Aaron S., Wallace, Gregory, Miller, Claudia, Kenyon, Cynthia, Sweet, Kristin, Martin, Karen, et al., 2014. An Outbreak of Measles in an Undervaccinated Community. Pediatrics 134(1), e220-e228.

Institute of Medicine, 2000. Calling the Shots: Immunization Finance Policies and Practices. National Academy Press: Washington, D.C.

Institute of Medicine, 2013. The Childhood Immunization Schedule and Safety: Stakeholder concerns, scientific evidence, and future studies. National Academy Press: Washington, D.C.

Kaiser Family Foundation, 2015. Medicaid/CHIP Upper Income Eligibility Limits for Children, 2000-2015. http://kff.org/medicaid/state-indicator/medicaidchip-upper-income-eligibility-limits-for-children-2000-2015/ [24 August 2015].

King, Miriam, et al**.** 2015. *Integrated Public Use Microdata Series, Current Population Survey: Version 3.0***.** [Machine-readable database]. Minneapolis: University of Minnesota**.**

Lipton, Brandy J., and Decker, Sandra L., 2015. ACA Provision Associated With Increase in Percentage of Young Adult Women Initiating and Completing the HPV Vaccine. Health Affairs 34(5), 757-764.

Luca, Dara Lee, 2014. The Long-Term Effects of Post-Neonatal Childhood Health: Evidence from Mandatory School Vaccination Laws. Working paper.

Malone, Kevin M., and Hinman, Alan R.., 2003. Vaccination mandates: the public health imperative and individual rights. Law in public health practice, 262-84.

National Council of State Legislatures, 2015a. Immunizations Policy Issues Overview. http://www.ncsl.org/research/health/immunizations-policy-issues-overview.aspx. [27 June 2015].

National Council of State Legislatures, 2015b. States With Religious and Philosophical Exemptions from School Immunization Requirements. http://www.ncsl.org/research/health/school-immunization-exemption-state-laws.aspx . [27 June 2015].

Parker, Amy A., Staggs, Wayne, and Dayan, Gustavo H., 2006. Implications of a 2005 measles outbreak in Indiana for sustained elimination of measles in the United States. New England Journal of Medicine 355, 447-455.

Philipson, Tomas, 2000. Economic epidemiology and infectious diseases. *Handbook of Health Economics*, *1*, 1761-1799.

Rosenbach, Margo et al., 2003. Implementation of the State Children's Health Insurance Program: Synthesis of State Evaluation. Mathematica Policy Research.

Rosenbach, Margo et al., 2007. National Evaluation of the State Children's Health Insurance Program: A Decade of Expanding Coverage and Improving Access. Mathematica Policy Research.

Singleton, Rosalyn J., Hess, Sarah, Bulkow, Lisa R., Castrodale, Louisa, Provo, Ginger, and McMahon, Brian J., 2010. Impact of a Statewide Childhood Vaccine Program in Controlling Hepatitis A Virus Infections in Alaska. Vaccine 28, 6298-6304.

U.S. Department of Health and Human Services. Healthy People 2020: Immunization and Infectious diseases. http://www.healthypeople.gov/2020/topics-objectives/topic/immunization-and-infectious-diseases/objectives. [27 June 2015].

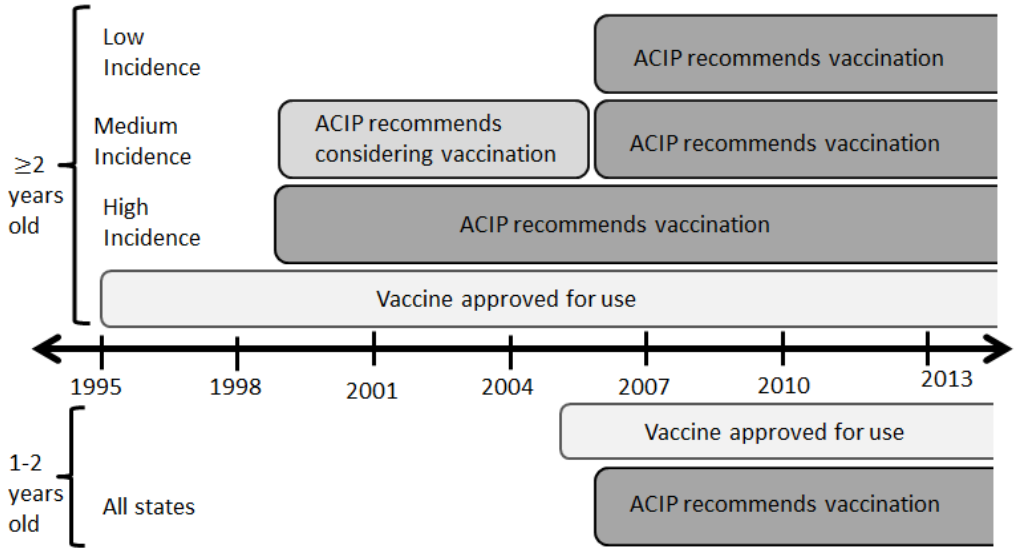
Ward, Courtney J., 2011. The Effects of Immunization Mandates: Does Prenatal Exposure to State School Immunization Policy Impact Later Economic Well-Being? Dalhousie University Working Paper.

Ward, Courtney J. , 2014. Influenza Vaccination Campaigns: Is an Ounce of Prevention Worth a Pound of Cure?. American Economic Journal: Applied Economics 6(1), 38-72.

Wasley, Annemarie, Samandari, Taraz, and Bell, Beth P., 2005. Incidence of Hepatitis A in the United States in the Era of Vaccination. Journal of the American Medical Association 294(2), 194-201.

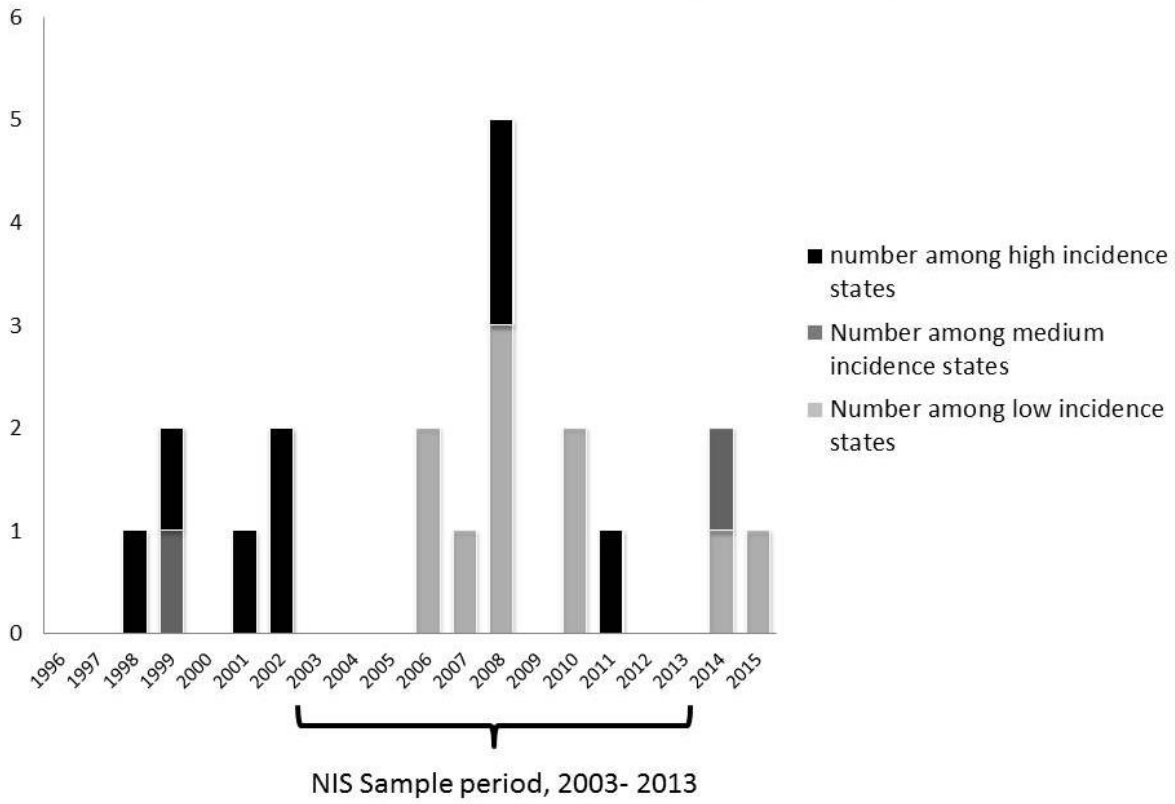
Zhou, Fangjun, Shefer, Abigail, Weinbaum, Cindy, McCauley, Mary, and Kong, Yuan, 2007. Impact of hepatitis A vaccination on health care utilization in the United States, 1996-2004. Vaccine 25, 3581-3587.

Figure 1**:** Timeline of Hepatitis A Vaccine Approval and ACIP Recommendations, 1995-2013



Notes: Figure created by author using information from CDC (1996, 1999, 2006, 2012).

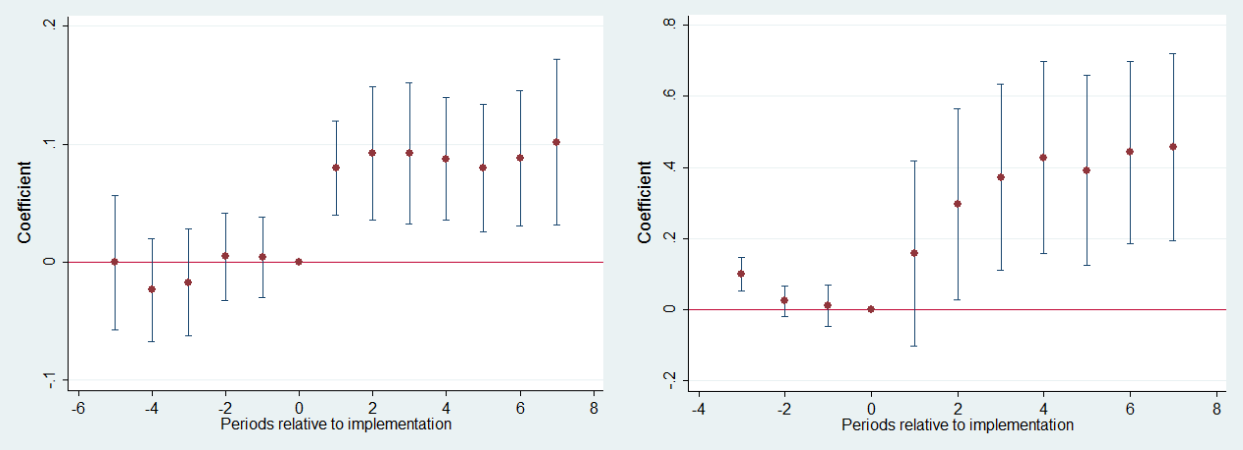
Figure 2**:** Number of Mandates per Year, by Incidence Group



Notes: Figure created by author using information from IAC and CDC publications, and independent review of state statutes.

Figure 3**:** Initiation of vaccination results, event study coefficients

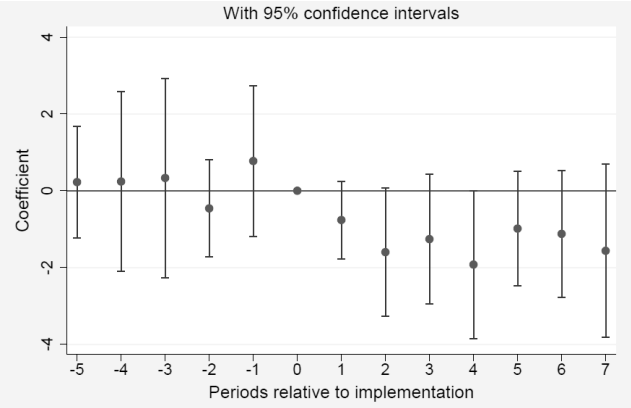
(a) Mandate coefficients (b) Strong ACIP rec. coefficients



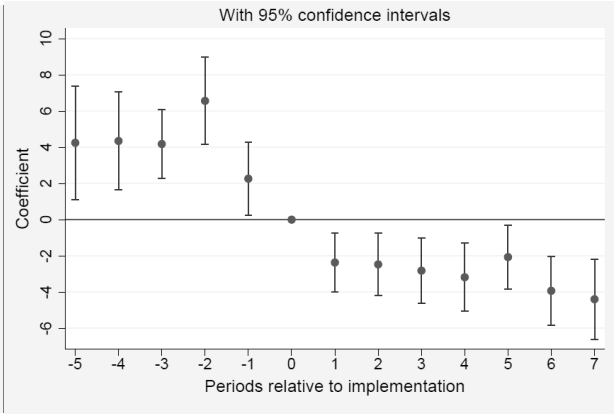
Notes: Each figure presents a subset of the estimated coefficients from a single regression done using data from the National Immunization Survey, where the outcome variable is receipt of at least one dose of the hepatitis A vaccine. The sample is restricted to children 24-35 months of age, for 2003-2013. State and year fixed effects and a full set of individual and state-level controls are included in the regression, as specified in the empirical strategy. The regression is estimated using NIS-Provider weights; standard errors are clustered at the state level and coefficients are shown with 95% confidence intervals.

Figure 4: Morbidity results, event study coefficients

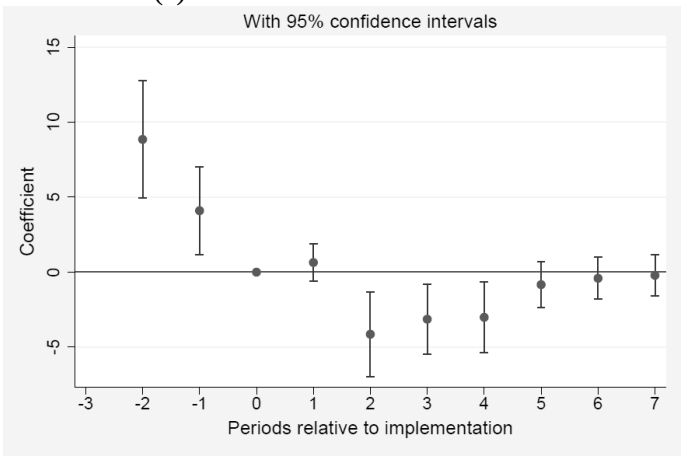
(a) Mandate coefficients



(b) Strong ACIP rec. coefficients



(c) Weak ACIP rec. coefficients



Notes: Each figure presents a subset of the estimated coefficients from a single regression done using data from the CDC's NNDSS, 1997-2013, where the outcome variable is number of reported hepatitis A cases per 100,000 people. State and year fixed effects and a full set of state-level controls are included in the regression, as specified in the empirical strategy. The regression is estimated using NIS-Provider weights; standard errors are clustered at the state level and coefficients are shown with 95% confidence intervals.

Table 1: Year of Hepatitis A Mandate Implementation

	Year in effect			Year in effect	
State	Child care	Kindergarten	State	Child care	Kindergarten
Alaska	2001	2001	New Mexico	2008	
Arizona	1999*		North Dakota	2008	
Arkansas	2014	2014	Oklahoma	1998	1998
Connecticut	2010	2011	Oregon	2008	2008
Dist. of Columbia	2008	2008	Pennsylvania	2006	
Georgia	2007	2007	Rhode Island	2015	
Idaho	2011	2011	Tennessee	2010	2011
Kansas	2008		Texas	1999	2009
Minnesota	2014		Utah	2008	2002
Nevada	2002	2002	West Virginia	2006	

Sources: Immunization Action Coalition, CDC, state Department of Health websites, and state statutes.
Notes: If a state is not listed that indicates it did not pass a mandate as of January 1, 2015.
*Required in Maricopa County only

Table 2-A**:** Descriptive Statistics, National Immunization Survey

	24-35 months old, 2003-2013			
	Full Sample (mean)	**Vaccinated subsample (mean)**	**Unvaccinated subsample (mean)**	**Fraction vaccinated, HepA**
Child Characteristics:				
Vaccinated, HepA†	0.55	1	0	1
Vaccinated, UTD 4:3:1:3	0.833	0.89	0.764	0.587
Female	0.487	0.486	0.488	0.549
Male	0.513	0.514	0.512	0.55
Hispanic	0.253	0.306	0.188	0.666
White	0.519	0.459	0.592	0.487
Black	0.131	0.124	0.14	0.52
Other ethnicity	0.097	0.111	0.081	0.626
Age:19-23 mos	0	0	0	0
Age: 24-29 mos	0.486	0.483	0.489	0.547
Age: 30-25 mos	0.514	0.517	0.511	0.552
State of Residence Characteristics:				
Effective mandate	0.204	0.291	0.099	0.782
High incid.	0.22	0.294	0.129	0.736
Medium incid.	0.146	0.173	0.114	0.649
Low incid.	0.634	0.533	0.757	0.462
Mother Characteristics:				
Age: <20 yrs	0.022	0.021	0.023	0.524
Age: 20-29 yrs	0.395	0.382	0.411	0.532
Age: 30+ yrs	0.583	0.597	0.566	0.563
<High school	0.18	0.193	0.163	0.592
High school	0.302	0.284	0.323	0.518
Some college	0.201	0.201	0.202	0.548
College grad	0.317	0.322	0.312	0.558
Income: <$20K	0.278	0.297	0.255	0.587
Income: $20-30K	0.130	0.129	0.132	0.544
Income:$30-40K	0.0979	0.0896	0.108	0.503
Income:$40-50K	0.0765	0.0684	0.0862	0.492
Income: $50K+	0.417	0.416	0.419	0.548
Observations	127589	64942	62647	

Notes: Author's calculations from NIS provider-sample data. UTD 4:3:1:3 is an indicator for if the child is up-to-date on a standard set of shots, which consists of 4+ doses of diphtheria and tetanus, 3+ doses of polio, 1+ dose of measles, and 3+ doses of Haemophilus Influenzae Type B vaccines. All estimates exclude Arizona, obtained using weights NIS-provider weights (landline only for 2003-2011, dual weights for 2012 and 2013). † For the purposes of this table, a child is considered vaccinated against hepatitis A if they have initiated the hepatitis A vaccine series.

Table 2-B**:** Descriptive Statistics, National Immunization Survey

	19-35 months, 2007-2013			
	Full sample (mean)	**Vaccinated Subsample (mean)**	**Unvaccinated subsample (mean)**	**Fraction vaccinated, HepA**
Child Characteristics:				
Vaccinated, HepA†	0.737	1	0	1
Vaccinated, UTD 4:3:1:3	0.796	0.868	0.593	0.804
Female	0.487	0.487	0.487	0.737
Male	0.513	0.513	0.513	0.737
Hispanic	0.26	0.285	0.19	0.808
White	0.508	0.477	0.595	0.692
Black	0.131	0.13	0.132	0.734
Other ethnicity	0.102	0.109	0.083	0.786
Age:19-23 mos	0.299	0.285	0.337	0.704
Age: 24-29 mos	0.34	0.349	0.316	0.756
Age: 30-25 mos	0.361	0.366	0.348	0.747
State of Residence Characteristics:				
Effective mandate	0.246	0.282	0.146	0.844
High incid.	0.222	0.247	0.151	0.821
Medium incid.	0.149	0.159	0.12	0.788
Low incid.	0.63	0.594	0.729	0.695
Mother Characteristics:				
Age: <20 yrs	0.025	0.025	0.027	0.721
Age: 20-29 yrs	0.383	0.38	0.391	0.731
Age: 30+ yrs	0.592	0.595	0.582	0.741
<High school	0.182	0.188	0.164	0.763
High school	0.283	0.277	0.301	0.72
Some college	0.207	0.203	0.217	0.724
College grad	0.328	0.332	0.318	0.745
Income: <$10K	0.281	0.293	0.247	0.769
Income: $10-20K	0.123	0.124	0.122	0.740
Income:$20-30K	0.0899	0.0879	0.0956	0.720
Income:$30-50K	0.0714	0.0687	0.0790	0.709
Income: $50K+	0.435	0.427	0.457	0.723
Observations	107608	78099	29509	

Notes: Author's calculations from NIS provider-sample data. UTD 4:3:1:3 is an indicator for if the child is up-to-date on a standard set of shots, which consists of 4+ doses of diphtheria and tetanus, 3+ doses of polio, 1+ dose of measles, and 3+ doses of Haemophilus Influenzae Type B vaccines. All estimates exclude Arizona, obtained using weights NIS-provider weights (landline only for 2003-2011, dual weights for 2012 and 2013). † For the purposes of this table, a child is considered vaccinated against hepatitis A if they have initiated the hepatitis A vaccine series.

Table 3: Effects of ACIP recommendations and vaccine mandate, baseline results

Panel A: Initiation of HepA series

Subsample:	*24-35 mos, 2003-2013 sample*			*19-35 mos, 2007-2013 sample*		
	(1)	(2)	(3)	(4)	(5)	(6)
HepA Mandate	0.0973***	0.0818***	0.0879**	0.0729*	0.0564	0.0769**
	(0.0208)	(0.0238)	(0.0417)	(0.0426)	(0.0425)	(0.0380)
Strong ACIP	0.340***	0.273***	0.120***	-	-	-
	(0.0229)	(0.0275)	(0.0192)			
Weak ACIP	0.189***	0.193***	0.102***	-	-	-
	(0.0266)	(0.0214)	(0.0271)			
State and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time-varying controls	No	Yes	Yes	No	Yes	Yes
State-specific linear time trends	No	No	Yes	No	No	Yes
Observations	127589	127303	127303	107608	107401	107401
R-Squared	0.432	0.441	0.445	0.101	0.117	0.124
Mean of Dependent	0.550	0.550	0.550	0.737	0.737	0.737

Panel B: Receipt of 2+ HepA doses

Subsample:	*24-35 mos, 2003-2013 sample*			*19-35 mos, 2007-2013 sample*		
	(7)	(8)	(9)	(10)	(11)	(12)
HepA Mandate	0.0846***	0.0811***	0.0596	0.0603	0.0636	0.0644
	(0.0224)	(0.0225)	(0.0360)	(0.0444)	(0.0409)	(0.0396)
Strong ACIP	-0.0175	-0.0246	-0.0964***	-	-	-
	(0.0151)	(0.0201)	(0.0178)			
Weak ACIP	-0.0397	-0.0335	-0.0694*	-	-	-
	(0.0387)	(0.0342)	(0.0375)			
State and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time-varying controls	No	Yes	Yes	No	Yes	Yes
State-specific linear time trends	No	No	Yes	No	No	Yes
Observations	127589	127303	127303	107608	107401	107401
R-Squared	0.330	0.338	0.340	0.0730	0.145	0.146
Mean of Dependent	0.351	0.351	0.351	0.449	0.449	0.449

Notes: Within each panel, each column reports coefficients from a separate regression estimated using data from the National Immunization Survey. The outcome variable for all regressions in Panel A is receipt of at least one dose of the hepatitis A vaccine; in Panel B the outcome variable is receipt of two or more doses of the hepatitis A vaccine. Regressions in columns (1)-(3) and (7)-(9) are estimated using the subsample of individuals between 24 and 35 months of age, for 2003-2013; in columns (4)-(6) and (10)-(12) all regressions are estimated using the subsample of 19-35 month olds, for 2007-2013. All regressions include state and year fixed effects and are estimated using NIS-Provider weights. Standard errors are in parentheses and are clustered at the state level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Effects of ACIP Recommendation and Mandates on rate of HepA cases, 1997- 2013

Dep. var: *HepA cases per 100,000 people*	(1)	(2)	(3)
HepA Mandate	-2.833	-2.108**	-1.466*
	(1.929)	(0.937)	(0.849)
Strong ACIP rec.	-1.491**	-2.802***	-4.288***
	(0.674)	(0.477)	(0.709)
Weak ACIP rec.	-1.347*	-1.676**	-3.273***
	(0.730)	(0.752)	(1.014)
State and year fixed effects	Yes	Yes	Yes
Time-varying controls	No	Yes	Yes
State-specific linear time trends	No	No	Yes
Observations	848	848	848
R-Squared	0.639	0.732	0.846
Mean of Dependent	2.691	2.691	2.691

Notes: Each column reports coefficients from a separate regression estimated using date from the CDC's NNDSS. All regressions are weighted by state population and include state and year fixed effects. Standard errors are in parentheses and are clustered at the state level.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
regressions are weighted by state population and include state-controls and state and year fixed effects. Standard errors are in parentheses and are clustered at the state level.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Effects of ACIP Recommendation and Mandates on probability of vaccination - by subpopulations

***Panel A*: By Race/Ethnicity**

	Mean Vacc. Rate	Mandate		Strong ACIP		Weak ACIP	
	Δ (2013-2003)	Coef.	% explained	Coef.	% explained	Coef.	% explained
Hispanic	0.658	0.0800	12.16	0.305***	46.35	0.281***	42.71
		(0.0417)		(0.0285)		(0.0186)	
White	0.748	0.0840***	11.23	0.262***	35.03	0.133***	17.78
		(0.0191)		(0.0279)		(0.0253)	
Black	0.777	0.0858**	11.04	0.329***	42.34	0.204***	26.25
		(0.0319)		(0.0438)		(0.0275)	
Other	0.748	0.0819*	10.95	0.314***	41.98	0.147***	19.65
		(0.0368)		(0.0245)		(0.0321)	

***Panel B*: By Mother's Education**

	Mean Vacc. Rate	Mandate		Strong ACIP		Weak ACIP	
	Δ (2013-2003)	Coef.	% explained	Coef.	% explained	Coef.	% explained
<HS	0.670	0.0636	9.49	0.270***	40.3	0.201***	30.00
		(0.0336)		(0.0285)		(0.0272)	
HS grad	0.739	0.0961**	13.00	0.238***	32.21	0.202***	27.33
		(0.0317)		(0.0337)		(0.0166)	
Some college	0.725	0.0818*	11.28	0.272***	37.52	0.186***	25.66
		(0.0346)		(0.0252)		(0.0290)	
College+	0.775	0.0759***	9.79	0.305***	39.35	0.176**	22.71
		(0.0196)		(0.0342)		(0.0607)	

***Panel C*: By Family Income**

	Mean Vacc. Rate	Mandate		Strong ACIP		Weak ACIP	
	Δ (2013-2003)	Coef.	% explained	Coef.	% explained	Coef.	% explained
<$20K	0.721	0.0753*	10.44	0.302***	41.89	0.231***	32.04
		(0.0296)		(0.0233)		(0.0198)	
$20-30K	0.713	0.0816	11.44	0.267***	37.45	0.210***	29.45
		(0.0424)		(0.0351)		(0.0296)	
$30-40K	0.733	0.0857*	11.69	0.236***	32.2	0.148***	20.19
		(0.0392)		(0.0320)		(0.0221)	
$40-50K	0.699	0.0913***	13.06	0.194***	27.75	0.111***	15.88
		(0.0231)		(0.0356)		(0.0217)	
$50K+	0.758	.0768***	10.13	0.273***	36.02	0.187**	24.67
		(0.0185)		(0.0396)		(0.0541)	

Notes: The coefficients listed in each row are from a separate regression using a subsample of data from the National Immunization Survey, where the outcome variable is receipt of at least one dose of the hepatitis A vaccine. The sample is restricted to children 24-35 months old for 2003-2013, and a full set of individual and state-level controls are included in each regression as specified in the empirical strategy. The regression is estimated using NIS-Provider weights; standard errors are in parentheses and are clustered at the state level. * p<0.10, ** p<0.05, *** p<0.01.

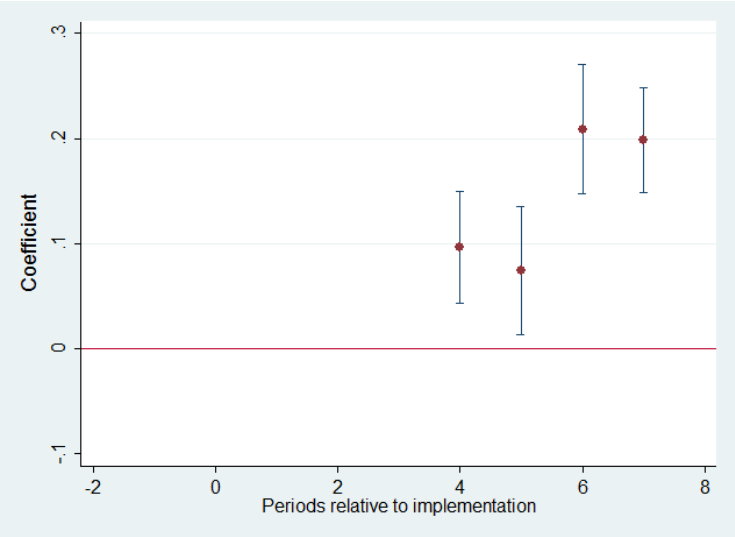
Table 6: Effects of ACIP recommendations and vaccine mandate, by child care attendance

	(1) Any HepA shots	(2) 2+ HepA shots
Child care attend	0.0300	0.0250
	(0.0232)	(0.0286)
HepA child care mandate	0.699***	0.382***
	(0.0448)	(0.0435)
Mandate × Child care attend	0.0700***	0.0799**
	(0.0154)	(0.0305)
Observations	3636	3347
R-Squared	0.142	0.146
Mean of Dependent	0.588	0.292

Notes: Each column reports coefficients from a separate regression estimated using data from the 2003 National Survey of Children's Health. The outcome variable in column (1) is receipt of at least one dose of the hepatitis A vaccine; in column (2) the outcome variable is receipt of at least two doses of the hepatitis A vaccine. Child care attendance is defined as regular attendance in the past month at a child care center outside the home or an early head start program. In this specification, a state is considered to have a hepatitis A mandate in effect at the start of the calendar year following the implementation of a *child care* mandate. All regressions include individual and state controls, and are estimated using sample weights. Standard errors are in parentheses and are clustered at the state level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

1.8. Appendix

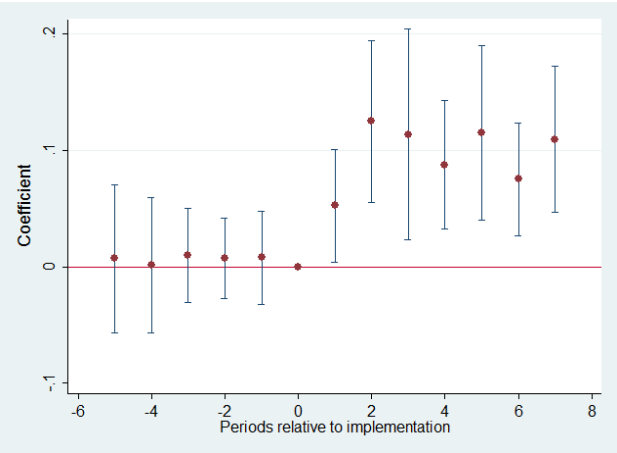
Appendix Figure 1: Effects on initiation of vaccination, Weak ACIP event study coefficients



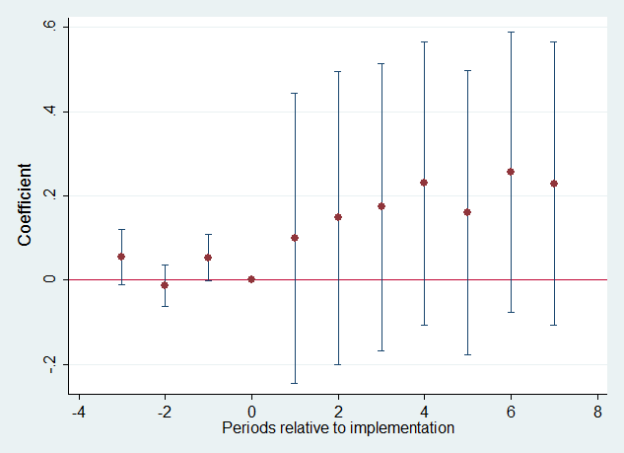
Notes: This figure presents a subset of the estimated coefficients from a single regression done using data from the National Immunization Survey, where the outcome variable is receipt of at least one dose of the hepatitis A vaccine. The sample is restricted to children 24-35 months of age, for 2003-2013. State and year fixed effects and a full set of individual and state-level controls are included in the regression, as specified in the empirical strategy. The regression is estimated using NIS-Provider weights; standard errors are clustered at the state level and coefficients are shown with 95% confidence intervals.

Appendix Figure 2: Effects on receipt of 2+ doses, Event study coefficients

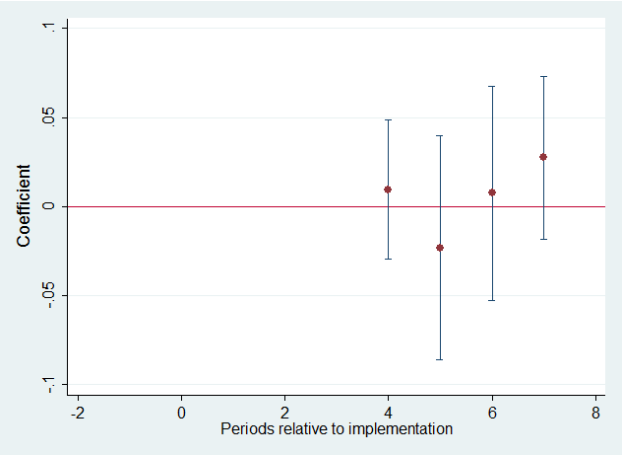
(a) Mandate coefficients



(b) Strong ACIP rec. coefficient



(c) Weak ACIP rec. coefficients



Notes: Each figure presents a subset of the estimated coefficients from a single regression done using data from the National Immunization Survey, where the outcome variable is receipt of at least two doses of the hepatitis A vaccine. The sample is restricted to children 24-35 months of age, for 2003-2013. State and year fixed effects and a full set of individual and state-level controls are included in the regression, as specified in the empirical strategy. The regression is estimated using NIS-Provider weights; standard errors are clustered at the state level and coefficients are shown with 95% confidence intervals.

Appendix Table 1: Healthy People 2020 Immunization Goals, 19-35 month olds

Vaccine, doses	Baseline Coverage (%)	Goal (%)
DTP, 4	84.6	90
Hib, 3/4	54.8	90
HepB, 3	93.5	90
MMR	92.1	90
Polio, 3	93.6	90
Varicella	90.7	90
PCV,4	80.1	90
HepA, 2	40.4	85
Rotavirus, 2/3	43.9	80

Source: U.S. Department of Health and Human Services, http://www.healthypeople.gov/2020/topics-objectives/topic/immunization-and-infectious-diseases/objectives

Notes: DTP, diphtheria, tetanus, and pertussis vaccine; Hib, *Haemophilus influenzae* type b vaccine; HepB, hepatitis B vaccine; MMR, measles, mumps, and rubella vaccine; HepA, hepatitis A vaccine. The baseline year is 2008 for all vaccines except Rotavirus and Hib, which have 2009 as their baseline year.

Appendix Table 2: Effects on ln(HepA cases), 1997-2013

Dep. var. ln(*HepA cases)*	(1)	(2)
HepA Mandate	-0.242**	0.0244
	(0.109)	(0.121)
Strong ACIP rec.	-0.204**	-0.370**
	(0.0894)	(0.139)
Weak ACIP rec.	-0.127	-0.360*
	(0.175)	(0.202)
State-specific linear time trends	No	Yes
Observations	839	839
R-Squared	0.936	0.952
Mean of Dependent	4.846	4.846

Notes: Each column reports coefficients from a separate regression estimated using data from the CDC's NNDSS, where the outcome variable is ln(*HepA cases).* All regressions include state and year fixed effects, and control for ln(*population)* in addition to the full set of state-level controls as discussed in Section 4.1. Regressions are weighted by state population; standard errors are in parentheses and are clustered at the state level. *p <0.10, **p<0.05, *** p<0.01.

Appendix Table 3: Hepatitis A Vaccination Policies and Other Childhood Vaccines

	(1) Hep A	(2) UTD HepB	(3) Varicella	(4) UTD Hib	(5) UTD MMR	(6) UTD PCV	(7) UTD Polio	(8) UTD DTP
HepA Mandate	0.0818***	-0.00595	0.000841	-0.00451	0.000738	-0.00658	-0.00604	-0.00695**
	(0.0238)	(0.00516)	(0.00508)	(0.00734)	(0.00525)	(0.0129)	(0.00379)	(0.00321)
Strong ACIP	0.273***	-0.0102**	-0.0105	-0.0102	-0.00917*	-0.0192	-0.00322	-0.00418
	(0.0275)	(0.00452)	(0.00663)	(0.00812)	(0.00543)	(0.0174)	(0.00363)	(0.00434)
Weak ACIP.	0.193***	0.00648	-0.00884	-0.0104	-0.00873	-0.00945	0.0115*	0.00241
	(0.0214)	(0.00753)	(0.00687)	(0.0131)	(0.00816)	(0.0194)	(0.00654)	(0.00530)
Observations	127303	127303	127303	127303	127303	127303	127303	127303
R-Squared	0.441	0.0118	0.0199	0.0286	0.00858	0.0880	0.0131	0.0153
Mean Rate	0.550	0.925	0.902	0.924	0.927	0.872	0.933	0.957

Notes: Each column reports coefficients from a separate regression estimated using data from the National Immunization Survey, 2003-2013, for children 24-35 months of age, where the outcome variable is receipt of the vaccine listed in the column header. Abbreviations used for vaccine names mean the following: HepB: hepatitis B vaccine; Hib: Haemophilus influenza type b vaccine; MMR: measles, mumps, and rubella vaccine; PCV: Pneumococcal conjugate; DTP: diphtheria, tetanus, and pertussis vaccine. All regressions include individual and state-level controls and state and year fixed effects, and are estimated using NIS Provider weights. Standard errors are in parentheses and are clustered at the state level.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table 4: Effects of ACIP Recommendations and Mandates on Incidence of Other Diseases

	(1) HepA	(2) HepB	(3) Measles	(4) Pertussis	(5) Giardia	(6) Salmonel	(7) Meningoc.	(8) TB
HepA Mandate	-2.108**	-0.385	-0.0161	0.0636	-0.643	-0.0437	0.0437	0.350
	(0.937)	(0.357)	(0.0124)	(0.908)	(0.712)	(0.787)	(0.0534)	(0.259)
Strong ACIP rec.	-2.802***	-0.481*	-0.00757	-1.352	-0.243	0.0704	-0.0220	-0.210
	(0.477)	(0.257)	(0.0112)	(0.958)	(0.633)	(0.451)	(0.0306)	(0.138)
Weak ACIP rec.	-1.676**	0.0988	0.00969	-0.667	0.811	0.684	-0.0198	-0.194
	(0.752)	(0.247)	(0.00835)	(1.527)	(0.741)	(1.345)	(0.0493)	(0.144)
Observations	848	841	849	850	753	850	850	850
R-Squared	0.732	0.647	0.178	0.430	0.836	0.814	0.816	0.942
Mean of Dependent	2.691	2.019	0.0316	5.818	8.496	15.85	0.535	4.823

Notes: Each column reports coefficients from a separate regression estimated using data from the CDC's NNDSS, where the outcome variable is the number of reported cases per 100,000 population of the disease listed in the column header. All regressions include state-level controls and state and year fixed effects, and are weighted by state population. Standard errors are in parentheses and are clustered at the state level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.0$

CHAPTER 2

DIRECT AND SPILLOVER EFFECTS OF MIDDLE SCHOOL VACCINATION REQUIREMENTS

With Christopher S. Carpenter

2.1. Introduction

Reductions in vaccine-preventable diseases through increased uptake of vaccinations are some of the most significant public health improvements in American history (Centers for Disease Control 1999). These improvements have been particularly striking for diseases that have historically harmed infants and young children such as measles, mumps, and rubella. Public policies, information and education campaigns, and general changes in attitudes have all received credit for dramatically reducing the incidence of these childhood diseases.

Vaccination of slightly older adolescent children is also a key health priority, but improvements for this age group have been slower and less remarkable than for elementary school-age children. For example, while HealthyPeople 2020 (HP2020) recommends maintenance of the already high vaccination rates for kindergarten age children, those same recommendations explicitly acknowledge the need to increase vaccination coverage for adolescents. The Advisory Committee on Immunization Practices (ACIP) – an advisory body that issues recommendations regarding vaccinations (similar to the United States Preventive Services Task Force) – currently recommends four vaccinations for routine administration to middle school age youths: one dose of tetanus-diphtheria-acellular pertussis (Tdap) booster vaccine, one dose of meningococcal conjugate vaccine (MCV), the human papillomavirus (HPV)

vaccine series, and an annual influenza vaccine.[41] Of these, only the Tdap booster vaccination rates currently meet their HP2020 target of 80 percent.[42] A particular challenge in vaccinating adolescents is that they primarily encounter healthcare providers only for acute injuries and sports-related physicals, and as a result they have much lower rates of attachment to the healthcare system than individuals in other age groups (Woodwell and Cherry 2004, Humiston and Rosenthal 2005).

In an effort to increase adolescent vaccination rates and reduce the morbidity consequences of vaccine-preventable diseases, in the last decade 46 states have adopted laws requiring adolescents to receive a Tdap booster prior to middle school entry.[43] We provide the first comprehensive quasi-experimental evaluation of the effects of these middle school vaccination mandates on vaccination take-up and on pertussis (whooping cough) morbidity using the staggered timing of mandate adoption. Prior studies in public health have examined the effects of these vaccination policies by comparing means across states stratified based on mandate status or have examined the experiences of single states before and after a middle school mandate. However, no prior work has used multiple states and years in the two-way fixed effects and event study frameworks that have become standard in the economics literature.

The primary outcomes we consider are receipt of vaccinations by the age of 13 for Tdap

[41] During our sample period the HPV vaccine was recommended to be administered as part of a 3-dose series. As of December 2016 the recommendation has been updated to reflect new evidence demonstrating that receiving only the first 2 doses of the series is of equivalent efficacy to the full 3-dose series. ACIP now recommends that individuals initiating the series before the age of 15 receive only 2 doses of the vaccine.

[42] In contrast, the vaccination rate for 13-15 year olds for MCV in 2012 was 73.8 percent (target of 80 percent), and the seasonal influenza vaccination rate for children 6 months to 17 years was 46.9 percent in the 2010-11 flu season (target of 70 percent). The case of HPV is even worse: only 35.1 percent of 13-15 year olds (50 percent of girls and 20.9 percent of boys) had initiated the HPV vaccine by 2012, far below of the HP2020 target of 80 percent.

[43] As of January 2016, 22 of those 46 states also required MCV vaccination, and only two states had adopted requirements that students receive the HPV vaccine series. No state requires students to receive the influenza vaccine.

(direct effect) and for MCV, HPV, and influenza (possible cross-vaccine spillover effects). Using the same empirical models, we also estimate mandate effects on the incidence of pertussis (which is protected against by the Tdap booster) and tuberculosis (which is not protected against by the Tdap booster) in the population and by ten-year age groups. These morbidity analyses allow us to address the extent to which population morbidity effects are due to adolescents being directly targeted by vaccine mandates versus morbidity spillover effects accruing to infants, younger children, adults, and/or the elderly (i.e., cross-age spillovers).

Understanding the effects of middle school vaccination requirements is important for several reasons. First, the large majority of states have adopted these requirements, and so it is important to document whether these laws have worked to increase take-up of the covered vaccines and reduce morbidity from the associated diseases. Notably, Figure 1 shows that adolescent vaccination rates for Tdap and MCV have both increased sharply since they were approved by the Food and Drug Administration (FDA) in 2005: while no youths were receiving these vaccinations prior to 2005, by 2014 over 70 percent of adolescents had received the immunizations.[44] Second, there is substantial latitude for further improvements if the middle school mandates are found to be effective at increasing vaccination and reducing morbidity. In addition to the remaining states adopting a first vaccination requirement, states with existing requirements could strengthen them (for example by requiring other vaccines in addition to Tdap).

Third, by estimating population-level morbidity effects of increased Tdap vaccination our research augments the existing randomized control trial (RCT) evidence on the efficacy of the

[44] Disentangling the extent to which this increase is driven by mandates is particularly relevant given that mandating vaccination prior to school entry has become increasingly controversial as an anti-vaccination movement has gained popularity in the United States.

Tdap vaccine.[45] In the presence of population morbidity spillovers, individual-level RCT estimates of vaccine effectiveness will understate the true reduction in pertussis in the population that may result from receipt of the Tdap vaccine. Analyses of morbidity effects at the population level, however, provide a measure of the overall effectiveness of a vaccine at reducing disease incidence. Although we face limitations in our ability to identify the effects of the mandate on vaccination rates across all age groups, we believe our results provide important new evidence on the overall effectiveness of the Tdap vaccine at reducing pertussis.

Fourth, the literature specifically regarding determinants of adolescent HPV vaccination has largely failed to identify meaningful policy levers that could increase HPV vaccine uptake among adolescents. As the HPV vaccine has the largest gap between current and targeted immunization rates for adolescents, understanding any credible policy lever to increase HPV vaccine uptake in this age group is important. Finally, the literature on the effectiveness of public policies at promoting adolescent health is relatively underdeveloped compared to literatures on children at the younger and older ends of the age spectrum. While we know a substantial amount about the causes and consequences of early child health (Almond and Currie 2011, Almond et al. 2017) and high school student health (Gruber 2001), there is comparatively less research on the critical period of early adolescence. In addition to the clinical changes associated with puberty, the vast majority of high risk behaviors are initiated during adolescence. Documenting the role vaccination policies play in adolescent health therefore contributes to a more complete picture of child development.[46]

To preview, we find clear evidence that state laws requiring youths to obtain a Tdap

[45] Randomized control trial evidence of the efficacy of the acellular pertussis vaccine among adolescents and adults estimates overall vaccine efficacy to be 92 percent, with a 95 percent confidence interval ranging from 32 to 99 percent (Ward et al. 2005).

[46] In fact, one reason why HPV-promoting public policies have been controversial is that some believe the HPV vaccine promotes sexual promiscuity.

booster prior to middle school entry were very effective at directly increasing Tdap booster take-up. Using the staggered timing of implementation of the Tdap booster requirements across states, we find that adoption of a Tdap booster mandate increased the likelihood that an adolescent received a Tdap booster between 10 and 12 years of age by 13.5-13.7 percentage points. We also estimate the same difference-in-differences type models on pertussis morbidity and find substantial reductions in disease incidence as a result of the mandates. These reductions in pertussis morbidity are observed primarily for adolescents who were targeted by the mandates, with some additional evidence of spillovers to infants and prime age adults.

Finally, we find strong evidence of cross-vaccination spillovers: although most state mandates only required the Tdap booster, we find significant increases in other vaccinations that were also recommended for young adults. For example, we estimate that state Tdap booster requirements increased MCV vaccination rates by 2.2-2.9 percentage points. Even more striking, we find that these Tdap booster policies significantly increased HPV vaccination initiation by 4.2-4.9 percentage points and HPV vaccination completion by 2.5-3.3 percentage points. These spillover effects are larger for youths from households with low socioeconomic status (SES). Our results are the first to document that middle school vaccination requirements induced large improvements in adolescent and child health. Furthermore, given the spillover effects to HPV vaccination, there are likely to be large longer-run payoffs due to reduced risk of HPV-related cancers in both men and women, especially cervical cancer.

Our paper proceeds as follows: Section 2.2 provides institutional background on the mandates and conditions we study, and Section 2.3 provides a brief literature review. Section 2.4 describes the data and outlines the empirical approach. Section 2.5 presents the results, and Section 2.6 discusses and concludes.

2.2. Institutional Background

In this section we briefly describe the diseases and vaccinations under study as well as the middle school mandates and the mechanisms for spillovers.[47]

2.2.1. Conditions Under Study

Tetanus, diphtheria, and pertussis (or 'whooping cough') are all diseases caused by bacteria, and vaccination against them with a combination vaccine series (currently DTaP) has been routinely recommended for young children since the 1940s and 1950s. In 2005 a booster for the series, the Tdap vaccine, was approved for use in adolescents and was recommended to be administered at age 11 or 12. Tetanus and diphtheria are now extremely rare diseases, but pertussis remains endemic in the United States. Pertussis is a highly contagious respiratory disease that is transmitted from person-to-person through respiratory secretions.[48] Infants under 12 months of age are hospitalized in 63 percent of pertussis cases (compared to 2 percent of infected adolescents) and account for 90 percent of the pertussis-related mortality. Notably, infants cannot be vaccinated against pertussis until 2 months of age.

Meningococcal disease includes infections of the lining of the brain and spinal cord (meningitis) and of the bloodstream (septicemia and bacteremia). We focus on the quadrivalent meningococcal conjugate vaccine (MCV4), which provides protection against most meningococcal disease serogroups and has been routinely recommended for children age 11 or 12 since 2005.

Human papillomavirus (HPV) is the most common sexually transmitted infection in the United States: the CDC estimates that nearly all sexually active men and women will get HPV at

[47] The Appendix provides more detailed information on each condition we study.
[48] Figure 2 plots population pertussis rates in the United States from 2000-2015.

some point in their lives. Most HPV infections are asymptomatic and resolve on their own. High risk types of HPV cause the large majority of the cancers of the cervix, vagina, penis, anus, mouth, and throat. The first HPV vaccine was licensed for use in females in the United States in June 2006, and it was further approved for males in October 2009. The vaccine is only effective if it is given before an infection occurs. It is currently recommended that all youths initiate the HPV vaccine series between ages 11-12.

Seasonal flu (common in fall and winter months) is an acute and highly contagious viral infection that causes mild to severe illness; among infants and the elderly there is elevated risk of death due to complications. The flu vaccine varies from season to season with respect to the particular strains of the influenza virus that it protects against. The annual influenza vaccine was routinely recommended for children over the age of 6 months for the first time in 2010.

2.2.2. Middle School Vaccination Requirements and ACIP Recommendations

There is a long history in the United States of using school-based mandatory vaccination laws as a tool to increase vaccination rates, in part because compulsory schooling laws provide an effective means for enforcement.[49] Although all states presently mandate the receipt of some vaccines, there is considerable variation in the set required for school attendance in each state (Malone and Hinman 2003).[50] As of January 2016, forty-six states have adopted middle school

[49] A limitation to the effectiveness of mandates is the availability of individual exemptions. During our sample period exemptions could be obtained for individuals whose religious beliefs oppose vaccination in all but 2 states, and 20 states additionally allowed exemptions for personal/philosophical beliefs (NCSL 2015a). All states grant exemptions for children who cannot be vaccinated due to medical reasons. To our knowledge there is not good evidence on how children who do not meet the vaccination requirements are induced to get the required vaccinations (i.e., how the laws are enforced). School-based nurses are unlikely to be able to fulfill the vaccination requirements, however, because most schools lack the administrative requirements to handle the billing and reimbursement for the vaccinations.

[50] There have been school vaccine mandates implemented in all 50 states and Washington D.C. since 1980.

entry requirements for the Tdap booster (Figure 3). The mandates we study apply to both private and public school students in the vast majority of states; only in four states is the treatment of private school students unclear (CDC 2016b).

In the United States recommendations on the use of vaccines are set by the Advisory Committee on Immunization Practices (ACIP). The ACIP is a 15 member committee composed of doctors and public health professionals and was established in 1964. Their guidelines are directly linked to a number of health policies, as many states anchor their laws to current ACIP recommendations.[51] As of January 2016, the ACIP recommended that 11-12 year olds receive an annual influenza vaccination, one dose of Tdap, the HPV vaccine series, and a single dose of quadrivalent meningococcal conjugate vaccine.[52]

2.2.3. Spillovers

In this paper we examine the direct effects of Tdap booster mandates on take-up of the Tdap booster and on pertussis morbidity among the targeted age group (5-14 year olds), but we are also interested in two types of spillover effects. First, we examine the effects of the mandates on the pertussis morbidity rates of younger and older individuals in the state. These cross-age spillovers may occur due to reduced disease transmission among the directly targeted

[51] For example, under the Affordable Care Act (ACA) preventive care provision (effective September 23, 2010), all new insurance plans must provide all ACIP-recommended vaccines without cost sharing. Moreover, once the ACIP designates a vaccine as 'routinely recommended', the Vaccines for Children (VFC) program has to pay for them. Individuals are eligible for free vaccinations under the VFC program if they are 18 years of age or younger, and are Medicaid-eligible, uninsured, American Indian or Alaskan Native, or are underinsured.

[52] Out-of-pocket cost for this bundle of vaccines is potentially high. At this time of this writing, Walgreens, for example, charged $249.99 for the first dose of the HPV vaccine, $214.99 for both the second and third doses of the HPV vaccine, $133.99 for the meningococcal vaccine, $63.99 for the Tdap booster, and $31.99 for the influenza immunization, for a total expense of nearly $700 (Walgreens 2016). Prior to the ACA, some private insurance plans covered some portion of these vaccines, and several states adopted laws requiring private insurance plans in the state to cover the vaccines (see Chang 2016a for evidence on these).

adolescents, which is referred to as the 'herd immunity' or 'community' effect in the medical and public health literatures. Additionally, cross-age spillovers may occur if the middle school mandates cause behavioral spillovers that result in increased vaccination among non-targeted age groups.

The second type of spillover we study is a cross-vaccine spillover from state Tdap mandates to immunization rates for other non-mandated vaccines, such as the MCV, HPV, or flu vaccines. These types of spillovers may occur through several different channels. For example, Tdap mandates lead to an implicit price reduction for the other vaccines that are recommended for adolescents by requiring the youth to seek out a health care provider. These interactions with providers may also lead to information exchange whereby providers inform patients about and recommend receipt of other age-appropriate vaccinations. Alternatively, the mandates may directly increase parental knowledge about other vaccines, perhaps through local news coverage or information provided by the school or state department of health.[53]

2.3. Literature Review

Our paper relates to a substantial literature on the economics of infectious diseases and vaccination (Philipson 2000). Philipson (1996) shows that higher measles prevalence in an individual's state is associated with earlier age at first measles vaccination, suggesting that vaccination responds to disease prevalence. Oster (2016) finds a similar result for pertussis: whooping cough disease outbreaks increase vaccination rates of children in the following year,

[53] Appendix Figure 1 shows an example of this type of information provided to parents by the Wisconsin Department of Health. Question 9 on the flyer asks 'Are there any other vaccines that are recommended for my adolescent?'. The answer provided instructs parents that, even though Tdap is the only immunization required under law for middle school entry, adolescents in this age group are also recommended to receive MCV, HPV, and seasonal influenza vaccinations.

with effect sizes that are too large to reflect actual changes in disease risk. Schaller et al. (2017) also study pertussis outbreaks but focus on infants, finding that outbreaks increase infant vaccinations not only for pertussis but also for other vaccine-preventable diseases. Multiple studies have examined the vaccination effects of the MMR-autism controversy in which a study in a major medical journal in the UK suggested that the measles, mumps, and rubella vaccine might cause autism, showing that highly educated mothers responded to the information by reducing MMR vaccination rates for their children (Anderberg et al. 2011, Chang 2016b).[54]

Our study of middle school vaccination requirements is also related to several quasi-experimental studies in economics that have examined similar vaccination mandates for kindergarten or childcare entry. Abrevaya and Mulligan (2011) show that such vaccination mandates for varicella were associated with significant increases in varicella vaccination rates for young children using data from the 1996-2007 National Immunization Survey (NIS). Lawler (2017) also uses NIS data to study similar requirements for hepatitis A and finds that both ACIP recommendations and state vaccination requirements significantly increased vaccination rates for hepatitis A and reduced hepatitis A morbidity. Ward (2011) and Luca (2014) both consider the implementation of the first modern school vaccination laws (adopted between 1963 and 1980) and find reductions in morbidity and mortality for the vaccine-targeted diseases.[55]

[54] Numerous subsequent studies have failed to confirm a link between the MMR vaccine and autism, and the original study that purported the connection was retracted in 2010.

[55] Other economics studies examine the role of non-mandate related vaccination policies. For example, Chang (2016a) finds that state insurance mandates for various childhood vaccinations significantly increased infant vaccination rates, and Ward (2014) finds that influenza immunization campaigns are effective at increasing influenza vaccination rates. A number of studies focus particularly on the HPV vaccine, although we are not aware of any quasi-experimental literature that has identified significant causal determinants of adolescent HPV vaccination rates. Moghtaderi and Adams (2016) use NIS-Teen data from 2008-2011 and find no effects of: requirements that parents and/or students receive education and information about the HPV vaccine; mandates requiring the vaccine for school entry; mandates requiring private insurers to cover the HPV vaccine; laws granting pharmacists the authority to give vaccinations; and general awareness campaigns. Trogdon et al. (2016) use NIS-Teen data from 2008-

Within the medical and public health literature there are a number of papers that have considered the effects of state middle school vaccination mandates. These studies generally use only a limited number of years (e.g., 2009 and 2010 in Bugenske et al. 2012) or study the experiences of a small number of states (e.g., New York in Kharbanda et al. 2010), though it is important to note that some of these studies have explicitly examined the possibility of cross-vaccine spillovers from Tdap vaccination mandates to take-up of MCV and HPV vaccines (see, for example, Dempsey and Schaffer 2010). Our work builds on the prior work in public health by using much more comprehensive nationally representative data spanning adoption of numerous state Tdap vaccination mandates. The data and variation allow us to carefully test the parallel trends assumption required for identification in difference-in-differences models and to estimate credible event study models that trace out the immediate and medium term effects of the mandates. We also go further by directly examining age-specific morbidity effects.

2.4. Data Description and Empirical Approach

Data on adolescent vaccination come from the 2008-2013 waves of the National Immunization Survey – Teen (NIS-Teen).[56] The NIS-Teen is a random digit dialing telephone survey which targets adolescents between 13 and 17 years of age and includes provider-verified immunization histories and household sociodemographic characteristics. Approximately 33,500 households complete the survey each year;[57] among these households there is adequate provider

2014 and also find no significant relationship between pharmacist vaccination authority and either HPV vaccine initiation or completion.

[56] Due to a survey revision in 2014, later waves of the NIS-Teen survey are not directly comparable to the 2008-2013 waves (CDC 2015b). For completeness, however, we show that our results are robust to adding the 2014 and 2015 waves in Appendix Table 10.

[57] Among land-line samples the response rate ranges from 51.1 to 58.7 percent; among the cell-phone samples (administered in addition to the land-line survey for the 2011-2013 survey waves) response rates were substantially lower and ranged from 22.4 to 23.6 percent.

data for 58.7 percent of sample teens.[58] In these data we observe immunization status for Tdap, MCV, HPV, and seasonal influenza vaccinations, as well as for other childhood vaccines. Importantly for our analyses, these data include the age (in years) at which the child received each vaccination, even if it occurred years prior to the NIS-Teen interview. We use this information to restrict our analysis to vaccination doses received between 10 and 13 years of age – the age range for which middle school mandates are most likely to be binding. Our effective sample for vaccination outcomes is therefore individuals who were age 13 between 2004 and 2013.

Our data on pertussis disease incidence were obtained directly from the CDC. These data consist of counts of cases of a subset of nationally notifiable diseases by state, year, and ten-year age group.[59] Availability of information on age group enables us to separately estimate the direct effects (on the ages targeted by the mandates) and indirect effects (on other age groups) of the middle school mandates on disease incidence in the population. We observe morbidity outcomes for pertussis (covered by Tdap) and tuberculosis (a control condition transmitted in the same manner as pertussis, but not protected against by the Tdap vaccine) from 2000-2015. We also use population morbidity data for a range of other diseases (e.g., Hepatitis A, Hepatitis B,

[58] Teens that completed the household interview may lack adequate provider data either because the household did not provide consent to contact providers (between 23.2 and 35.1 percent of households in a given survey wave) or because the contacted providers did not have medical records for the teen. Across all survey waves provider response rates were extremely high, ranging from 92.7 to 96.3 percent.

[59] The number of cases of nationally notifiable diseases is voluntarily reported to the CDC by state and territorial jurisdictions for nationwide monitoring of disease. These data are considered the most comprehensive information available on U.S. national disease incidence, although they only include diagnosed cases (i.e. they exclude cases where the individual did not go to a health care provider or were misdiagnosed) and thus represent a substantial undercount of true disease incidence. The reliance on provider diagnosis represents a potentially important limitation in this context, as providers may adjust the intensity of their surveillance in the presence of a vaccine mandate, thus biasing our morbidity results. Furthermore, it is difficult to sign this bias: Tdap mandates may increase provider surveillance intensity by increasing their awareness of pertussis, or it may decrease their surveillance if they lower their expectation of encountering a patient with pertussis.

meningococcal disease, measles, Lyme disease, and salmonellosis) as additional falsification tests.

To estimate the effect of the Tdap mandates, we estimate standard difference-in-differences models that rely on plausibly exogenous variation in the timing of mandate adoption across states. Specifically, we estimate:

$$\textbf{(1)} \quad Y_{ist} = \beta_0 + \beta_1 X_{ist} + \beta_2(\text{MIDDLE SCHOOL ENTRY VACCINATION MANDATE})_{st} + \beta_3 Z_{st} + \beta_4 S_s + \beta_5 T_t + \beta_6 S_s * \text{TREND} + \varepsilon_{ist}$$

where Y_{ist} are the vaccination take-up outcomes available in the NIS-Teen data for individual *i* in state *s* who was age 13 in year *t*. X_{ist} is a vector of individual characteristics available in the NIS-Teen, including: child's gender, fixed effects for child's age at time of survey, child's race/ethnicity (Hispanic, white, black, with other as the excluded category), number of other children under 18 years old living in the home (only 1 child, 2 to 3 children, with 4 or more children as the excluded category), maternal education (less than high school, high school, some college, with college or above as the excluded category), maternal age group (34 years old or younger, 35 to 44 years old, with 45 years or older as the excluded category) and an indicator variable for whether the mother is married.[60]

MIDDLE SCHOOL ENTRY VACCINATION MANDATE is a vector of disease-specific indicator variables equal to one in the states and years in which there is a vaccination mandate in effect. Since all vaccination outcomes are observed at age 13 in year *t*, a vaccination mandate is considered in effect for individual *i* in state *s* if there was a binding mandate for 12

[60] The number of other children living in the home and maternal education, age group, and marital status are all observed at the time of the survey, not at the time the child was age 13. Our main results are not sensitive to removing the controls in the X vector.

year olds in year *t-1* or for 11 year olds in year *t-2* in state *s*.[61] This vector captures vaccination mandates for the tetanus, diphtheria, and pertussis booster (Tdap),[62] the meningococcal vaccine (MCV), and the human papillomavirus series (HPV). These three vaccines are the only immunizations for which routine administration is recommended for the first time at age 11 or 12. The influenza vaccine is additionally recommended annually for children ages 6 months through 18 years, although as of 2016 no state has mandated receipt of the influenza vaccine for school attendance. Information on the timing of adoption of these mandates was taken from the Immunization Action Coalition.[63]

Additionally contained in the vector MIDDLE SCHOOL ENTRY VACCINATION MANDATE are indicator variables that capture if individuals faced a newly binding `catch up' middle school entry mandate for hepatitis A, hepatitis B, varicella, or a measles-containing vaccine. These vaccines are frequently required for middle school entry, although they are routinely recommended for children much younger than middle school age. Consequently, many states have companion kindergarten entry mandates for these diseases. State requirements regarding these other diseases are still relevant, however, because some share of young adults are

[61] There is variation across states in the age for which a middle school mandate is binding. For example, some states require vaccination by age 11, while in others the requirement is by age 12. Additionally, some requirements are by grade level, in which case we consider 6th grade entry equivalent to age 11 and 7th grade entry equivalent to age 12. We assume that there is no cross-state mobility between ages 11 and the time at which the child is surveyed (age 13-17); in a robustness test we have confirmed that our results are not sensitive to restricting attention to the 78 percent of our sample whose current state of residence matches their birth state of residence.

[62] Among the states that have Tdap booster mandates, 9 previously had mandates requiring receipt of a TD-containing vaccine prior to middle school entry. In the baseline specification we consider a TD-containing mandate to be equivalent to a mandate for the Tdap booster.

[63] Only two states over our sample period ever adopted a mandate for HPV vaccination (Washington DC and Virginia). Given the well-documented challenges associated with credibly estimating difference-in-differences models with a small number of policy changes (Conley and Taber 2011, MacKinnon and Webb 2016), we do not present estimates for this variable, as they are highly sensitive to specification. Twenty two states adopted MCV vaccination requirements, and we control for these throughout. Note that a state never adopted a middle school vaccination requirement for MCV prior to adopting one for Tdap.

'caught' by them (i.e., they were too old at time of implementation of the disease-specific kindergarten vaccination mandate in their state to have been treated by it).[64]

Z_{st} is a vector of other potentially relevant state vaccination-related public policies, some of which have been studied in prior work. These include: state mandates requiring insurance policies to cover various vaccinations (Chang 2016a) and well-child visits;[65] nonmedical exemption policy (Bradford and Mandich 2015);[66] state education requirements for the HPV and meningococcal vaccines (Moghtaderi and Adams 2016, Bugenske et al. 2012); high school and college immunization requirements for the meningococcal vaccine; immunization mandates for childcare/kindergarten entry for other diseases such as hepatitis A (Lawler 2017); and income eligibility thresholds for the state Medicaid/Children's Health Insurance Program.[67] The Z vector also includes controls for state unemployment rates and state demographic characteristics (fraction female; fraction black, Hispanic, and other non-white races; fraction of individuals with high school degrees and college or more; fraction of individuals under 21 and between 21-64; and fraction of individuals below the federal poverty line).[68] In order to best capture the state characteristics that would have feasibly been relevant to the vaccination decisions considered

[64] Specifically, we consider there to be an effective (newly binding) 'catch up' mandate if a child residing in state *s* who is age 13 in year *t* was subject to the mandate for middle school entry (i.e. there was a mandate effective for 12 year olds in year *t-1* or for 11 years olds in year *t-2)* and was *not* subject to a mandate for the same vaccine prior to kindergarten entry (i.e. there was not a mandate in effect in state *s* for the same vaccine when the child was age 5 in year *t-8*).

[65] Note that the preventive services requirement of the Affordable Care Act (ACA) required most insurance plans to cover ACIP-recommended vaccinations and well-child visits without cost-sharing beginning September 2010. As such, we turn the insurance coverage indicator 'on' for all observations in years 2011 and later.

[66] Over our sample period only two states changed their exemption policy for vaccinations; both did so by eliminating the personal belief exemption.

[67] In a series of robustness checks we verify our results are unaffected by the inclusion of several additional controls for which we have data only for a subset of our sample years. These include: state Section 317 funding, state Vaccines For Children (VFC) policies, and scope of practice laws regarding pharmacist prescribing authority (Trogdon et al. 2016).

[68] State unemployment rates come from the Bureau of Labor Statistics. State demographic characteristics are from the Census Bureau. Our main results are not sensitive to removing the controls in the Z vector.

here, all variables contained in the Z_{st} vector are measured in the year in which the child was 11 (year *t-2).* We also include in the Z_{st} vector the lagged population-wide pertussis and meningococcal disease rates in the state, following Philipson (1996) and Oster (2016). All models additionally control for a full set of state and birth cohort fixed effects. In some models we further control for state-specific linear cohort trends where we interact each state fixed effect with a variable TREND that equals 1 for individuals who were age 13 in 2004, 2 if age 13 in 2005, and so forth. We use sample weights provided by NIS-Teen, and we cluster standard errors at the state level (Bertrand, Duflo, and Mullainathan 2004).[69]

β_2 represents our coefficient of interest and reflects the direct and indirect (i.e., spillover) effects of middle school vaccination requirements. The key identifying assumption in this difference-in-differences style model is that vaccination outcomes would have evolved similarly in states that did and did not adopt a middle school vaccination requirement in the absence of the mandate, or alternatively that there were no other unobserved shocks to vaccination outcomes in states coincident with adoption of the middle school vaccination requirements. In some models we replace the vector of Tdap, MCV, and HPV middle school vaccination requirements with a series of indicator variables representing years relative to adoption of the respective state vaccination requirement. This event-study style framework allows us to explicitly address and visually inspect the parallel trends assumption in the two-way fixed effects framework.

For analyses of the morbidity data we estimate a variant of equation (1) where the outcome is the age-specific morbidity rate in state *s* and year *t*, measured as number of cases per

[69] In 2011 NIS-Teen switched from single frame landline-only sampling to dual frame sampling that included landlines and cell phones, and in that year only both single and dual frame weights are provided. In all reported estimates we use dual frame weights starting in 2011. None of the main results is sensitive either to this decision or to the exclusion of weights.

100,000 population.[70] Age-specific morbidity rates are calculated using the number of cases for each disease by age group (as provided to us by the Centers for Disease Control and Prevention) and age-specific population estimates from the Surveillance and Epidemiologic End Results (SEER) system. In this more aggregate level model, we include year fixed effects instead of birth cohort fixed effects, and all policies are considered in effect at the start of the calendar year following implementation. These models use age-specific state population weights.

2.5. Results

2.5.1. Descriptive Statistics

Appendix Table 1 presents means of key variables relating to Tdap, MCV, HPV, and influenza vaccination-related outcomes and demographic characteristics from the NIS-Teen 2008-2013 sample. By age 13, 45 percent of the NIS-Teen sample received the Tdap booster, and 35.7 percent received the MCV vaccine. These rates are respectively higher in states that had implemented a middle school entry mandate for the Tdap booster by 2013. Notably, MCV and HPV vaccination rates were also higher in states with Tdap vaccination requirements in place by 2013, though the same is not true for seasonal influenza vaccination rates. In the full sample, HPV and seasonal influenza vaccination rates are both substantially lower than Tdap booster vaccination rates at 23.6 and 12.2 percent, respectively. As mentioned previously, Figure 1 shows the trends in Tdap, MCV, and HPV vaccination rates for adolescents over our sample period; all have increased substantially since 2005. Appendix Table 1 also shows that slightly less than half the NIS-Teen sample is female, over 57 percent is white, 20 percent is

[70] We note that given the nature of disease contagion, there is potential for cross-state spillover in reduced disease incidence, which would bias our estimated effects towards zero using this identification strategy. Ideally we would test for the presence of this type of geographic spillover, however doing so would require morbidity measures at a sub-state level, which the CDC does not release due to confidentiality concerns.

Hispanic, and over 14 percent is black. At the time of the survey, over a third of the mothers in the NIS-Teen sample were college educated, while 69.6 percent were married.

2.5.2. Direct Effects of Tdap Mandates on Tdap Vaccination and Pertussis Cases

In Table 1 we present difference-in-differences estimates of the effects of state middle school vaccination mandates on vaccine take-up and morbidity outcomes that take explicit advantage of the plausibly exogenous variation in the timing of policy adoption across states. Columns 1 and 2 (without and with linear state trends, respectively) of Table 1 present results from separate regressions of the model specified in equation (1) where the outcome variable is receipt of the Tdap booster between ages 10 and 12. We report the coefficients on the policy indicator for the state Tdap booster requirement.

The results in columns 1 and 2 of Table 1 provide strong evidence that Tdap vaccination mandates for middle school entry were effective at increasing take-up of the Tdap vaccine. The estimate in column 1 indicates that Tdap mandates were associated with a 13.5 percentage point increase in the likelihood that an adolescent received a Tdap booster between 10 and 12 years of age, and this finding is invariant to the inclusion of smooth state-specific linear time trends. Figure 1 showed that over our sample period Tdap vaccination rates increased from about 0 to 80 percent; the estimates in columns 1 and 2 of Table 1 indicate that Tdap mandates can explain about 17 percent of this overall increase.[71] We show visually event-study-based estimates of the direct effect of Tdap mandates on Tdap-vaccine uptake in Figure 3 (the actual estimates from the event study specification are presented in Appendix Table 2). Figure 3 shows that the Tdap

[71] Note that vaccination rates are not 100%. This is due in part to the fact that five states still have not adopted requirements for the Tdap booster as a condition of middle school entry. It is also due to some amount of noncompliance, though the channels of noncompliance are quite rare. For example, adolescents and parents can evade state Tdap booster requirements for middle school entry by homeschooling their children, though nationally the rate of homeschooling is less than 3.5 percent during our sample period (Snyder, de Brey, and Dillow 2016).

mandates induced large, immediate, and significant increases in Tdap booster take-up, and there is no evidence of systematic trends prior to Tdap mandate adoption. This is consistent with the validity of the parallel trends assumption required for identification.

Were these increases in vaccination rates effective at reducing morbidity? We present difference-in-differences estimates of the effect of Tdap mandates on population-wide pertussis morbidity in columns 3 and 4 of Table 1. The outcome variable in these columns is the population incidence rate of pertussis per 100,000 population from 2001-2015.[72] The estimates in columns 3 and 4 of Table 1 provide some evidence that the Tdap booster requirements for middle school entry were effective at reducing population-wide pertussis incidence. Specifically, we estimate that adoption of a Tdap booster mandate reduced pertussis morbidity by 2.2 cases per 100,000 population, or by about 32 percent relative to the sample mean.[73] The point estimate on the Tdap booster requirement variable is statistically significant in the two-way fixed effects model of column 3; adding linear state trends in column 4 reduces the estimate somewhat and renders it statistically insignificant.[74] We additionally present event-study estimates of the effect of the Tdap mandates on population-wide pertussis morbidity in Figure 5

[72] Note that although we have disease incidence data for 2000-2015, the inclusion of a lagged measure of disease incidence in our baseline specification means that we are only able to examine disease incidence as an outcome variable for the years 2001-2015.

[73] In additional analyses presented in Appendix Table 3 we investigate potential nonlinearities in the effect of the mandate based on initial levels of disease prevalence. We find no significant interaction effect when we interact the mandate with baseline (2004) incidence rates, although estimates from models that include interactions with disease incidence rates in the year prior to mandate implementation suggest that mandates are especially effective at reducing pertussis in states with higher pertussis rates. When combined with the event study evidence that Tdap mandates were not systematically adopted in response to sharp upward spikes in pertussis incidence (as shown in Figure 5), this suggests the potential importance of nonlinearities in the effects of the policies.

[74] As a sensitivity check we also estimated the morbidity analyses using log (pertussis cases + 1) as the outcome variable. Our results are robust to this alternative specification.

(coefficient estimates are presented in Appendix Table 4).[75] Although the visual evidence of a population-wide pertussis reduction appears quite short-lived, there is no evidence that Tdap mandates were implemented in response to pertussis outbreaks in a state.[76]

We examine cross-age morbidity spillover effects in Table 2. Specifically, Table 2 makes use of age-specific morbidity data for two diseases: pertussis and tuberculosis (which is not protected against by the Tdap vaccine). With these data we estimate two-way fixed effects models as in columns 3 and 4 of Table 1, but we replace the outcome variable with an age-group specific rate of pertussis incidence. All regressions are weighted by age-group specific population measures. The results from this analysis are presented in columns 1 and 2 of Table 2, and we report only the coefficient on the single Tdap mandate indicator. Thus, each table entry is the coefficient from a separate regression, where the relevant age group is provided in the row label. All regressions include the full set of state-level controls and state and year fixed effects; column (2) adds state-specific linear time trends.

The results in Table 2 provide evidence that the middle school vaccination requirements for the Tdap booster were effective at reducing morbidity among the targeted group: 5-14 year olds. We estimate that a Tdap mandate reduced pertussis cases of 5-14 year olds by 9 cases per 100,000 population, and this estimate is statistically significant at the five percent level. Including linear state trends reduces the magnitude somewhat but continues to suggest large,

[75] Figures 3 and 4 (event studies for Tdap vaccine take-up and pertussis morbidity, respectively) show estimates from models without linear state trends. Estimates from the models with trends were qualitatively similar (see Appendix Tables 2 and 4).

[76] There are many reasons why a sustained increase in Tdap vaccination rates might result in only a short term reduction in pertussis rates. One is that the immunity effect wears off after a couple of years, which is why many states require periodic vaccination 'boosters'. Another is that many states implemented the Tdap mandate by requiring the vaccine not only for those in 6th or 7th grade, but also for students through 9th, or in some cases 12th, grade, with the idea that they wanted to increase Tdap vaccination as much as possible among these youths. This means that in practice, in the years after initial Tdap mandate adoption, only the new sixth or seventh grade youths (depending on the grade configuration in the state) or new enrollees would be required to be newly vaccinated.

though not significant, reductions in pertussis in the targeted age group when Tdap mandates are adopted. Notably, we also estimate that state Tdap mandates significantly reduced pertussis morbidity for infants age 0-4 and adults age 25-34. These findings are consistent with the possibility of herd immunity effects induced by the increased vaccination of disease transmitters (adolescents).[77] Although the statistical significance of these estimates is somewhat affected by the inclusion of linear state trends, the estimated magnitudes are large and consistently suggest meaningful reductions in pertussis incidence.[78] Spillover effects to infant pertussis morbidity are not surprising, as infants cannot be vaccinated against pertussis until two months of age, and it

[77] As noted previously, the cross-age morbidity spillovers documented in Table 2 might not be herd immunity effects if there were cross-age *behavioral* spillovers to increased vaccination rates of non-targeted age groups. We tested this possibility directly in Appendix Tables 5 and 6. In Appendix Table 5 we examine the effects of the mandate on vaccination rates among 7-9 year olds, 14-15 year olds, and 16-17 year olds, using NIS-Teen data and the same specification as in our baseline vaccination estimates. For the 14-5 and 16-17 year olds we limit our sample to states that did not require the Tdap booster for any ages above 13, so that we could credibly identify behavioral spillovers. We find suggestive evidence of behavior spillovers to 16-17 year olds, although estimates are small in magnitude (1.3-2.3 percentage points). In Appendix Table 6 we use vaccination data from the 2003-2015 National Immunization Survey, which is a counterpart to (and precursor of) the NIS-Teen and which targets children age 19-35 months. Using a similar two-way fixed effects model as presented in equation (1), we estimate the effect of the Tdap mandates for middle school entry on the probability that a young child is up-to-date with the infant diphtheria, tetanus, and pertussis vaccine, DTaP (for infants age 19-35 this is 4 doses). We find no evidence that Tdap mandates were associated with meaningful changes in infant DTaP vaccination rates, and this null finding was not sensitive to the presence of other children in the household. In results not reported but available upon request we also estimate effects on adults using data from the CDC BRFSS from 2012-2016. For 12 states these data include answers to the question "Have you received the Tdap vaccine since 2005?" for a subset of years (for a total of 40 state-year observations). Although identification for this analysis is only based on three states, we do find suggestive evidence that the mandates increased Tdap vaccination rates among adults by 1.1-1.2 percentage points. Given the data limitations, however, we interpret these results cautiously.

[78] In Appendix Figure 2 we present age group specific pertussis incidence rates in the year prior to the vaccine development (2004) and in the last year of the sample (2015). We also visually present, in Appendix Figure 3, the estimated proportional pertussis morbidity reduction attributable to the Tdap mandates (relative to the age-group specific 2004 mean) across the life course. Appendix Figure 3 confirms that the effects of the Tdap mandates for middle school entry were large across all age groups but were particularly effective for infants and prime age adults.

takes multiple doses over several months for them to develop a high level of protection.[79]

As a robustness/falsification analysis we also estimate the effects of the Tdap mandates on age-specific tuberculosis morbidity, the only other disease with a plausibly similar transmission mechanism for which we were able to obtain age-specific morbidity data at the state/year level from the CDC.[80] Tuberculosis is a relatively common infection caused by bacteria, and it is transmitted from person-to-person through the air.[81] Symptoms include a cough that typically lasts at least 3 weeks, chest pain, fatigue, and a fever. Tuberculosis, while similar to pertussis in transmission mode and clinical symptoms, is not prevented by the Tdap vaccine; thus, if we observed effects of the Tdap booster mandates on tuberculosis morbidity for 5-14 year olds (or for other age groups), this would be suggestive of a model misspecification or an omitted variables problem. We present the estimates of the Tdap mandates on tuberculosis morbidity in columns (3) and (4) of Table 2. The estimates are small and statistically insignificant in nearly all models. Thus, overall we find strong evidence that the Tdap mandates for middle school entry generated large reductions in pertussis morbidity that extended beyond the directly targeted age group (5-14 year olds). Some of these morbidity effects for other age groups – particularly infants – could be consistent with herd immunity from increased vaccinations of middle school age youths.

[79] This result is consistent with findings in the epidemiological literature, which, in a different context, similarly document that the herd immunity effects of the Tdap vaccine primarily occur for infants (Rohani et al. 2010, Domenech de Cellès et al. 2016).

[80] We also present in Appendix Table 7 a set of falsification analyses using a number of other nationally notifiable diseases for which we were able to obtain morbidity data at the population level only. We find no significant effect of the Tdap mandate on any of the other disease we consider, and the estimated effects are consistently very small in magnitude.

[81] The mean rate of tuberculosis during our sample period was 4.1 cases per 100,000 population.

2.5.3 Cross-Vaccination Spillovers

We next consider the potential for cross-vaccination spillovers among middle school-aged children. For these analyses we take advantage of the fact that among the 46 states that mandate receipt of *any* of the vaccines routinely recommended for 11-12 year olds prior to middle school entry, all mandate the Tdap booster, less than half mandate the MCV vaccine, only 2 mandate HPV, and none mandate seasonal influenza. In all states, Tdap was the first among this set of vaccines to be required for middle school entry. If after controlling for all other middle school vaccination mandates there is an effect of the Tdap mandate on receipt of other vaccines among middle school-aged individuals, then we interpret this as evidence of cross-vaccination spillovers from Tdap booster mandates to non-Tdap vaccination rates.

We present these findings in Table 3 for the other ACIP-recommended vaccines for adolescents: MCV (columns 1-2), HPV vaccine initiation by age 13 (columns 3-4), HPV vaccine completion by age 13 (columns 5-6), and seasonal influenza vaccine between the ages of 10 and 13 (columns 7-8) for models without and with linear state trends in the odd and even-numbered columns, respectively.[82] Results in Table 3 indicate the presence of cross-vaccine spillover effects of Tdap mandates for middle school entry. The estimate in columns 1 and 2 of Table 3, for example, indicate that Tdap mandates increased the probability an adolescent received the MCV vaccine by 2.2-2.9 percentage points, and these estimates are statistically significant at the ten percent level in models with linear state trends. Note that since the Tdap vaccine was always in the first set of vaccines to be mandated for middle school entry, the Tdap mandate effect in these models is identified from the 27 states that adopted Tdap requirements but *not* MCV

[82] To account for the fact that the HPV vaccine was not approved for use in males until 2009, the estimation sample for HPV vaccination outcomes is restricted to females who were age 13 between 2007-2013 and males who were age 13 between 2011-2013.

requirements, as well as from the small number of states that first adopted a Tdap requirement and then years later adopted an MCV requirement.

Columns 3 through 6 of Table 3 also show striking evidence of sizable cross-vaccination spillover from Tdap mandates to HPV initiation (columns 3 and 4) and completion (columns 5 and 6).[83] Specifically, our estimates in columns 3 and 4 suggest that the Tdap mandates increased HPV vaccine initiation by 4.2-4.9 percentage points, and these estimates are statistically significant. Moreover, columns 5 and 6 indicate that the Tdap mandates also significantly increased completion of the three-dose series of the HPV vaccine on the order of 2.5-3.3 percentage points.[84] Finally, columns 7 and 8 of Table 3 provide no evidence that Tdap mandates increased take-up of the seasonal influenza vaccine.

What might explain the null effect of the Tdap mandates on seasonal influenza vaccination? One possibility is timing. Whereas vaccines for Tdap, MCV, and HPV are generally available throughout the year – including prior to the start of the school year – the same is not true for seasonal influenza. Typically seasonal flu vaccines become available in

[83] For completeness we also estimated the spillover effects to the receipt of at least two doses of the HPV vaccine series, since the ACIP recently revised its guidelines to recommend that younger adolescents obtain just two doses of the HPV vaccine instead of three. Our estimates suggest that the Tdap mandates significantly increased the probability of having received at least two doses of the HPV vaccine series by 2.8-2.9 percentage points.

[84] Appendix Table 8 shows event study estimates for the Tdap mandate spillovers to MCV vaccination, HPV vaccine initiation, and HPV vaccine completion. In general we find little evidence of systematic pre-trends in outcomes prior to Tdap mandate adoption and significant immediate increases in vaccination rates for MCV, HPV initiation, and HPV completion, none of which were mandated by the policy whose event time coefficients are reported. Appendix Table 9 shows that if we define cross-vaccine spillovers in a different way by considering outcomes that are the combination of the Tdap booster with each of the other ACIP-recommended vaccines, we continue to find that the Tdap mandates for middle school entry had spillover effects at increasing take-up of MCV and HPV vaccines. Appendix Table 10 shows that our spillover estimates are robust to adding data from the 2014 and 2015 NIS-Teen which used different criteria for determining completeness of provider vaccination data than earlier years. Appendix Table 11 shows that the spillover effects to MCV and HPV are largely driven by years in which the respective vaccine was ACIP-recommended for adolescents. Note that once a vaccine is ACIP-recommended, the Vaccines for Children program must pay for it for low-income children.

September, after most adolescents have started the school year. Thus, it could be that when parents take their child to a healthcare provider for the required Tdap vaccine prior to middle school entry, the MCV and HPV vaccines are in stock but the seasonal flu vaccine is not.[85]

2.5.4. Heterogeneity

In Table 4 we investigate heterogeneity in the effects of the Tdap mandates for middle school entry on Tdap vaccination rates (the direct effect) and on vaccination rates for the other routinely recommended vaccines for youths in this age range where we find spillovers: MCV, HPV vaccine initiation, and HPV vaccine completion. In each entry of Table 4 we present the relevant subsample mean and the coefficient on the Tdap mandate (and its associated standard error) from a separate fully saturated regression model with linear state trends. The outcome variable for each regression is provided in the column header, and each row reports results for a different subsample; we reprint the results for the full sample in the top row. We separately consider the effects of the Tdap mandate on vaccination by gender of the child (rows 2 and 3), race/ethnicity (rows 4-6), and maternal education (rows 7 and 8).

Table 4 reveals several intriguing patterns with respect to heterogeneous effects. First, we find that the direct compliance effect of the Tdap mandate on Tdap vaccination rates (column 1) is larger for girls than for boys and is larger for mothers with lower education relative to mothers with higher education. This latter gradient could reflect that the children with lower educated mothers have a lower vaccination rate in the absence of the mandate and thus have

[85] Also, the flu vaccine is different from the other vaccines in that it was the most recent to be recommended for routine vaccination, and it is also recommended for adolescents and the rest of the members of the household on an annual basis. It could be that getting the flu vaccine is a qualitatively different experience for the family, since everyone in the household is recommended to get the influenza vaccine every year.

further to go to achieve compliance.[86]

In terms of spillover effects, several patterns are notable. The gender difference in the direct effect (i.e., larger effects for girls) is also observed for the spillover effect of Tdap mandates to MCV and HPV vaccination. For race/ethnicity, we find that although the direct effect of the Tdap mandate is largely invariant to race/ethnicity, the spillover effects to HPV vaccine initiation are much larger for Hispanic youth compared to white youth, while the spillover effects to HPV vaccine completion are largest for black youths.

Finally, the spillover effects of Tdap mandates also vary by maternal education. Lower educated mothers are much more likely to take-up the MCV vaccine and the first dose of the HPV vaccine for their children compared to highly educated mothers when their state requires their child to receive the Tdap booster. This could happen for several possible reasons, including the possibility that the information sent home to parents is more of a treatment for low educated mothers than for highly educated mothers (who may have known about the other ACIP-recommended vaccines even in the absence of the Tdap mandate). It could also be that the low-educated mothers are complying with the Tdap mandate in qualitatively different ways than the high-educated mothers, for example by visiting different types of providers where the interaction leads to different types of cross-vaccine spillovers.[87] Finally, it could be an income effect: if

[86] Specifically, in states and years in which there is not an effective Tdap mandate for middle school entry, the Tdap vaccination rate by age 13 for children whose mothers have a bachelor's degree is 35.9 percent, compared to 27.8 percent of children whose mothers whose highest level of education is less than a bachelor's degree. A similar pattern holds if we stratify by household income instead of mother's education.

[87] In results not reported but available upon request, we additionally considered heterogeneity in mandate effects by type of provider and by insurance status. For provider type, the NIS-Teen data allow us to identify whether the child received her vaccines exclusively at public institutions (e.g., public clinics), exclusively at private institutions (e.g., a physician's office or retail clinic), or in a mixture of public and private settings. Acknowledging that the type of setting chosen for vaccination is endogenous, we do find that the spillover effects of the Tdap mandates were significantly larger for individuals whose vaccinations were received exclusively at public providers. We also test for differential effects of the

low-educated mothers are more likely to be eligible for free vaccines under the Vaccines for Children program, the increased take-up of the MCV vaccines could reflect downward sloping demand. We explore mechanisms in the next section.

2.5.5. Mechanisms

Our final sets of analyses attempt to disentangle mechanisms for the cross-vaccination spillovers observed in Tables 3 and 4. In addition to the implicit price reduction for the non-mandated vaccines brought about by the fact that the child has to see a provider to obtain the required Tdap vaccine, there are also possible roles for parents and providers. For example, it could be that state Tdap mandates cause parents to receive new information about other age-recommended vaccines, and this causes them to get their child vaccinated against those conditions even though it is not required. Alternatively, it could be that the Tdap mandates simply cause parents to have increased contact with the healthcare system whereby a provider informs them about other age-appropriate vaccinations for their child. These mechanisms have different implications for the most effective policy for increasing immunizations.

We investigate these issues in a variety of ways. First, we consider a range of outcomes available in the NIS-Teen data: whether the parent had ever heard of human papillomavirus or HPV; whether the parent had ever heard of a vaccine for HPV called Gardasil or Cervarix (the trade names for the HPV vaccine); whether the parent reports that her doctor ever recommended the HPV vaccine; and whether the child had an 11-12 year old well-child visit. A positive effect

---

mandate in states that allow pharmacists to administer vaccines to adolescents, but we do not find evidence of a significant interaction between the two policies. Limiting our sample to adolescents aged 13 at the time of survey (since we only observe the child's insurance status at the time of the survey, not at the time of vaccination), we find no evidence of heterogeneous effects of the mandate by insurance status. We further examine, separately by child insurance status, if mandates had differential effects in states with immunization insurance mandates or after the ACA preventive services mandate went into effect. We find no evidence of heterogeneous effects of the mandates along these dimensions.

of the Tdap mandates on these last two outcomes – receipt of a physician recommendation for the HPV vaccine or the likelihood that the youth had a well-child visit (and thus interacted with the healthcare system) – would provide evidence in favor of the provider mechanism. The first two outcomes, parental knowledge of HPV and of the HPV vaccine, are more ambiguous and could be affected through receipt of new information regarding vaccination from the school or through the provider channel. In the absence of other evidence for the provider mechanism, however, an effect on these outcomes would lend support for the idea that patient behavior underlies the spillover.

Table 5 presents these results for the sample of youths who were age 13 at the time of survey (and for whom the reference window of the questions is most recent and relevant).[88] We find little evidence that Tdap mandates are significantly associated with increases in the likelihood of any of the outcomes except for a robust and statistically significant increase in the likelihood of having had an 11-12 year old well-child visit. This offers some mixed support for the provider mechanism, though in this case we would have also expected Tdap mandates to have increased the likelihood of having received a physician recommendation for the HPV vaccine.[89]

We also investigated the patient mechanism using data from Google Trends which captures the relative popularity of specific search terms in an area from 2005 to the present.

[88] Because these analyses are done using a subset of the sample used in our main vaccination analyses presented in Tables 1 and 3, we re-estimate effects on Tdap, MCV, and HPV uptake for this more limited sample. Results are presented in Appendix Table 12 and return patterns similar to those from the full sample.

[89] It could also be that children are receiving vaccines that they or their parents are not aware they are receiving. Anecdotally some parents follow a rule of thumb whereby they instruct the provider to give any vaccination that is recommended for their child. While vaccine information statements are required to be provided to parents, it is not obvious how much the parent/provider interaction is an informed negotiation.

These data have been used by other scholars studying a range of topics, including vaccination (see, for example, Oster 2016). The advantage of the Google Trends data in our setting is that we can examine the popularity of searches for, say, 'Tdap' to see if adoption of Tdap mandates for middle school entry at the state level is associated with meaningful increases in search behavior. Since parents far outnumber providers (and we think providers are not using Google to find out about various vaccinations), any relationship between the mandates and the search behavior is likely to reflect parent behavior. At a minimum it may suggest that information about the Tdap vaccine is disseminating broadly in the community following Tdap mandate adoption. Moreover, we can examine searches for MCV and HPV-related terms as well to provide additional tests of the role of information and parent search behavior in driving the spillover effects.

The results of the Google Trends analyses are presented in Table 6. Specifically we present coefficients on the Tdap mandate in a two-way fixed effects regression on the relative search popularity score provide by Google for each state, where each state's popularity is anchored at 100 in the month/year combination for that state where the search was most popular. We also report the coefficient on the pertussis rate in the state as an additional validity check, as Oster (2016) shows using Google Trends data that disease outbreaks increase vaccination in part by increasing information. The results in Table 6 provide striking evidence in favor of an information-based mechanism driving the direct and spillover effects of Tdap mandates for middle school entry. Columns 1 and 2 (without and with linear state trends, respectively) show that a Tdap mandate for middle school entry is significantly and positively associated with increased searches for 'tdap' and that the current pertussis rate in a state is also significantly and positively associated with searches for 'tdap'. Columns 3 and 4 and columns 5 and 6,

respectively, show that the former relationship is also true for searches related to the meningococcal vaccine and HPV: the popularity of both searches in a state is estimated to increase significantly when the state adopts a Tdap mandate. This is strongly consistent with parent behavior playing an important role in driving the cross-vaccine spillovers identified above.[90]

2.6. Discussion and Conclusion

We provide a variety of analyses showing that state mandates requiring Tdap vaccination prior to middle school entry were highly effective at significantly increasing Tdap vaccine uptake between the age of 10 and 12 by 13.5-13.7 percentage points. Event study analyses show that the direct vaccination effects of the mandates occur immediately and are sustained over time. Similarly specified models of population-wide morbidity suggest a population-wide reduction on the order of 32 percent of the sample mean. Disaggregated age-specific pertussis morbidity data confirm that the Tdap mandates for middle school entry substantially reduced pertussis rates among 5-14 year olds (whose vaccination rates were directly affected) but also induced meaningful reductions in pertussis morbidity for infants and young adults. Some of these effects may have occurred due to herd immunity (i.e., the reduced transmission attributable to directly targeted adolescents).

We also find clear evidence of cross-vaccination spillovers: state requirements that middle school youths obtain the Tdap booster resulted in increases in MCV vaccination even in

[90] We also note that the fact we find any effect of state Tdap mandates on completion of the HPV vaccine series – which over our time period required three doses, each administered during separate visits to a healthcare provider over a minimum of 6 months – strongly suggests that patient behavior has to play an important role. Notably, this finding contrasts with that in Lawler (2017) who finds in the context of a different vaccine (hepatitis A) that vaccination recommendations are effective at inducing initiation but not completion of a vaccine series in young children.

states that did not require MCV vaccination for middle school entry. More striking, the Tdap mandates also significantly increased HPV vaccination rates. We also find that these spillover effects are larger for females, nonwhites, and children of less educated mothers. When we investigate mechanisms, we find some evidence that the mandates increased contact with healthcare providers. There is stronger evidence that the laws increased Google search behavior for information on the Tdap booster, meningococcal disease, and HPV. Taken together these patterns suggest that both parents and providers are responsible for the remarkable cross-vaccine spillovers attributable to state Tdap mandates.

Our results suggest that the private and social returns to middle school vaccination requirements for the Tdap booster are extremely large. Estimates from Table 2 indicate that, if implemented nationally, Tdap mandates would reduce pertussis incidence by 1,890 cases per year among 0-4 year olds (19.9 million 0-4 year olds in US * 9.49 cases/100,000 population) and 3,700 cases per year among 5-14 year olds. Additionally, using conservative estimates of the pertussis fatality rate, we find that these mandates potentially save the lives of 7-9 infants and children each year (CDC 2015a, Purdy et al. 2004). For adults, reductions are smaller but still substantial; we estimate the mandates would reduce pertussis incidence nationally by 380 cases per year among 25-34 year olds.

To estimate the value of this averted pertussis morbidity, we refer to Purdy et al. (2004), who provide age-group-specific cost estimates of pertussis morbidity. Their cost estimates include both direct costs due to outpatient and inpatient health care, as well as indirect costs due to lost work productivity (due to own illness or to care for sick family members). Based on their estimates, on average each averted infant case saves approximately $6,432, each averted child case saves approximately $3,757, and each averted adult case saves approximately $1,374. In

total, this suggests that the reductions in pertussis morbidity resulting from national implementation of middle school Tdap mandates would generate approximately $24.3 million per year of social savings. Reductions in pertussis mortality, valued using an estimate of the value of statistical life of $9.1 million, would result in an additional $65.8 million in social savings annually (Viscusi and Aldy 2003).

For estimates of policy cost we separately consider the costs of the increased vaccination and of policy enforcement. Our results in Table 1 suggest that national implementation of the Tdap mandates would increase the number of administered Tdap doses by approximately 540,000 doses per year (4 million 11 year olds in the US * 0.135). Using estimates from Whitney et al. (2014) and the CDC's Vaccine Price List (2018), we estimate the cost of each additional Tdap vaccine administered to be approximately $112, for a total cost of approximately $60.7 million per year. This estimate incorporates measures of the value of caregiver time and travel costs, vaccine administration costs, and the cost of the vaccine dose itself.[91] We also allow for an overall rate of vaccine wastage of five percent.

As an estimate of policy enforcement costs, we use personnel costs from a school-based health clinic vaccine administration study done by Kempe et al. (2012). In this study, school-based health clinic staff first checked student immunization records and then proceeded to meet with and administer vaccines to those with missing doses, for a per child average personnel cost of $2.21. Scaling this estimate by the total number of 11 year olds in the United States suggests an upper bound on school-based enforcement costs of approximately $8.84 million dollars per

[91] We account for the substantial differences in the price of a vaccine dose and its administration across public and private providers by using a weighted average price that reflects the distribution of adolescents across providers and the relative estimated effect sizes for adolescents that see each provider type in our sample. In our calculations we use an estimated price per dose of Tdap of $34.67, with an associated administrative cost of $16.57.

year.

Overall, our estimates suggest that national implementation of middle school Tdap booster mandates would generate approximately $90.1 million in social savings per year (due to reductions in pertussis morbidity and mortality) while costing approximately $69.5 million annually. These estimates imply a benefit-cost ratio of 1.30:1, or equivalently, that for each additional dollar spent, middle school Tdap mandates yield $1.30 in social benefits. Notably, this analysis likely underestimates the social benefits of the Tdap mandates, as our spillover estimates further suggest potentially large returns due to increased HPV vaccination. For example, our most conservative estimate suggests that HPV vaccine completion rates increased by 2.5 percentage points (column 5 of Table 3). Given that there are 4 million 11 year olds in the United States, this translates to about 100,000 adolescents and young adults who received three doses of the HPV vaccine because their state required them to get a Tdap booster prior to middle school entry. The American Cancer Society indicates that the lifetime risk of developing cervical cancer is about 0.6 percent; given that the HPV vaccine protects against the viruses that cause 70% of all cervical cancers, we estimate that Tdap mandates will prevent about 210 cases of cervical cancer (50,000 adolescent girls having completed the HPV vaccine due to Tdap mandates * 0.006 * .70). Similar calculations suggest that the Tdap booster mandates will also prevent 659 cases of throat cancer, 160 cases of anal cancer, and 74 cases of cancer of the vulva.[92]

Future work could also examine other longer term consequences of the Tdap booster mandates for middle school entry. For example, since the laws increased interactions with

[92] Information on lifetime risk of developing various cancers comes from the American Cancer Society (2017) and the National Cancer Institute (2017a, b). Information on the proportion of cancers by type that are caused by HPV comes from the CDC (2016a).

healthcare providers, it is possible that other adolescent health outcomes and behaviors could have been affected. And by identifying an exogenous increase in HPV vaccine uptake, our work offers a new setting for tests of the moral hazard concerns about increased risky sexual behaviors in the context of HPV vaccination. One might also imagine that the policy changes had longer term effects on preventive cancer screenings for the youths whose HPV vaccine behavior was affected. These and related effects on longer term outcomes are fruitful avenues for future work.

2.7. References

Abrevaya, Jason, and Karen Mulligan (2011). "Effectiveness of state-level vaccination mandates: Evidence from the varicella vaccine," *Journal of Health Economics*, 30: 966-976.

Almond, Douglas and Janet Currie (2011). "Human Capital Development Before Age Five." In Handbook of Labor Economics, David Card and Orley Ashenfelter, Eds. Amsterdam: Elsevier.

Almond, Douglas, Janet Currie, and Valentina Duque (2017). "Childhood Circumstances and Adult Outcomes: Act II," NBER Working Paper #23017.

American Cancer Society (2017). "Lifetime Risk of Developing or Dying from Cancer." Available at: http://www.cancer.org/cancer/cancer-basics/lifetime-probability-of-developing-or-dying-from-cancer.html. Accessed on January 18, 2017.

----- (2015). "Cancer Facts & Figures for Hispanics/Latinos 2015-2017." Atlanta: American Cancer Society. Report available at: http://www.cancer.org/acs/groups/content/@research/documents/document/acspc-046405.pdf. Accessed on September 7, 2016.

Anderberg, Dan, Arnaud Chevalier, and Jonathan Wadsworth (2011). "Anatomy of a Health Scare: Education, Income and the MMR Controversy in the UK." *Journal of Health Economics*, 30(3): 515-530.

Bertrand, Marianne, Esther Duflo, and Sendhil Mullainathan (2004). "How Much Should We

Trust Difference-In-Differences Estimates?," *Quarterly Journal of Economics*, 119(1): 249-275.

Bradford, W. David, and Anne Mandich (2015). "Some State Vaccination Laws Contribute To Greater Exemption Rates And Disease Outbreaks In The United States," *Health Affairs*, 34(8): 1383-1390.

Bugenske, Erin, Shannon Stokley, Allison Kennedy, and Christina Dorell (2012). "Middle school vaccination requirements and adolescent vaccination coverage," *Pediatrics*, 129(6): 1056-1063.

Cameron, A. Colin, Jonah Gelbach, and Douglas Miller (2008). "Bootstrap-Based Improvements for Inference with Clustered Errors," *Review of Economics and Statistics*, 90(3): 414-427.

Centers for Disease Control and Prevention (2018). "CDC Vaccine Price List," National Center for Immunization and Respiratory Diseases, Centers for Disease Control and Prevention. Available at: https://www.cdc.gov/vaccines/programs/vfc/awardees/vaccine-management/price-list/index.html Accessed on January 12, 2018.

----- (2016a). "HPV and Cancer," Division of Cancer Prevention and Control. Available at: https://www.cdc.gov/cancer/hpv/statistics/cases.htm. Accessed on January 17, 2017.

----- (2016b). "State School Immunization Requirements and Vaccine Exemption Laws," Office for State, Tribal, Local and Territorial Support, Centers for Disease Control and Prevention. Available at: http://www.cdc.gov/phlp/docs/school-vaccinations.pdf. Accessed on October 16, 2016.

----- (2015a). "Epidemiology and Prevention of Vaccine-Preventable Diseases." Eds: Hamborsky J, Kroger A, Wolfe S. 13th ed. Washington D.C. Public Health Foundation.

----- (2015b). "National Immunization Survey-Teen: A User's Guide for the 2014 Public-Use Data File," National Center for Immunization and Respiratory Diseases and National Center for Health Statistics, Centers for Disease Control and Prevention. Available at: ftp://ftp.cdc.gov/pub/Health_Statistics/NCHS/Dataset_Documentation/NIS/NISTEENPUF14_DUG.pdf. Accessed on January 5, 2017.

----- (1999). "Ten Great Public Health Achievements – United States, 1900-1999," *Morbidity and Mortality Weekly Report*, 48(12): 241-243.

Chang, Lenisa V. (2016a). "The Effect of State Insurance Mandates on Infant Immunization Rates," *Health Economics*, 25(3): 372-386.

---- (2016b). "The Measles-Mumps-Rubella Vaccine and the Autism Controversy: Did Autism Concerns Affect Vaccine Take Up?" working paper.

Conley, Tim and Christopher Taber (2011). "Inference with 'Difference in Differences' with a small number of policy changes," *Review of Economics and Statistics* 93(1): 113-125.

Dempsey, Amanda F. and Sarah E. Schaffer (2011). "Human papillomavirus vaccination rates and state mandates for tetanus-containing vaccines," *Preventive Medicine*, *52*(3): 268-269.

Dempsey, Amanda F. and Gregory D. Zimet (2015). "Interventions to Improve Adolescent Vaccination: What May Work and What Still Needs to be Tested," *American Journal of*

Preventive Medicine, 49(6S4): S445-S454.

Domenech de Cellès, Matthieu, Maria A. Riolo, Felicia MG Magpantay, Pejman Rohani, and Aaron A. King (2014). "Epidemiological evidence for herd immunity induced by acellular pertussis vaccines," *Proceedings of the National Academy of Sciences*, 111(7): E716-E717.

Georgia Department of Health (2014). "New 7th Grade Vaccination Requirements: Guidance for School Nurses & Public Health Nurses." Report available at: http://dph.georgia.gov/sites/dph.georgia.gov/files/Immunizations/Tdap_Men_SchoolsQ&A_FINAL_022414_0.pdf. Accessed on February 8, 2016.

Gruber, Jonathan (2001). Risky Behavior Among Youths: An Economic Analysis. Chicago: University of Chicago Press.

Humiston, Sharon G. and Susan L. Rosenthal (2005). "Challenges to vaccinating adolescents: vaccine implementation issues," *Pediatric Infectious Disease Journal*, 24(6S): S134-S140.

Kempe, Allison, Jennifer Barrow, Shannon Stokley, Alison Saville, Judith E. Glazner, Christina Suh, Steven Federico et al. (2012). "Effectiveness and cost of immunization recall at school-based health centers." *Pediatrics* 129 (6): E1446-E1452.

Kharbanda, Elyse Olshen, Melissa S. Stockwell, James Colgrove, Karthik Natarajan, and Vaughn I. Rickert (2010). "Changes in Tdap and MCV4 Vaccine Coverage Following Enactment of a Statewide Requirement of Tdap Vaccination for Entry Into Sixth Grade," *American Journal of Public Health*, 100(9): 1635-1640.

Lawler, Emily C. (2017). "Effectiveness of Vaccination Recommendations versus Mandates: Evidence from the hepatitis A vaccine," *Journal of Health Economics*, 52: 45-62.

Luca, Dara Lee (2014). "The Long-Term Effects of Post-Neonatal Childhood Health: Evidence from Mandatory School Vaccination Laws," working paper.

MacKinnon, James G. and Matthew D. Webb (2016). "Randomization Inference for Difference-in-Differences with Few Treated Clusters," Queen's Economics Department Working Paper No. 1355.

Moghtaderi, Ali and Scott Adams (2016). "The Role of Physician Recommendations and Public Policy in Human Papillomavirus Vaccinations," *Applied Health Economics and Health Policy*, 14: 349-359.

National Cancer Institute (2017a). "Cancer Stat Facts: Vulvar Cancer." Available at: https://seer.cancer.gov/statfacts/html/vulva.html. Accessed on January 18, 2017.

----- (2017b). "Cancer Stat Facts: Anal Cancer." Available at: https://seer.cancer.gov/statfacts/html/anus.html. Accessed on January 18, 2017.

National Council of State Legislatures (2015a). Immunizations Policy Issues Overview. http://www.ncsl.org/research/health/immunizations-policy-issues-overview.aspx. [27 June 2015].

----- (2015b). States With Religious and Philosophical Exemptions from School Immunization Requirements. ttp://www.ncsl.org/research/health/school-immunization-exemption-state-laws.aspx . [27 June 2015].

O'Brien, Judith A. and J. Jaime Caro (2005). "Hospitalization for pertussis: profiles and case costs by age," *BMC Infectious Diseases*, open access available at: http://bmcinfectdis.biomedcentral.com/articles/10.1186/1471-2334-5-57. Accessed on January 10, 2017.

Oster, Emily (2016). "Does Disease Cause Vaccination? Disease Outbreaks and Vaccination Response," NBER Working Paper #22464.

Philipson, Tomas (2000). Economic epidemiology and infectious diseases. *Handbook of Health Economics, 1*, 1761-1799.

----- (1996). "Private Vaccination and Public Health: An Empirical Examination for US Measles," *Journal of Human Resources*, 31(3): 611-630.

Purdy, Kenneth W., Joel W. Hay, Marc F. Botteman, and Joel I. Ward (2004). "Evaluation of strategies for use of acellular pertussis vaccine in adolescents and adults: a cost-benefit analysis." *Clinical Infectious Diseases* 39(1): 20-28.

Rohani, Pejman, Xue Zhong, and Aaron A. King (2010). "Contact network structure explains the changing epidemiology of pertussis," *Science,* 330(6006): 982-985.

Schaller, Jessamyn, Lisa Schulkind, and Teny Shapiro (2017). "The Effects of Perceived Disease Risk and Access Costs on Infant Immunization," NBER Working Paper #23923.

Snyder, Thomas D., Cristobal de Brey, and Sally A. Dillow (2016). *Digest of Education Statistics 2014.* National Center for Education Statistics, Institute of Education Sciences,

U.S. Department of Education. Washington, DC.

Trogdon, Justin, Paul Shafer, Parth Shah, and William A. Calo (2016). "Are state laws granting pharmacists authority to vaccinate associated with HPV vaccination rates?" *Vaccine*, 34(38): 4514-9.

U.S. Department of Health and Human Services. Healthy People 2020: Immunization and Infectious diseases. http://www.healthypeople.gov/2020/topics-objectives/topic/immunization-and-infectious-diseases/objectives. [27 June 2015].

Viscusi, W. Kip and Joseph E. Aldy (2003). "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World," *Journal of Risk and Uncertainty*, 27(1): 5-76.

Walgreens (2016). "Price Menu: Vaccines." Available at: https://www.walgreens.com/topic/healthcare-clinic/price-menu.jsp. Accessed October 16, 2016.

Ward, Courtney J. (2014). "Influenza Vaccination Campaigns: Is an Ounce of Prevention Worth a Pound of Cure?," *American Economic Journal: Applied Economics*, 6(1), 38-72.

----- (2011). "The Effects of Immunization Mandates: Does Prenatal Exposure to State School Immunization Policy Impact Later Economic Well-Being?" Dalhousie University Working Paper.

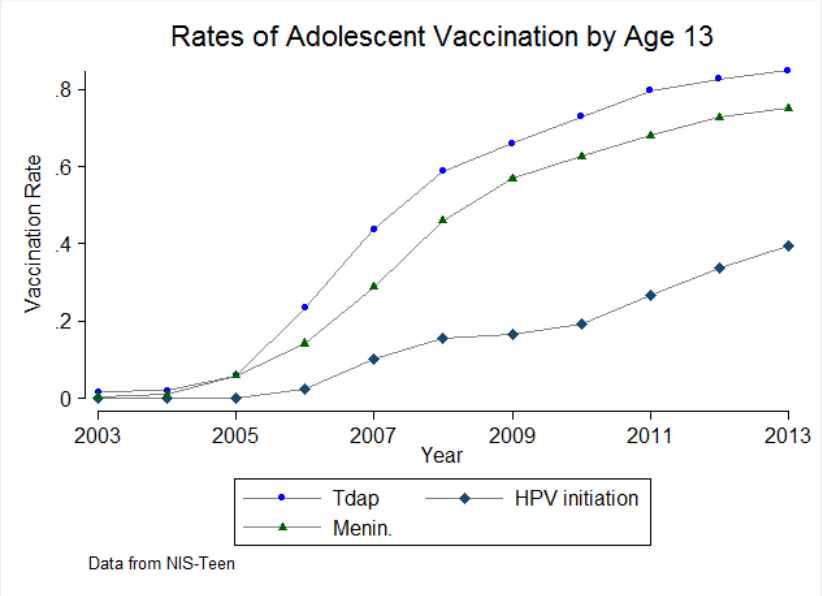
Ward, Joel I., James D. Cherry, Swei-Ju Chang, Susan Partridge, Hang Lee, John Treanor, David P. Greenberg et al. (2005). "Efficacy of an acellular pertussis vaccine among adolescents

and adults," *New England Journal of Medicine,* 353(15): 1555-1563.

Whitney, Cynthia G., Fangjun Zhou, James Singleton, Anne Schuchat, and Centers for Disease Control and Prevention (2014). "Benefits from immunization during the vaccines for children program era—United States, 1994–2013." *Morbidity and Mortality Weekly Report,* 63(16): 352-355.

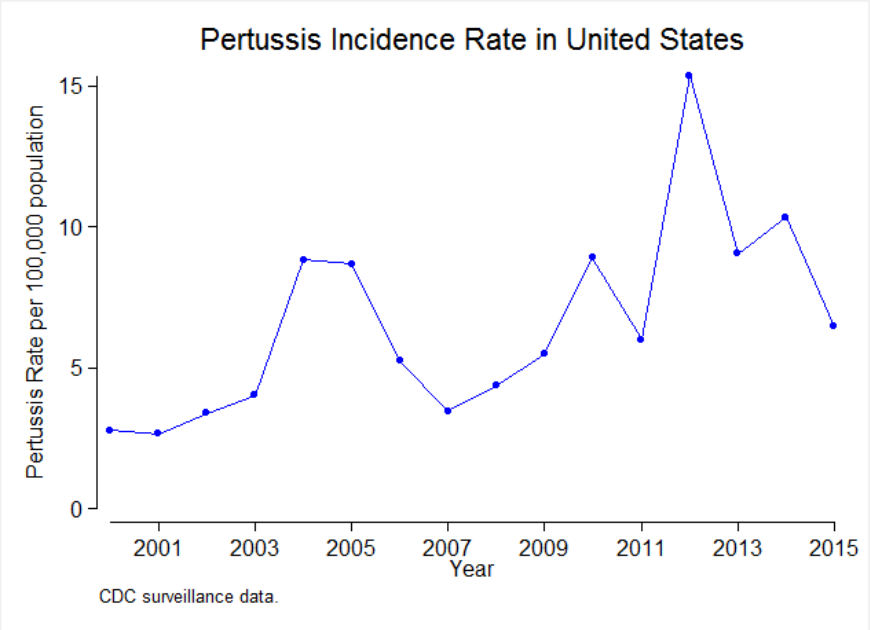
Woodwell, Donald A. and Donald K. Cherry (2004). "National Ambulatory Medical Care Survey: 2002 summary," *Adv Data*, 346: 1-44.

Figure 1: Trends in Adolescent Vaccination Rates for ACIP-Recommended Vaccines



Notes: Data are from NIS-Teen. Vaccination status is measured directly prior to age 13, and assigned to the year in which the individual was age 12.

Figure 2: Trends in Population-Wide Pertussis Incidence, 2000-2015



Notes: Data from the Centers for Disease Control and Prevention.

Figure 3: Timing of Tdap Mandate Policy Adoption

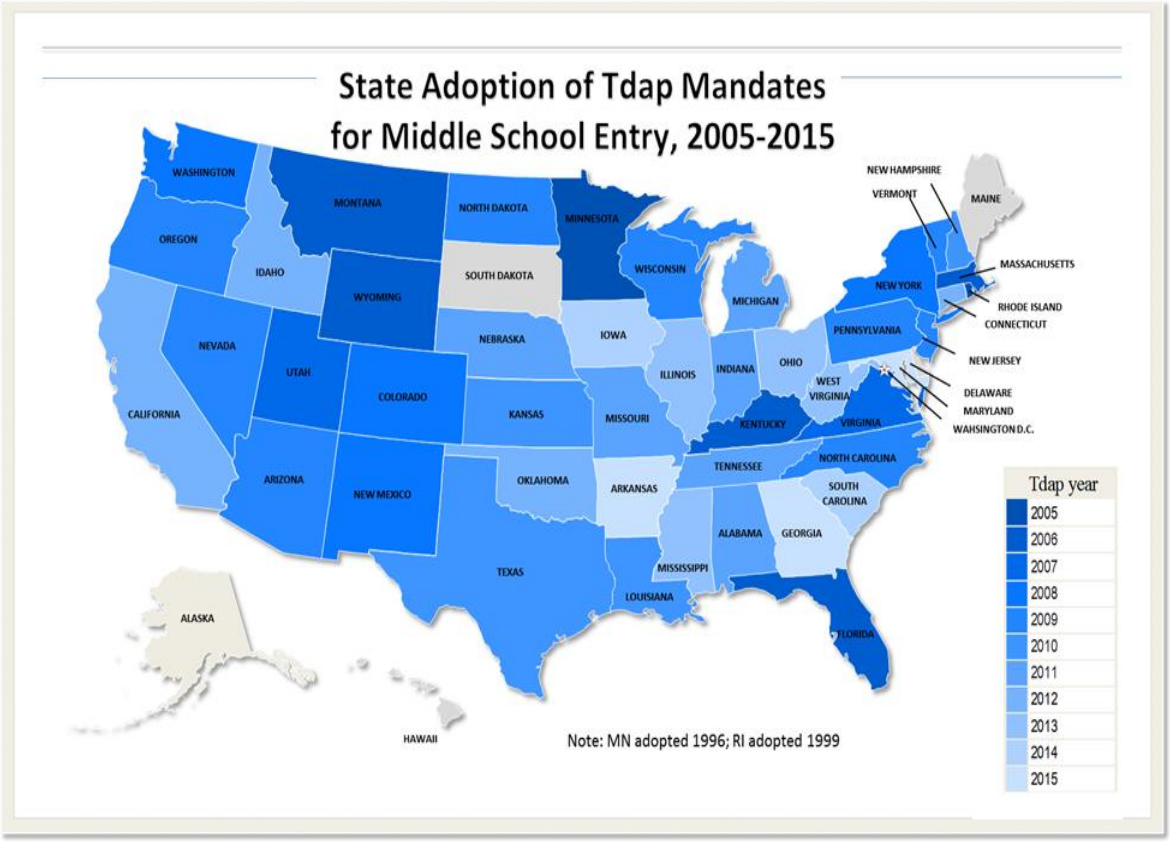
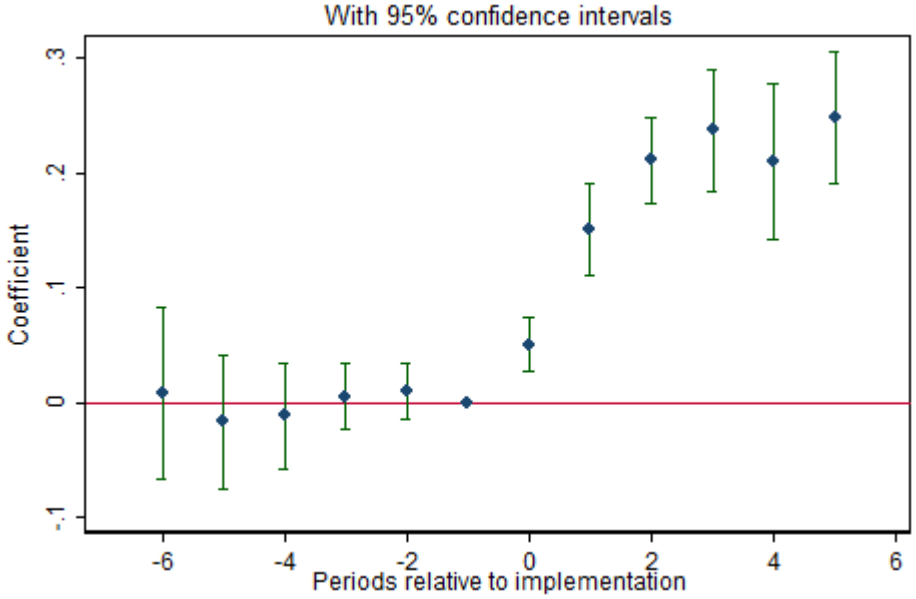
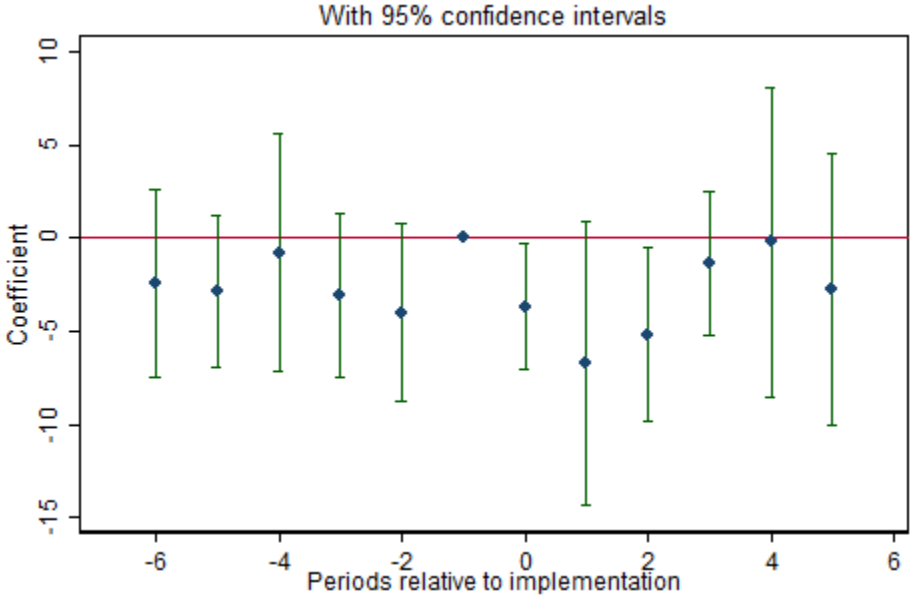


Figure 4: Event Study Estimates of the Direct Effects of Middle School Vaccination Requirements for the Tdap Booster



Notes: Coefficients are relative to the excluded group of the year prior to policy implementation. The coefficients presented for -6 periods and 5 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior to implementation and 5 or more years since implementation, respectively.

Figure 5: Event Study Estimates of Effects of Middle School Vaccination Requirements for the Tdap Booster on Population Pertussis Morbidity



Notes: Coefficients are relative to the excluded group of the year prior to policy implementation. The coefficients presented for -6 periods and 5 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior to implementation and 5 or more years since implementation, respectively.

Table 1: Middle School Tdap Vaccination Requirements Increased Tdap Vaccination Rates by age 13 and Reduced Population Pertussis Morbidity
NIS-Teen (2008-2013) and CDC Data (2001-2015)

	(1)	(2)	(3)	(4)
	1 dose Tdap booster	1 dose Tdap booster	Pertussis morbidity	Pertussis morbidity
Sample mean	0.449	0.449	6.889	6.889
Δ (final year - base year mean)	*0.814*	*0.814*	*3.792*	*3.792*
Tdap Mandate for Middle School Entry	0.135***	0.137***	-2.241*	-2.220
	(0.0140)	(0.0164)	(1.262)	(1.543)
R-squared	0.335	0.338	0.439	0.486
N	116304	116304	763	763
Individual characteristics?	Y	Y	Y	Y
Other policy controls?	Y	Y	Y	Y
Other state/time varying Xs?	Y	Y	Y	Y
State and year fixed effects?	Y	Y	Y	Y
Linear state trends?	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. Results in columns 1 and 2 are from linear probability models and use NIS-Teen sampling weights. The outcome in columns 1 and 2 is an indicator for whether the individual received the Tdap booster by age 13. Individuals are observed at ages 13-17 between 2008 and 2013. All models include controls for individual demographic characteristics (age at observation fixed effects, gender, race, number of children in the household, and mother's age, education level, and marital status); state, year of survey, and birth cohort fixed effects; state mandates for insurance coverage of well-child visits and vaccines; state college and high school immunization and education requirements for MCV; state HPV policies (see text for details); state immunization mandates for child care/kindergarten entry; lagged state pertussis and meningococcal disease incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; and state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). Results in columns 3 and 4 are estimated using disease incidence data from the CDC and are weighted by state population. The dependent variable in columns 3 and 4 is the number of reported cases of pertussis per 100,000 population. These models include controls for state mandates for insurance coverage of well-child visits and vaccines; all child care/school vaccination mandates; state HPV and MCV policies; lagged pertussis incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level); and state and year fixed effects. Columns 2 and 4 also include linear state trends. Standard errors are clustered at the state level.

Table 2:Middle School Tdap Vaccination Requirements Reduced Pertussis Morbidity, CDC Data 2001-2015

	(1) Pertussis incidence rate	(2) Pertussis incidence rate	(3) TB incidence rate	(4) TB incidence rate
Direct effect:				
Age 5-14	-8.986 (4.318)**	-8.242 (5.479)	-0.0950 (0.0716)	-0.0309 (0.0775)
Spillover effects:				
Age 0-4	-9.490 (4.709)**	-9.698 (5.650)*	0.0647 (0.190)	0.0208 (0.233)
Age 15-24	-1.260 (1.324)	-1.533 (1.503)	0.205 (0.132)	0.245 (0.130)*
Age 25-34	-0.861 (0.481)*	-0.746 (0.525)	0.0335 (0.176)	0.153 (0.175)
Age 35-44	-0.886 (0.561)	-0.703 (0.630)	-0.130 (0.156)	-0.0754 (0.112)
Age 45-54	-0.603 (0.470)	-0.470 (0.489)	-0.0630 (0.170)	0.0511 (0.158)
Age 55-64	-0.516 (0.332)	-0.539 (0.362)	-0.129 (0.118)	-0.0258 (0.123)
Age 65+	-0.318 (0.239)	-0.349 (0.295)	0.0606 (0.171)	0.0288 (0.178)
Linear state trends?	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. The dependent variable is the number of reported cases of each disease per 100,000 population, separately by age group (reported in each row). Each entry is from a separate regression and represents the coefficient on the Tdap mandate. All models include controls for state mandates for insurance coverage of well-child visits and vaccines; all child care/school vaccination mandates; state HPV and MCV policies; lagged pertussis incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level); and state and year fixed effects. Columns 2 and 4 also include linear state trends. Regressions are weighted by age-specific state population. Standard errors are clustered at the state level.

Table 3: Middle School Tdap Vaccination Requirements Had Cross-Vaccine Spillovers to Other ACIP-Recommended Vaccines for Adolescents, NIS-Teen 2008-2013

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	1 dose MCV	1 dose MCV	Initiated HPV vaccine	Initiated HPV vaccine	Completed HPV vaccine	Completed HPV vaccine	Had influenza vaccine, age 10-13	Had influenza vaccine, age 10-13
Sample mean	0.357	0.357	0.236	0.236	0.0987	0.0987	0.122	0.122
Δ (final year - base year mean)	*0.724*	*0.724*	*0.306*	*0.306*	*0.139*	*0.139*	*0.436*	*0.436*
Tdap Mandate for Middle School Entry	0.0223	0.0290*	0.0490***	0.0416***	0.0247***	0.0331***	0.0123	0.00709
	(0.0159)	(0.0148)	(0.0151)	(0.0152)	(0.00863)	(0.0107)	(0.00815)	(0.00657)
R-squared	0.285	0.289	0.111	0.113	0.065	0.066	0.172	0.175
N	116304	116304	57133	57133	57133	57133	116304	116304
Linear state trends?	N	Y	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. Columns 3-6 are restricted to females who were age 13 between 2007-2013 and males who were age 13 between 2011-2013.

Table 4: Heterogeneity in the Effects of Middle School Tdap Vaccination Requirements, NIS-Teen 2008-2013

	(1) 1 dose Tdap (direct effect)	(2) 1 dose MCV (spillover effect)	(3) Initiated HPV vaccine (spillover effect)	(4) Completed HPV vaccine (spillover effect)
1. Full sample, mean	0.449	0.357	0.236	0.099
Tdap mandate effect:	0.137***	0.0290*	0.0416***	0.0331***
	(0.0164)	(0.0148)	(0.0152)	(0.0107)
2. Girls, mean	0.448	0.355	0.265	0.117
Tdap mandate effect:	0.152***	0.0392*	0.0349**	0.0361**
	(0.0170)	(0.0196)	(0.0147)	(0.0136)
3. Boys, mean	0.449	0.358	0.123	0.028
Tdap mandate effect:	0.122***	0.0190	-0.0609	0.0301
	(0.0167)	(0.0133)	(0.0482)	(0.0481)
4. White, mean	0.453	0.343	0.205	0.095
Tdap mandate effect:	0.150***	0.0378**	0.0438**	0.0332***
	(0.0192)	(0.0182)	(0.0174)	(0.0111)
5. Black, mean	0.412	0.347	0.238	0.078
Tdap mandate effect:	0.150***	0.0757***	0.0454	0.0637***
	(0.0390)	(0.0243)	(0.0354)	(0.0224)
6. Hispanic, mean	0.456	0.389	0.303	0.118
Tdap mandate effect:	0.128***	0.0305	0.0972**	0.0470**
	(0.0142)	(0.0189)	(0.0368)	(0.0197)
7. Mother has at least BA, mean	0.509	0.403	0.206	0.094
Tdap mandate effect:	0.111***	0.00570	0.0290	0.0314***
	(0.0207)	(0.0202)	(0.0185)	(0.0108)
8. Mother has less than BA, mean	0.418	0.333	0.252	0.101
Tdap mandate effect:	0.149***	0.0397***	0.0474***	0.0349**
	(0.0180)	(0.0145)	(0.0173)	(0.0140)

* significant at 10%; ** significant at 5%; *** significant at 1%. Columns 3 and 4 are restricted to females aged 13 between 2007-2013, and males aged 13 between 2011-2013. See notes to Table 1 for details on the specification and control variables. All models include state trends.

Table 5: Evidence on Mechanisms, NIS-Teen 2008-2013

	(1) Ever heard of HPV	(2) Ever heard of HPV	(3) Ever heard of HPV shot	(4) Ever heard of HPV shot	(5) Doctor recom-mended HPV vaccine	(6) Doctor recom-mended HPV vaccine	(7) Had an 11-12yo well child visit	(8) Had an 11-12yo well child visit
Sample mean:	0.947	0.947	0.922	0.922	0.480	0.480	0.915	0.915
Δ (final year - base year mean)	*-0.001*	*-0.001*	*-0.009*	*-0.009*	*0.056*	*0.056*	*0.041*	*0.041*
Tdap Mandate for Middle School Entry	-0.00171	0.0368	0.0236	0.0443*	0.0312	0.0348	0.0331***	0.0382**
	(0.0178)	(0.0249)	(0.0175)	(0.0222)	(0.0222)	(0.0433)	(0.00973)	(0.0166)
R-squared	0.0810	0.101	0.0879	0.0994	0.105	0.109	0.0349	0.0385
N	7757	7757	7764	7764	17399	17399	24144	24144
Linear state trends?	N	Y	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. All samples are restricted to individuals who have adequate provider vaccination data and are age 13 at time of survey, as the outcomes in columns 1-6 are measured at time of interview; they are not able to be retrospectively measured at age 13. The outcomes in columns 1-4 are only reported for 2008-2011, and so the estimation sample for these outcomes is females who are age 13 at the time of survey, 2008-2011. The actual question for the outcome in Columns 3 and 4 asks about the cervical cancer vaccine, genital warts vaccine, HPV shot, Gardasil, or Cervarix. The estimation sample for columns 5 and 6 consists of the set of females aged 13 at time of survey, for the 2008-2013 survey waves and males aged 13 at time of survey for the 2011-2013 survey waves.

Table 6: Further Evidence on Mechanisms, Google Trends 2005-2013

	(1) Relative Google search popularity for 'Tdap'	(2) Relative Google search popularity for 'Tdap'	(3) Relative Google search popularity of the 'Meningococcal vaccine' topic	(4) Relative Google search popularity of the 'Meningococcal vaccine' topic	(5) Relative Google search popularity for 'hpv'	(6) Relative Google search popularity for 'hpv'
Sample mean	30.82	30.82	56.63	56.63	43.83	43.83
Δ (2013 mean - 2005 mean)	*25.54*	*25.54*	*-30.98*	*-30.98*	*1.18*	*1.18*
Tdap Mandate for Middle School Entry	4.230**	7.248***	2.236	3.622**	2.019**	1.450**
	(1.763)	(1.613)	(1.875)	(1.575)	(0.875)	(0.665)
Pertussis rate in the state	0.125*	0.202**	0.00178	0.00801	-0.0321	-0.0310
	(0.0647)	(0.0755)	(0.0245)	(0.0210)	(0.0245)	(0.0273)
R-squared	0.666	0.733	0.614	0.657	0.793	0.803
N	4845	4845	4825	4825	5508	5508
Linear state trends?	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. The outcome variable is a measure of the popularity of a given search term or topic, in which, for each state, the month of peak search volume is normalized to 100. All models include the state policy controls and state demographics as described in the notes to Table 1 as well as fixed effects for each state and for each month-year. Columns 2, 4, and 6 also include linear state trends.

2.8. Appendix

This Appendix describes in greater detail the diseases under study.

2.8.1 Tetanus, Diphtheria, and Pertussis

Tetanus, diphtheria, and pertussis are all diseases caused by bacteria, and vaccination against them with a combination vaccine series (DTP or DTaP) has been routinely recommended for young children since the 1940s and 1950s. In early 2005 a new vaccine, Tdap (tetanus, diphtheria toxoid and acellular pertussis), was approved for use in adolescents and was recommended for preteens aged 11 or 12 as a booster for their DTP/DTaP series.[93]

Over the past 50 years there have been consistently high immunization rates for DTP/DTaP and, likely as a result, tetanus and diphtheria have become extremely rare in the United States.[94] That vaccine series has proven less effective against pertussis in the long-run, however, and so pertussis (or 'whooping cough') remains endemic in the United States.

Pertussis is a highly contagious respiratory disease,[95] and its symptoms include nose and throat inflammation and a violent cough. It is transmitted from person-to-person through respiratory secretions expelled while coughing or sneezing. The morbidity consequences of pertussis are most severe for infants under 12 months of age – they are hospitalized in 63 percent of cases (compared to 2 percent of infected adolescents) and account for 90 percent of the pertussis-related mortality.

[93] Prior to the development of the Tdap vaccine, it had been recommended that adolescents receive a dose of the tetanus and diphtheria toxoids vaccine (Td) at age 11 or 12. This vaccine did not provide protection against pertussis, however. Protection under the acellular pertussis vaccines (DTaP and Tdap) wanes between 5-10 years after vaccination.

[94] Specifically, for the duration of our study period there have been 41 or fewer cases of tetanus (an infection that attacks the nervous system and causes muscle spasms) per year in the United States (approximately 0.01 cases per 100,000 population). Over that same time period that have been 2 or fewer cases of diphtheria (an infection that causes a thick covering in the back of the throat) per year. Due to the extremely low incidence of these diseases we are unable to credibly examine the effect of middle school vaccination mandates on the prevalence of diphtheria and tetanus.

[95] Secondary cases are estimated to occur at a rate of 80 percent among susceptible contacts in a household in which there has been a case of pertussis (CDC 2015a).

2.8.2 Meningococcal Disease

Meningococcal disease encapsulates the set of infections caused by the bacteria *Neisseria meningitidis* and includes infections of the lining of the brain and spinal cord (meningitis) and of the bloodstream (septicemia and bacteremia). There are numerous different serogroups (variations) of the bacteria; serogroups A, B, C, Y, and W are the most significant sources of meningococcal disease in the United States.[96] In our analysis we focus on the quadrivalent meningococcal conjugate vaccine (MCV4), which provides protection against serogroups A, C, Y, and W and has been routinely recommended for children age 11 or 12 since 2005.[97] Older teens are recommended to receive a second booster shot of MCV4 when they are 16 years old.

2.8.3 Human Papillomavirus (HPV)

HPV is the most common sexually transmitted infection in the United States: the CDC estimates that nearly all sexually active men and women will get HPV at some point in their lives. An estimated 79 million Americans are currently infected with HPV, with about 14 million people becoming newly infected each year. Most HPV infections are asymptomatic and typically resolve on their own. In some cases, however, infections persist and cause symptoms which can take years to develop. There are numerous types of HPV: low-risk types which can cause skin warts, and high risk types which cause the majority of the cancers of the cervix, vagina, penis, anus, mouth, and throat.[98] In the United States, rates of cervical cancer incidence and mortality are substantially higher among blacks and Hispanics

[96] The relative importance of each serogroup varies by age group: among children under the age of 5, serogroup B accounts for 60 percent of the cases of meningococcal disease, while for individuals over the age of 10, serogroups C, Y, and W cause 73 percent of the cases.

[97] The first vaccine providing protection against serogroup B was not approved in the United States until late 2014.

[98] Nearly all cervical cancer (11,000 cases per year in the United States) is due to HPV, with two specific types (HPV16 and HPV18) accounting for over 65% of all cervical cancers, 55% of all cancers of the vagina, 49% of all cancers of the vulva, 48% of all cancers of the penis, 79% of all cancers of the anus, 79% of all cancers of the rectum, and 60% of all cancers of the throat (CDC 2016a).

(American Cancer Society 2015).[99]

The first HPV vaccine was licensed for use in females in the United States in June 2006, and it was further approved for males in October 2009. This vaccine is a 3-dose series and provides protection against HPV types 6, 11, 16, and 18. The vaccine is only effective if it is given before an infection occurs, and so should be given prior to an individual's sexual debut. The ACIP currently recommends that all boys and girls initiate the HPV vaccine series between ages 11 and 12. Individuals who are not vaccinated by age 13 are recommended to receive catch-up vaccinations through age 21 (26) for men (women).

2.8.4 Seasonal influenza

Seasonal flu (common in fall and winter months) is an acute viral infection that can cause mild to severe illness with fever, cough, sore throat, runny nose, muscle aches, fatigue, vomiting, and/or diarrhea. It is highly contagious; individuals can infect other people up to an entire day before and up to a week after symptoms develop. Young children, the elderly, and people with compromised immune systems are at particularly high risk for seasonal flu complications. The flu vaccine varies from season to season with respect to the particular strains of the influenza virus that it protects against. The annual influenza vaccine was routinely recommended for children over the age of 6 months for the first time in 2010; in the subsequent flu season less than half of youths between 6 months and 17 years of age received the influenza vaccine. Each year millions of people in the United States become ill from the seasonal flu, hundreds of thousands are hospitalized, and tens of thousands die.

[99] In the United States over the period 2008-2012, cervical cancer incidence rates were 44 percent higher for Hispanics and 41 percent higher for blacks, relative to whites. Over that same time period, mortality rates for Hispanics were 35 percent higher and 105 percent higher for blacks, relative to whites.

Appendix Figure 1: Example of State Department of Health Flyer for Middle School Vaccination Requirement, Wisconsin

Fact Sheet for Parents

Tdap Requirements for Middle and High School Students

The Wisconsin Student Immunization law requires that all students entering the 6th grade receive a dose of Tdap vaccine. To be compliant with the school law, parents must provide their child's school with proof of immunization or claim a waiver.

1. **What is Tdap?**
   Tdap is a vaccine that protects against Tetanus, Diphtheria, and Pertussis (whooping cough).

2. **What grades are affected and what vaccine is required?**
   All students entering grades 6 through 12 must have one dose of Tdap.

3. **What do parents need to do?**
   Have your child vaccinated with Tdap vaccine if he or she has not already received the vaccine. Record the date of the immunization in the appropriate box on the enclosed Student Immunization Record, sign the form and return it to your child's school. Be sure to add the Tdap vaccination date to the permanent immunization record you keep for your child. In the future, your child may need to give these dates to other schools, colleges or employers.
   To claim a waiver for health, religious or personal conviction reasons, follow the instructions on the Student Immunization Record and return the signed form to your child's school.

4. **Are there exceptions to the Tdap vaccine requirements?**
   Yes. If your child has received a tetanus-containing vaccine (such as Td) in the five years before he/she enters the grade in which it is required, your child is compliant and is not required to receive a Tdap. Check the box marked "Td" on the Student Immunization Record, enter the date it was received and return the signed form to school.

5. **Once my child meets the Tdap requirement will he or she need to get another dose in a different grade?**
   No. Tdap is a one-time requirement. Once a child meets the vaccine requirement for the grade to which the requirement applies, no further doses are required. In other words, a student who receives Tdap before starting 6th grade does not need any more doses. If a child received a dose of Td vaccine within 5 years of entering 6th grade, that child has met the Tdap requirement (even though s/he has not actually received Tdap vaccine) and will not be required to receive Tdap vaccine now or in a future grade.

Appendix Figure 1, continued:
Example of State Department of Health Flyer for Middle School Vaccination Requirement, Wisconsin

6. If my child already had pertussis (whooping cough) disease, should he or she still get the Tdap vaccine?

A history of pertussis disease is not an exception to the Tdap requirement. Children who have had pertussis should still receive Tdap because the length of protection provided by the disease is unknown and because the diagnosis can be difficult to confirm in some instances.

7. Where can I get Tdap vaccine for my child?

Tdap is available from your child's medical provider, local health departments and some pharmacies. Please have your child immunized well in advance of school opening to avoid the late summer rush as doctor's offices and immunization clinics.

8. Why is Tdap required?

Pertussis is a serious disease. It is easily passed from person-to-person and can cause outbreaks in schools. Wisconsin has experienced two state-wide pertussis outbreaks in the past 10 years. People who are ill with pertussis must stay home from work or school for at least five days. Studies have shown that the protection gained from the DTP/DTaP vaccines received as a young child begins to decline 5 to 10 years after vaccination; the Tdap vaccine will boost that immunity and help protect your adolescent from pertussis.

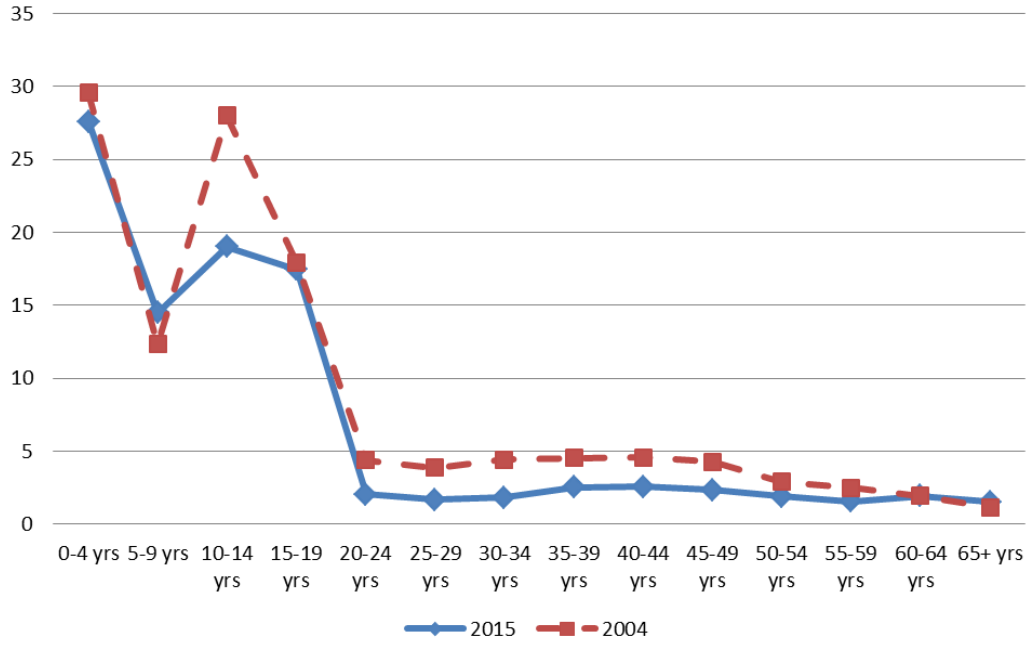
9. Are there any other vaccines that are recommended for my adolescent?

Yes. There are three other vaccines that are routinely recommended for teens. The Human Papillomavirus Vaccine (HPV) vaccine protects against a virus that is a common cause of cancer. The meningococcal conjugate vaccine protects against meningococcal disease (meningitis), and an annual influenza vaccine is recommended for everyone 6 months of age and older.

10. Where can I get more information?

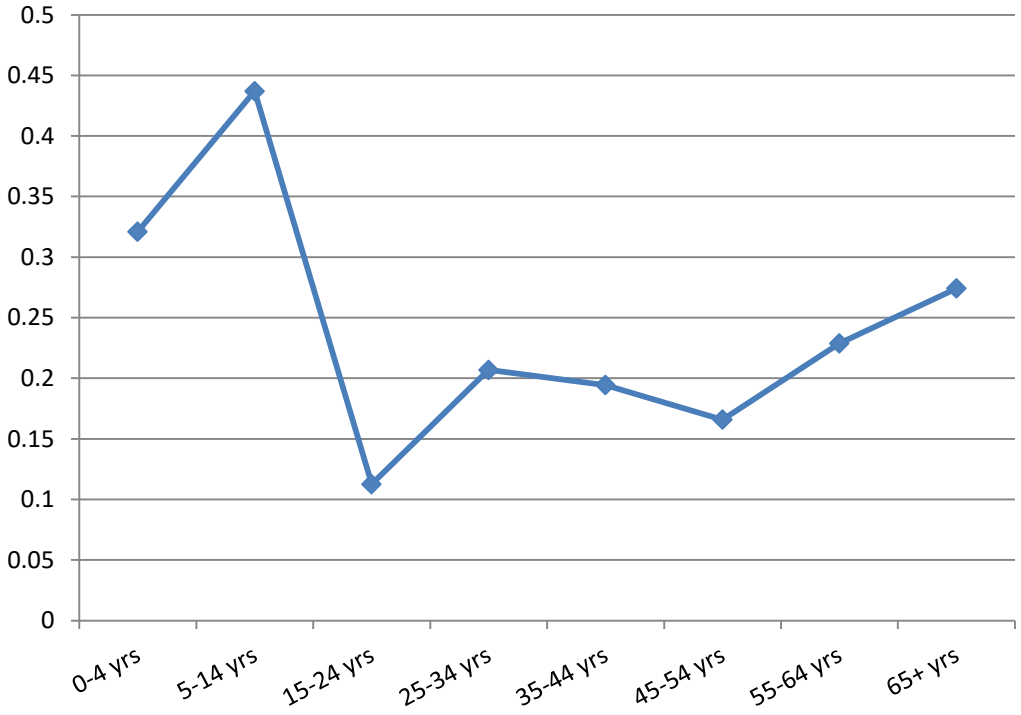
- Center for Disease Control (CDC): http://www.cdc.gov/vaccines/vpd-vac/pertussis/default.htm
- Wisconsin Immunization Program: https://www.dhs.wisconsin.gov/immunization/pertussis.htm
- Your child's medical provider or local health department

Appendix Figure 2: Age Profile of Pertussis Incidence, 2004 and 2015



Notes: Each point represents the age-group specific pertussis rate per 100,000 population, calculated at the national level using CDC data.

Appendix Figure 3: Estimated Effect Sizes of Direct and Spillover Effects of Tdap Mandates on Pertussis Incidence Across the Life Course (relative to 2004)



Notes: Each point is equal to the coefficient on the Tdap mandate indicator variable from a regression in which the outcome variable is the rate of disease incidence for the given age group, divided by the age-group specific disease incidence rate in the base year of 2004. These values are then multiplied by negative one, in order to obtain the estimated percent reduction in disease incidence. All coefficients are from specifications that include the full set of state policy controls as described in the notes to Table 1and state-specific linear time trends.

Appendix Table 1: Descriptive Statistics, NIS-Teen 2008-2013

	(1) Full sample	(2) Individuals in states that had a Tdap mandate by 2013	(3) Individuals in states that did not have a Tdap mandate by 2013
Child's vaccination rates, by age 13			
Tdap Booster	0.449	0.454	0.379
Meningococcal Vaccine	0.357	0.360	0.312
Initiation of HPV series	0.236	0.238	0.204
Completion of HPV series	0.099	0.100	0.079
Influenza vaccine (past 3 years)	0.122	0.121	0.137
Child's characteristics			
Female	0.488	0.488	0.490
Hispanic	0.203	0.212	0.079
White	0.576	0.577	0.554
Black	0.142	0.134	0.251
Other ethnicity	0.079	0.076	0.116
11-12 year old check-up	0.897	0.898	0.888
Mother's characteristics			
Less than high school	0.140	0.143	0.099
High school	0.261	0.260	0.272
Some college	0.259	0.259	0.256
College degree or above	0.340	0.338	0.372
Married	0.696	0.697	0.684
Age: <35 yrs	0.094	0.093	0.102
Age: 35-44 yrs	0.455	0.455	0.451
Age: 45+ yrs	0.451	0.452	0.447
Morbidity Rates per 100,000 pop.			
Pertussis, population rate	6.96	6.92	8.88
Pertussis, 10-14 year old rate	21.7	21.6	27.7
Observations	116304	100899	15405

Notes: All values are weighted means calculated by the authors from NIS-Teen 2008-2013 data, using provided sample weights. The mean rates of HPV vaccine series initiation and completion are calculated using the sample of females who were aged 13 between 2007-2013 and males who were aged 13 between 2010-2013.

Appendix Table 2: Event Study Estimates of the Direct Effect of Middle School Vaccination Requirements, NIS-Teen 2008-2013

	(1)	(2)
	1 dose Tdap booster	1 dose Tdap booster
Sample mean	0.449	0.449
Δ (final year - base year mean)	*0.814*	*0.814*
6+ years before Tdap mandate	0.00831 (0.0375)	-0.122 (0.0755)
5 years before Tdap mandate	-0.0163 (0.0289)	-0.137 (0.0614)**
4 years before Tdap mandate	-0.0111 (0.0228)	-0.0975 (0.0427)**
3 years before Tdap mandate	0.00591 (0.0145)	-0.0613 (0.0298)**
2 years before Tdap mandate	0.0104 (0.0120)	-0.0280 (0.0176)
Year of Tdap mandate	0.0508 (0.0118)***	0.0799 (0.0156)***
1 year after Tdap mandate	0.151 (0.0197)***	0.204 (0.0342)***
2 years after Tdap mandate	0.212 (0.0186)***	0.290 (0.0422)***
3 years after Tdap mandate	0.238 (0.0265)***	0.351 (0.0512)***
4 years after Tdap mandate	0.211 (0.0336)***	0.351 (0.0732)***
5+ years after Tdap mandate	0.249 (0.0285)***	0.399 (0.0755)***
N	116304	116304
R-Squared	0.337	0.339
Other policy controls?	Y	Y
Other state/time varying Xs?	Y	Y
State and year fixed effects?	Y	Y
Linear state trends?	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables.

Appendix Table 3: Estimates of Non-linear Effects of Mandates Based on Prior Disease Incidence, CDC Data 2001-2015

	(1) Pertussis rate	(2) Pertussis rate	(3) Pertussis rate	(4) Pertussis rate
Sample mean	6.889	6.889	6.889	6.889
Δ (2015 mean - 2001 mean)	*3.792*	*3.792*	*3.792*	*3.792*
Lagged pertussis rate	0.0719	-0.00980	0.0718*	-0.0206
	(0.0439)	(0.0344)	(0.0419)	(0.0350)
Tdap mandate	-2.608*	-2.347	-1.000	0.378
	(1.376)	(1.632)	(1.362)	(1.177)
Tdap mandate * 2004 pertussis rate	0.0479	0.0162	---	---
	(0.0470)	(0.0592)		
Tdap mandate * Lagged pertussis rate	---	---	-0.137**	-0.299**
			(0.0570)	(0.122)
N	763	763	763	763
R-Squared	0.440	0.486	0.440	0.490
Linear state trends?	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables.

Appendix Table 4: Event Study Estimates of the Direct Effect of Middle School Vaccination Requirements, CDC Data 2001-2015

	(1) Pertussis Morbidity	(2) Pertussis Morbidity
Sample mean	6.889	6.889
Δ (2015 mean - 2001 mean)	*3.792*	*3.792*
6+ years before Tdap mandate	-2.404 (2.489)	-5.304 (2.715)*
5 years before Tdap mandate	-2.825 (2.016)	-4.181 (2.043)**
4 years before Tdap mandate	-0.776 (3.159)	-1.769 (2.860)
3 years before Tdap mandate	-3.039 (2.194)	-3.371 (1.973)*
2 years before Tdap mandate	-3.976 (2.386)	-3.846 (2.288)*
Year of Tdap mandate	-3.656 (1.677)**	-2.203 (1.384)
1 year after Tdap mandate	-6.701 (3.784)*	-5.146 (3.361)
2 years after Tdap mandate	-5.158 (2.341)**	-2.545 (2.190)
3 years after Tdap mandate	-1.382 (1.925)	1.767 (2.501)
4 years after Tdap mandate	-0.190 (4.125)	4.247 (4.320)
5+ years after Tdap mandate	-2.761 (3.640)	3.525 (4.643)
N	763	763
R-Squared	0.468	0.518
Other policy controls?	Y	Y
Other state/time varying Xs?	Y	Y
State and year fixed effects?	Y	Y
Linear state trends?	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables.

Appendix Table 5: Tdap Mandates Had No Effects on Diseases Other than Pertussis

	(1) Pertussis	(2) Hepatitis A	(3) Hepatitis B	(4) Mening-ococcal Disease	(5) Tuberculosis	(6) Measles	(7) Lyme Disease	(8) Salmon-ellosis
Sample mean	6.889	1.261	2.130	0.361	4.083	0.0441	9.443	12.25
Tdap mandate	-2.241*	0.0489	0.278	-0.0259	0.000313	0.111	-0.617	-0.563
	(1.262)	(0.105)	(0.553)	(0.0211)	(0.0773)	(0.0698)	(1.530)	(1.221)
Sample years:	2001-2015	2001-2015	2001-2015	2001-2015	2001-2015	2001-2015	2001-2015	2001-2015
Observations	763	760	748	764	764	763	749	745
R-Squared	0.439	0.751	0.601	0.834	0.969	0.211	0.862	0.710

* significant at 10%; ** significant at 5%; *** significant at 1%. Sample means are calculated over the full period. Results are estimated using disease incidence data from the CDC and are weighted by state population. The dependent variable is the number of reported cases of the disease per 100,000 population. These models include controls for state mandates for insurance coverage of well-child visits and vaccines; all child care/school vaccination mandates; state HPV and MCV policies; lagged pertussis incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level); and state and year fixed effects. Standard errors are clustered at the state level.

Appendix Table 6: Effects of mandates on Tdap vaccination of 7-9 and 14-17 year olds in NIS-Teen
NIS-Teen 2008-2013

	All states		Only states that did not mandate receipt for >13 year olds			
	(1)	(2)	(3)	(4)	(5)	(6)
	1 dose Td-containing vaccine, 7-9 year olds	1 dose Td-containing vaccine, 7-9 year olds	1 dose Td-containing vaccine, 14-15 year olds	1 dose Td-containing vaccine, 14-15 year olds	1 dose Td-containing vaccine, 16-17 year olds	1 dose Td-containing vaccine, 16-17 year olds
Sample mean	0.0232	0.0232	0.141	0.141	0.0419	0.0419
Δ(final-base year mean)	0.005	0.005	-0.255	-0.255	-0.183	-0.183
Tdap mandate	0.00436	0.000424	-0.0158	0.00114	0.0134**	0.0233***
	(0.00399)	(0.00492)	(0.0147)	(0.0172)	(0.00626)	(0.00801)
R-Squared	.0232	.0232	0.123	0.131	0.0906	0.0952
N	59981	59981	91041	91041	82060	82060
Individual characteristics?	Y	Y	Y	Y	Y	Y
Other policy controls?	Y	Y	Y	Y	Y	Y
Other state/time varying Xs?	Y	Y	Y	Y	Y	Y
State and year fixed effects?	Y	Y	Y	Y	Y	Y
Linear state trends	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. Sample means are calculated over the full period. Results are from linear probability models and use NIS-Teen sampling weights. All models include controls for individual demographic characteristics (age at observation fixed effects, gender, race, number of children in the household, and mother's age, education level, and marital status); state, and birth cohort fixed effects; state mandates for insurance coverage of well-child visits and vaccines; state college and high school immunization and education requirements for MCV; state HPV policies (see text for details); state immunization mandates for child care/kindergarten entry; lagged state pertussis and meningococcal disease incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; and state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). Even numbered columns also include linear state trends. Standard errors are clustered at the state level.

Appendix Table 7: Cross-Age Morbidity Effects Among Infants Were Disease-Related, Not Vaccination-Related (i.e., Consistent with Herd Immunity Effects, not Behavioral Spillover Effects)
NIS 2003-2015, 19-35 month olds

	(1) Up-to-date, 4 doses of DTaP	(2) Up-to-date, 4 doses of DTaP other children in HH	(3) Up-to-date, 4 doses of DTaP, no other children in HH
Sample mean	0.846	0.834	0.882
Δ (2015 mean - 2003 mean)	*0.001*	*0.000*	*-0.003*
Tdap Mandate for Middle School Entry	-0.00706	-0.00487	-0.0124
	(0.00479)	(0.00637)	(0.00793)
R-squared	0.0420	0.0445	0.0289
N	212202	159157	53045

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models and use NIS sampling weights. All models include controls for individual demographic characteristics (age at observation fixed effects, gender, race, number of children in the household, and mother's age, education level, and marital status); state and year fixed effects; state mandates for insurance coverage of well-child visits and vaccines; child care and school vaccination mandates; state HPV policies; lagged state pertussis and meningococcal disease incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; and state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). All models also include linear state trends. Standard errors are clustered at the state level.

Appendix Table 8: Event Study Estimates of the Spillover Effects of Middle School Vaccination Requirements for Tdap, NIS-Teen 2008-2013

	(1)	(2)	(3)	(4)	(5)	(6)
	1 dose MCV vaccination	1 dose MCV vaccination	1 dose HPV Vaccine	1 dose HPV Vaccine	Completed HPV Vaccine	Completed HPV Vaccine
Sample mean	0.357	0.357	0.236	0.236	0.0987	0.0987
Δ (final year mean - base year mean)	*0.724*	*0.724*	*0.306*	*0.306*	*0.139*	*0.139*
Years relative to Tdap mandate:						
6+ years before	-0.0725 (0.0292)**	-0.0881 (0.0412)**	-0.117 (0.0460)**	-0.112 (0.146)	-0.00172 (0.0262)	0.0442 (0.0939)
5 years before	-0.0792 (0.024)***	-0.109 (0.0345)***	-0.102 (0.0359)***	-0.110 (0.112)	-0.0214 (0.0194)	0.00906 (0.0729)
4 years before	-0.0396 (0.0204)*	-0.0600 (0.0259)**	-0.0921 (0.0228)***	-0.0744 (0.0786)	-0.0282 (0.0142)*	0.00822 (0.0539)
3 years before	-0.0511 (0.018)***	-0.0744 (0.021)***	-0.0682 (0.0177)***	-0.0655 (0.0506)	-0.0170 (0.0144)	0.00168 (0.0382)
2 years before	-0.0079 (0.0126)	-0.0249 (0.0128)*	-0.0335 (0.0136)**	-0.0446 (0.0256)*	-0.0161 (0.00880)*	-0.0160 (0.0190)
Year of	0.0282 (0.0104)***	0.0419 (0.0142)***	0.0573 (0.0129)***	0.0686 (0.0229)***	0.0260 (0.0126)**	0.0288 (0.0182)
1 year after	0.0482 (0.0183)**	0.0752 (0.0227)***	0.108 (0.0186)***	0.142 (0.0364)***	0.0507 (0.0140)***	0.0624 (0.0284)**
2 years after	0.0972 (0.0176)***	0.140 (0.0262)***	0.142 (0.0319)***	0.198 (0.0531)***	0.0492 (0.0198)**	0.0623 (0.0392)
3 years after	0.109 (0.0224)***	0.176 (0.0347)***	0.152 (0.0330)***	0.244 (0.0652)***	0.0615 (0.0223)***	0.0885 (0.0541)
4 years after	0.0949 (0.0306)***	0.191 (0.0450)***	0.171 (0.0449)***	0.284 (0.0747)***	0.0634 (0.0257)**	0.0888 (0.0617)
5+ years after	0.143 (0.0327)***	0.250 (0.0530)***	0.187 (0.0489)***	0.348 (0.0845)***	0.0649 (0.0306)**	0.104 (0.0718)
N	116304	116304	57133	57133	57133	57133
R-Squared	0.287	0.290	0.112	0.114	0.066	0.067
Linear trends?	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. Columns 3-6 are restricted to females who were aged 13 between 2007-2013 and males who were aged 13 between 2010-2013. All models include the full set of controls, columns 2, 4, and 6 additionally include state linear trends. Sample means are calculated using the base year of data.

Appendix Table 9: Other Ways to Measure Cross-Vaccine Spillover Effects of Tdap Mandates: Combinations of Outcomes, NIS-Teen 2008-2013

	(1)	(2)	(3)	(4)	(5)
	Had 1 dose Tdap AND 1 dose MCV	Had 1 dose Tdap AND Initiated HPV vaccine	Had 1 dose Tdap AND Completed HPV vaccine	Had 1 dose Tdap AND 1 dose MCV AND Initiated HPV vaccine	Had 1 dose Tdap AND 1 dose MCV AND Completed HPV vaccine
Sample mean	0.303	0.170	0.076	0.150	0.068
Δ (final year mean - base year mean)	*0.693*	*0.203*	*0.074*	*0.212*	*0.082*
Tdap Mandate for Middle School Entry	0.0458***	0.0445**	0.0505***	0.0479***	0.0461***
	(0.0123)	(0.0171)	(0.0163)	(0.0153)	(0.0136)
R-squared	0.297	0.161	0.082	0.145	0.073
N	116304	58474	58474	58474	58474

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. Columns 2-5 are restricted to females who were aged 13 between 2007-2013 and males who were aged 13 between 2011-2013. All models include the full set of controls, including linear state trends.

Appendix Table 10: Main Vaccination Results Are Robust to Including NIS-Teen 2014 and 2015 Sample Waves, NIS-Teen 2008-2015

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	1 dose Tdap booster	1 dose Tdap booster	1 dose MCV	1 dose MCV	Initiated HPV vaccine	Initiated HPV vaccine	Completed HPV vaccine	Completed HPV vaccine
Sample mean	0.530	0.530	0.438	0.438	0.265	0.265	0.111	0.111
Δ (final year mean - base year mean)	*0.824*	*0.824*	*0.773*	*0.773*	*0.431*	*0.431*	*0.203*	*0.203*
Tdap Mandate for Middle School Entry	0.137***	0.154***	0.0330**	0.0366**	0.0331***	0.0165	0.0180***	0.0156**
	(0.0138)	(0.0154)	(0.0137)	(0.0147)	(0.0119)	(0.0130)	(0.00520)	(0.00716)
R-squared	0.339	0.341	0.299	0.301	0.117	0.118	0.0601	0.0612
N	158268	158268	158268	158268	97233	97233	97233	97233
Linear state trends?	N	Y	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. Columns 5-8 are restricted to females who were age 13 between 2007-2015 and males who were age 13 between 2011-2015.

Appendix Table 11: Other Ways to Measure Cross-Vaccine Spillover Effects of Tdap Mandates: the Role of ACIP Recommendations, NIS-Teen 2008-2013

	(1) 1 dose MCV	(2) Initiated HPV vaccine	(3) Completed HPV vaccine	(4) Had seasonal influenza vaccine, age 10-13
Sample mean	0.357	0.236	0.099	0.122
Δ (final year mean - base year mean)	*0.724*	*0.306*	*0.139*	*0.436*
Tdap Mandate for Middle School Entry	-0.0482	0.00147	0.0199	0.00494
	(0.0317)	(0.0263)	(0.0142)	(0.00670)
Tdap Mandate × ACIP recommendation for MCV	0.0769***			
	(0.0246)			
Tdap Mandate × ACIP recommendation for HPV		0.0475**	0.0157	
		(0.0197)	(0.0117)	
Tdap Mandate × ACIP recommendation for Flu				0.0247*
				(0.0139)
R-squared	0.289	0.114	0.067	0.175
N	116304	57133	57133	116304

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. Columns 2-3 are restricted to females who were aged 13 between 2007-2013 and males who were aged 13 between 2011-2013. All models include the full set of controls, including linear state trends.

Appendix Table 12: Effects of Middle School Tdap Vaccination Requirements for Table 5 Samples, NIS-Teen 2008-2013

	(1) 1 dose Tdap	(2) 1 dose Tdap	(3) 1 dose MCV	(4) 1 dose MCV	(5) Initiated HPV vaccine	(6) Initiated HPV vaccine	(7) Completed HPV vaccine	(8) Completed HPV vaccine
1. 'Ever heard of HPV' sample	0.0811**	0.0720*	0.0767**	0.0145	0.0574	-0.0165	0.0733***	0.0346
	(0.0356)	(0.0381)	(0.0344)	(0.0729)	(0.0486)	(0.0504)	(0.0196)	(0.0275)
2. 'Ever heard of HPV shot' sample	0.0816**	0.0713*	0.0803**	0.0170	0.0564	-0.0235	0.0754***	0.0347
	(0.0355)	(0.0369)	(0.0337)	(0.0720)	(0.0481)	(0.0502)	(0.0194)	(0.0271)
3. 'Doctor recommended HPV vaccine' sample	0.135***	0.120***	0.0176	0.00520	0.0654***	0.0122	0.0430***	0.0450**
	(0.0221)	(0.0356)	(0.0182)	(0.0314)	(0.0233)	(0.0369)	(0.0119)	(0.0197)
4. 'Had an 11-12 yo well child visit' sample	0.129***	0.130***	0.0232	-0.0136	0.0528***	0.0117	0.0354***	0.0404***
	(0.0228)	(0.0304)	(0.0207)	(0.0266)	(0.0187)	(0.0223)	(0.00904)	(0.0131)
Linear state trends?	N	Y	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. The sample in row 1 corresponds to the sample in columns (1) and (2) of table 5; the sample in row 2 corresponds to the sample in columns (3) and (4) in table 5; the sample in row 3 corresponds to the sample in columns (5) and (6) of table 5; the sample in row 4 corresponds to the sample in columns (7) and (8) in table 5. See notes to Table 1 for details on the specification and control variables. Each entry is the coefficient on the Tdap mandate.

CHAPTER 3

GIVING TEENS A BOOST? EFFECTS OF MENINGOCOCCAL DISEASE VACCINATION POLICIES

3.1. Introduction

Increased availability and utilization of vaccines is often considered to be one of the key reasons why the United States has experienced dramatic reductions in disease incidence in the past century (CDC 1999). Historically, immunization programs have been primarily targeted towards young children, as they are a particularly vulnerable population and typically have faced the highest burdens of morbidity and mortality from vaccine-preventable diseases. Within the past several decades, however, new data and innovations have substantially increased the number of vaccines recommended for receipt during adolescence.[100] Accompanying these scientific innovations has been the implementation of a broad set of national and state policies aimed at increasing uptake of these adolescent vaccines; presently nearly all states have an adolescent immunization policy of some form in effect.

In this paper I provide the first evidence on the effectiveness of two vaccination policies targeted at high-school aged adolescents: national recommendations issued by the Advisory Committee on Immunization Practices (ACIP) in 2011 for 16 year olds to receive a booster dose of the quadrivalent meningococcal conjugate vaccine (referred to as MenACWY or MCV4), and state laws that require individuals to receive a dose prior to entry into either 11^{th} or 12^{th} grade. As of January 2017, eight states had implemented 11^{th} or 12^{th} grade mandates; six more states have already passed mandates that will go into effect over the next couple of years. Meningococcal

[100] For example, in 1989 only one vaccine, the tetanus and diphtheria (Td) vaccine, was recommended by the CDC for children over the age of 6. As of this writing, there are 5 separate vaccines recommended for receipt between the ages of 11 and 18.

disease is a severe and deadly disease, and vaccination is targeted at this age group due to increased incidence among 16 to 21 year olds. Notably, over the past two decades there have been substantial reductions in the incidence of meningococcal disease in the United States. Between 2000 and 2016 the population rate decreased from 0.80 meningococcal cases per 100,000 population to the historic low of 0.12 cases per 100,000 population. For 15-24 year olds the reductions were even larger, dropping from a rate of 1.22 cases per 100,000 population in 2000 to 0.18 cases per 100,000 population in 2016. I present these trends in Figure 1.

In my analyses I first estimate the effects of the ACIP recommendations and high school vaccine mandates on the probability that an individual receives a dose of the meningococcal vaccine at ages 16 or 17, using provider-reported immunization data from the National Immunization Survey-Teen (NIS-Teen). I focus on vaccine doses received at these ages because they are most directly affected by the policies, and notably, an age 16 booster dose is recommended even if an individual received their primary dose as recently as age 15. I then consider effects on morbidity, using data on meningococcal disease incidence at the state-year-age group level, which I obtained directly from the Centers for Disease Control and Prevention (CDC). These data were provided separately for 0-4 year olds, 5-14 year olds, 15-24 year olds, 25-64 year olds, and 65 years and older, which allows me to focus my analyses on incidence among the most directly targeted group, 15-24 year olds. The final set of analyses I do focuses on potential spillovers of the high school vaccine mandates to receipt of other forms of preventive care, as measured in the NIS-Teen dataset. Specifically, I consider potential spillovers to the probability of having a preventive care visit, receiving a dose of a non-mandated vaccine, or being diagnosed with any of a range of health conditions.

I use a difference-in-differences framework to identify the causal effects of the ACIP

recommendation and high school vaccine mandates on vaccination rates and disease incidence. However, because the ACIP recommendation was implemented at the national level, and school vaccination mandates were implemented at the state-level, my specific estimation strategy differs across the two policies. Broadly, my strategy for estimating the effects of the ACIP recommendation relies on the fact that the policy applied only to the meningococcal vaccine, and that it was specific to 16-18 year olds. To identify vaccination effects of the recommendation, I compare meningococcal vaccination rates over time to the vaccination rates of another vaccine that is approved for use but not routinely recommended for 16 and 17 year olds: the tetanus, diphtheria, acellular pertussis (Tdap) vaccine.

For estimates of the morbidity effects of the ACIP age 16 booster dose recommendation, I make a slightly different comparison: I analyze the change in meningococcal disease incidence among the directly targeted age group (15-24 year olds) relative to the change in incidence among all other (untargeted) age groups. Within these analyses I also estimate the morbidity effects of an earlier ACIP recommendation made in 2005, which recommended routine meningococcal vaccination of 11-12 year olds. Although I am unable to causally estimate the vaccination effects of the 2005 recommendation due to lack of a suitable vaccine control group, I am able to provide evidence of the resulting morbidity effects by comparing the change in disease incidence among 5-14 year olds to the change among all other age groups. A notable limitation of each of these differencing strategies, however, is that there is potential for positive spillovers of the ACIP recommendation to the control groups. If these spillovers occur, these strategies will underestimate the effects of the ACIP recommendations on vaccination rates and/or disease incidence.

Next, to estimate the effects of the state-level high school meningococcal booster

mandates, I take advantage of the fact that different states implemented the mandates at different times. For both vaccination and morbidity outcomes I implement more standard difference-in-differences models that include state and year fixed effects, and identify effects by comparing the change in outcomes over time in adopting versus non-adopting states. I am able to further extend these analyses and consider potential spillover effects of the mandates to receipt of other types of preventive care. As a final component to the analyses of both policies, I additionally estimate event study versions of all baseline models. These models allow me to estimate dynamic policy effects, as well as provide evidence to support the parallel trends assumption that is necessary for identification in the difference-in-differences framework,

Overall I find that both the ACIP age 16 booster recommendation and the high school vaccine mandates significantly increase the probability that an individual receives a dose of the meningococcal vaccine at ages 16 or 17. The magnitude of the effect is comparable across policies – I find a 20.6 to 25.7 percentage point increase following the implementation of the ACIP age 16 booster dose recommendation, and the subsequent implementation of a high school mandate further increased vaccination rates by 19.0 to 21.2 percentage points. Heterogeneity analyses of these vaccination results, however, reveal that the policy effects vary substantially across different demographic sub-groups. In particular, the ACIP recommendation appears to potentially exacerbate pre-existing disparities in receipt of the vaccine, as higher income and higher educated households are more responsive to the ACIP recommendation, while also being more likely to have been vaccinated in the period prior to the issuing of the recommendation.

My results also suggest that these policies led to reductions in meningococcal disease incidence. Results from the baseline specification show that, relative to other age groups, the ACIP age 16 booster dose recommendation significantly reduced incidence among 15-24 year

olds by 17 percent, while the recommendation targeted towards 11-12 year olds resulted in a robust 30 percentage point reduction in incidence among 5-14 year olds. Morbidity effects of the mandates are smaller and are not significant in the baseline difference-in-differences specification. Event study specifications, however, suggest there may be important dynamics to the morbidity effects of the mandates, as the point estimates show that two years after implementation there is a significant reduction in disease incidence among 15-24 year olds of over 50 percent.

Notably, my results also suggest that the high school vaccination mandates had significant effects on the probability of receiving additional (non-mandated) preventive care. I find a significant 6.9 percentage point increase in the probability of having a check-up at age 16 or 17, and approximately 4.7-5.4 percentage point increases in the probability of receiving a dose of the HPV or Tdap vaccine at those same ages. These findings are particularly striking, given that high school is the period of time when many high risk behaviors are initiated, and when children are least likely to have regular contact with a primary care provider (Gruber 2001; Uddin et al. 2016).

This paper makes a number of contributions. First, I provide important new evidence on the effects of one of the most widely implemented vaccination policies: ACIP recommendations. To date, only one other study has used quasi-experimental methods to estimate their effects on vaccination rates among *any* age group (Lawler 2017), and no other study has estimated the effects for high school-aged adolescents. Specifically, Lawler (2017) examines the effects of ACIP vaccination recommendations that apply to very young children (less than three years old), a group which has both very different patterns of health care utilization and a very different pre-existing vaccine policy environment relative to16 and 17 year olds. Given this, *a priori* it is

unclear the extent to which the findings from that study may apply to other populations. [101]

Second, these findings are directly informative for policy makers who may be considering the implementation of a high school vaccine mandate. Although school vaccination mandates have been more broadly studied than ACIP recommendations, previous papers have focused only on mandates that apply to younger age groups (see for example, Lawler 2017; Carpenter and Lawler 2018; Abrevaya and Mulligan 2011). Given that 37 states have not yet implemented a high school meningococcal congujate vaccine mandate, there is considerable scope for this research to directly affect policy decisions.

Finally, this paper provides important new evidence on how adolescents (or their parents) respond to age-targeted health policies. The teen years are a period of the life course when rates of provider contact are low, and when many high-risk behaviors are initiated, and yet comparatively little is known about the effectiveness of public policies targeted at this age group. My results suggest that simple non-binding recommendations have substantial potential to increase the receipt of the recommended preventive care among this age group. Moreover, the spillover effects I identify also suggests that there is substantial scope for vaccine-specific mandates to more broadly increase contact with health care providers and the receipt of preventive care among high school-aged adolescents.

The rest of this paper proceeds as follows: Section I provides background on meningococcal disease and the policies studied, Section II provides a brief literature review, and

[101] Notably, there is a clear need for this information among policy makers: although the stated goal of routine meningococcal vaccination is to reduce disease incidence during the higher risk ages of 16 to 21, policy makers initially recommended administration at ages 11 or 12, as opposed to later in adolescence, because they believed the higher rates of health care provider contact among 11-12 year olds would lead to greater take-up of the meningococcal vaccine (CDC, 2010). It was only after new evidence demonstrated immunity waned more quickly than believed, and therefore vaccines administered at ages 11-12 were not providing protection through the high risk ages of 16-21, that ACIP revised their recommendation to include an age 16 booster dose.

Section III describes the data and outlines the empirical approach. I present the main set of results in Section IV, with ancillary results presented in Section V. Finally, Section VI concludes.

3.2. Background

3.2.1 Meningococcal Disease & Vaccination

Meningococcal disease encapsulates the set of infections caused by the bacteria *Neisseria meningitidis*, and most commonly presents as an infection of the lining of the brain and spinal cord (meningitis), or of the bloodstream (septicemia). Illness from meningococcal disease is severe and has a high risk of mortality: even among those that receive treatment mortality rates range from 10 to 15 percent. Both meningococcal meningitis and meningococcal septicemia are characterized by sudden onset of fever and vomiting; symptoms of meningitis frequently also include headache and stiff neck, while septicemia is more frequently additionally associated with fatigue, chills, and a rash. Additionally, up to 20 percent of people who recover from meningococcal disease have permanent disabilities including brain damage, hearing loss, and cognitive impairment (CDC 2018).

The bacteria that cause meningococcal disease are spread by respiratory and throat secretions (e.g. saliva), transmitted through close person-to-person contact. In general, the communicability of meningococcal disease is considered to be limited, and studies indicate that secondary cases only occur at a rate of 3 to 4 percent among household contacts. Crowded living conditions and smoking are both considered to be environmental risk factors for meningococcal disease.[102] Infection rates peak among children less than 5 years of age, with a second peak

[102] Additionally, certain genetic factors and chronic illnesses are considered to be risk factors for infection.

occurring for adolescents and young adults aged 16 to 21. I present in Appendix Figure 1 age group-specific trends in meningococcal disease incidence in the United States for 2000-2016.

There are numerous different serogroups (variations) of the bacteria; serogroups A, B, C, W, and Y are the most significant causes of meningococcal disease in the United States.[103] This paper focuses specifically on vaccination against the A, C, W, and Y serogroups, for which a vaccine has been licensed in the United States since 1974.[104] The original meningococcal vaccines were polysaccharide (sugar molecule) vaccines, which generated immunity for only a relatively short duration, and were particularly ineffective among the most vulnerable age group (<5 year olds). Given this, these vaccines were never recommended for routine vaccination and instead were utilized primarily in cases of outbreaks or for particular high-risk individuals (CDC 2000).

In 2005 the first quadrivalent A, C, W, and Y *conjugate* (polysaccharide bonded to a protein) vaccine (MCV4) was approved in the United States. In general, this type of vaccine is preferred to the polysaccharide vaccine, as conjugate vaccines are typically able to generate a better and more long-lasting immune response, resulting in a more effective vaccine. Additionally, for meningococcal disease, the conjugate vaccine is more effective at reducing asymptomatic carriage of the *N. meningitdis* bacteria, which is necessary in order for vaccination to reduce disease transmission in a community and to generate herd immunity effects (CDC 2005). At the time of licensure, available evidence suggested that a dose of MCV4 would provide protection for at least 10 years, however, subsequent studies suggest that immunity may significantly decline within 3 to 7 years (CDC 2011; Cohn et al. 2017).

[103] The relative importance of each serogroup varies by age group: among children under the age of 5, serogroup B accounts for 60 percent of the cases of meningococcal disease, while for individuals over the age of 10, serogroups C, W, and Y cause 73 percent of the cases (CDC 2015).
[104] The first vaccine to provide protection against serogroup B was not approved in the United States until 2014.

3.2.2. Meningococcal vaccination policy

In the United States recommendations on the use of vaccines are set by the Advisory Committee on Immunization Practices (ACIP). The ACIP is a 15 member committee composed of doctors and public health professionals and was established in 1964. The recommendations issued by the ACIP are potentially very influential both because they serve as the *de facto* standard of care, and because they are directly tied to a number of state and national health laws.[105]

Routine vaccination against meningococcal disease was recommended by ACIP for the first time in 2005, following the approval of the first quadrivalent conjugate vaccine (MCV4) in January of that year. At that time ACIP recommended routine administration of 1 dose of the MCV4 vaccine at ages 11-12, with catch-up vaccination recommended through age 15, as well as routine vaccination of college freshman residing in dormitories. Recommendations for catch-up vaccination were extended through age 18 in 2007.[106] At the time of the 2005 ACIP recommendation, the expectation was that immunity from the vaccine would persist for at least 10 years, and so vaccination at age 11 or 12 was expected to provide adolescents with protection through the high-risk ages of 16 to 21. In January 2011, based on new data that suggest significant declines in the persistence of antibodies 3 to 7 years after vaccination, ACIP updated their recommendations once again to include a booster dose at age 16 (CDC 2011).[107]

---

[105] For example, under the Affordable Care Act (ACA) preventive care provision (effective September 23, 2010), all new insurance plans must provide all ACIP-recommended vaccines without cost sharing. Moreover, once the ACIP designates a vaccine as 'routinely recommended', the Vaccines for Children (VFC) program has to pay for them. Individuals are eligible for free vaccinations under the VFC program if they are 18 years of age or younger, and are Medicaid-eligible, uninsured, American Indian or Alaskan Native, or are underinsured.

[106] When MCV4 was first approved in 2005 there were concerns about there being sufficient vaccine supply to vaccinate all adolescents up to age 18. This supply issue was resolved in 2007 (CDC 2007).

[107] Specifically, the ACIP recommends receipt of a booster dose at age 16, even if the first dose was received as recently as age 15. Catch-up vaccination is recommended through age 18 (CDC 2011).

In addition to the 11-12 year old MCV4 dose and 16 year old MCV4 booster dose, the ACIP also recommends three other vaccines for routine administration to adolescents: the tetanus, diphtheria, and acellular pertussis (Tdap) vaccine, one dose of which is recommended at ages 11-12, the human papillomavirus vaccine (HPV), which was recommended to be administered as a three dose series initiated at ages 11-12 for the duration of my sample period, and the influenza vaccine, which is recommended annually for everyone over the age of 6 months.[108]

Since 2000, individual states have implemented a number of different policies that aim to increase meningococcal vaccination rates among targeted groups. These policies range from education mandates, which require schools to provide educational materials on meningococcal vaccination to students and/or their parents, to vaccine mandates, which require students to receive a dose of the meningococcal vaccine in order to attend school. States have targeted these policies at different age groups of students, with each policy generally applying to either middle school, high school, or college students.[109]

In this paper I focus on the effects of laws that require high school students to receive the booster dose of the meningococcal vaccine prior to entry into 11th or 12th grade. Over my sample period, eight states adopted 11th or 12th grade mandates, with West Virginia being the first state to adopt in 2012.[110] I graphically present in Figure 2 the timing of the roll out of the mandates

[108] As of December 2016, the HPV series is recommended as a two dose series if initiation occurs before age 15 (CDC 2016). The HPV vaccine was first approved and recommended for use in females in 2006. It was not until October 2009 that it was approved for use in males, and only in December 2011 was it routinely recommended for it to be administered to males.

[109] Information on vaccination policies was obtained from the Immunization Action Coalition (www.immunize.org) and the National Council of State Legislatures (2012), and independently verified with state statues, news articles, or school publications, when necessary.

[110] An additional six states have already passed mandates that will become effective over the next couple of years. Also, effective for the 2016-2017 school year, Delaware has a mandate requiring a dose of the

across states; of the states that had an effective mandate as of January 2017, there is notable geographic clustering, with no adopting states in the western census region.

Laws requiring vaccines for school entry are extremely common in the United States, with all states mandating at least one vaccine for school entry as early as 1980 (Malone and Hinman, 2003). Historically, however, these mandates have largely applied to childcare or elementary school entry and not to older adolescents. Notably, in all states except Alaska, MCV4 is currently the only vaccine with a binding mandate that applies to 11th and 12th grade students.[111] More recently, some states have also implemented vaccine mandates for college students or health care workers.

School vaccine mandates are an appealing policy tool, as compulsory schooling laws provide an effective means of enforcement. An important limitation of these laws, however, is the availability of individual exemptions (Bradford and Mandich 2015). As of January 2017, all states (including Washington D.C.) allow for exemptions due to medical reasons, while 48 states allow exemptions due to religious beliefs, and of those, 17 states additionally allow exemptions due to philosophical beliefs (NCSL 2017).

3.3. Literature review

This paper contributes to the broader economic literature on infectious disease and the causal determinants of vaccination (Philipson 2000). Of particular relevance is a number of existing papers that have focused on the effects of information shocks on vaccination rates. These shocks take a range of forms: Moghtaderi and Adams (2016) examine the effects of

---

meningococcal vaccine prior to 9th grade entry (age 14), although since this does not apply to 16 or 17 year olds, I do not treat this as an effective mandate.

[111] Alaska mandates receipt of the Tdap vaccine 10 years after completion of the childhood DTaP series, which is usually completed between ages 4 and 6. Alaska does not require receipt of the MCV4 vaccine for high school students.

awareness campaigns and provision of educational materials on the HPV vaccine, and show those programs have no effect on uptake of the HPV vaccine; Anderberg et al. (2011) and Chang (2018, forthcoming) examine the effects of media coverage of the purported link between the measles, mumps, and rubella (MMR) vaccine and autism, and find resulting reductions in childhood vaccination rates, especially in households with more highly educated mothers .[112]

To date, only one other paper has used a quasi-experimental framework to estimate the causal effects of ACIP recommendations.[113] Lawler (2017) examines ACIP recommendations for routine hepatitis A vaccination of young children (<3 years old), which were implemented across groups of states at different times based on historic hepatitis A incidence in the state. Using a difference-in-differences framework and data from the National Immunization Survey-Child, Lawler finds that those ACIP recommendations increased vaccination rates among 2-3 year olds by 27 percentage points. Given that these recommendations only applied to young children, however, who typically already receive preventive care at relatively high rates, it is not clear the extent to which these findings can be expected to apply to other age groups.

Another strand of the literature that is closely related to this work focuses on the effects of state-level vaccination mandates on targeted vaccination rates and associated morbidity. The majority of these studies focus on mandates that apply to child care or elementary school entry, and find large and significant increases in the uptake of the targeted vaccine (Abrevaya and Mulligan 2011; Lawler 2017), and/or reductions in associated morbidity (Lawler 2017; Luca

[112] Adjacent to this literature on the effects of information shocks is a set of papers that have examined the effects of disease outbreaks and found that they significantly increase the probability of being vaccinated against the relevant disease (Philipson 1996; Oster 2016; Schaller et al. 2017). To the extent that estimated effects on vaccination are too large to reflect actual changes in disease risk, these outbreaks may be serving as information shocks.

[113] There are a number of papers in the medical and public health literatures that have examined the effects of ACIP recommendations for adolescent vaccination, however these studies are limited in that they rely on before versus after comparisons to identify the effects (see for example MacNeil et al. 2018; Ackerson et al. 2017).

2016; Ward 2011). In a slightly different context, White (2018) examines mandates for health care workers in California to receive the influenza vaccine, and finds that they result in significant increases in healthcare worker vaccination rates and reductions in influenza hospitalizations.

Most similar to this paper is Carpenter and Lawler (2018), which estimates the effects of Tdap vaccine mandates that apply to middle school -aged adolescents. They find that the mandates increased uptake of the Tdap vaccine by age 13 by approximately 13.5 percentage points, and significantly reduced pertussis incidence among children and infants. Notably, they also find that the Tdap mandate caused spillovers to the uptake of the MCV4 and HPV vaccines, as well as increases in the probability of a well child check-up at ages 11 or 12 by 3 to 4 percentage points.

Overall, this article makes important contributions to the literature on immunization policy along several dimensions. In particular, this paper is the first to consider the effects of vaccination policies that target high school-aged adolescents. This is an important population to study given that they have much lower rates of contact with primary care providers compared to younger children, and that this is the period of time in which many high-risk behaviors are initiated. Due to these differences between high school-aged adolescents and younger age groups, the previous evidence on the effects of ACIP recommendations may not be informative for this population. Additionally, these differences suggest that there is a much larger scope for mandates to affect vaccination rates, and for potential spillovers to receipt of other types of preventive care. Finally, this paper is the first to estimate the effects of meningococcal disease-targeted vaccination policies on vaccination rates and disease incidence in a quasi-experimental framework. Given differences in transmission, contagion, and morbidity across diseases, disease-

specific analyses are necessary in order for policy makers to estimate the cost-effectiveness of a given vaccination policy.

3.4. Data and Empirical Strategy

3.4.1. Data sources

I utilize several different data sources for these analyses. Vaccination data are from the National Immunization Survey – Teen (NIS-Teen), 2008-2016. NIS-Teen is a random digit dialing survey that targets 13 to 17 year olds, and the data consist of both household demographic characteristics, collected during the household survey, as well as immunization data obtained directly from the adolescent's healthcare provider(s). In these data I observe the teen's vaccination status for a range of recommended childhood vaccines, as well as the age in years at which the vaccine dose was received. Because the policies of interest in these analyses apply to 16 or 17 year olds, I restrict my sample to individuals who were 17 years old at the time of survey, and I focus on vaccine doses received between the ages of 16 and 17. My primary outcome of interest is receipt of the quadrivalent meningococcal conjugate vaccine (MCV4), at ages 16 or 17.[114]

An important limitation of the NIS-Teen is that I am unable to observe the calendar month the survey was administered or the student's current school grade. Since most of the

[114] Due to changes in the coding of variables across survey waves, in some years individuals who received a meningococcal vaccine that provided protection against serogroups A,C,W, and Y, but for whom the vaccine subtype is unknown (e.g. if it is a conjugate vaccine or a polysaccharide vaccine), are unable to be distinguished from individuals who received a dose of a meningococcal vaccine that provided protection only against serogroup B. Therefore, for my main outcome variable, I require individuals to have documented receipt of a dose of MCV4. As a robustness check I re-estimate all models with the outcome variable of "receipt of any meningococcal-containing vaccine," which includes receipt of unknown subtype A,C, W, and Y serogroup vaccines, but also includes serogroup B vaccines. My results are robust to this alternative definition of the outcome variable.

booster mandates I am examining are binding on 17 year olds at entry into 12th grade, and I am unable to tell if the 17 year olds in my data are currently in 11th or 12th grade, I am likely underestimating the vaccination effects of these mandates.

Data on disease incidence were obtained directly from the CDC for the years 2000-2016, as reported by states to the Nationally Notifiable Disease Surveillance System. These data consist of counts of cases at the state-year-age group level (0-4 year olds, 5-14 year olds, 15-24 year olds, 25-64 year olds, and 65 and older), and allow me to estimate the effects of meningococcal vaccine policy on disease incidence at the population level and among the most directly targeted age group (15-24 year olds).[115] Notably, while these data represent the most comprehensive measure of meningococcal disease in the United States, because they rely on physician diagnosis they necessarily represent an underestimation of true disease incidence.

I present in Appendix Figure 2 trends in adolescent vaccination rates over time, and show summary statistics on key vaccination and morbidity outcomes, as well as sample demographics from the NIS-Teen in Appendix Table 1. In column 1 I present the statistics for the full sample of states and years; columns 2 and 3 respectively summarize the data for the years prior to and after the 2011 ACIP booster recommendation; presented in columns 4 and 5 are statistics for states with and without, respectively, a high school booster mandate in place by the end of 2016. These statistics show that vaccination rates among 16 and 17 year olds are increasing over time for the MCV4, HPV, and influenza vaccine. Rates among 16 and 17 year olds for the Tdap vaccine are actually decreasing, which is consistent with the fact that the Tdap vaccine is routinely recommended for 11-12 year olds, but was more commonly received by older cohorts

[115] For 2005-2016 the meningococcal disease data are additionally available by state-year-serogroup. I do not present results using these data, however, due to reports from contacts in the Meningitis and Vaccine Preventable Diseases Branch at the CDC that these data are of poor quality and suffer from "non-random missingness." Results from analyses using these data are available upon request, however, and support my primary findings.

as a catch-up vaccine in the initial years following introduction of the vaccine.

Vaccination rates across mandating and non-mandating states are generally comparable, although notably MCV4 rates are actually lower on average in states with the high school booster mandate. States with booster mandates also differ from non-adopting states along several demographic dimensions: samples in adopting states are more white, less Hispanic, and mothers in adopting states are slightly more likely to be older, unmarried, and have a high school degree as their highest level of education. Summary statistics on morbidity show that meningococcal disease incidence has declined substantially over time. Given the strong secular downward trend in meningococcal incidence in the years prior to the introduction of the MCV4 vaccine, the extent to which this decline is due to increased vaccination is an empirical question.

3.4.2. Estimation of ACIP Recommendation Effects

In my analyses I estimate the effects of the national-level ACIP meningococcal vaccine recommendations, as well as the effects of state laws requiring receipt of the MCV4 vaccine prior to entry into 11^{th} or 12^{th} grade. Given the differing levels of variation across these policies, I implement separate identification strategies in order to estimate the causal effect of each policy on vaccination rates and meningococcal disease incidence.

First, to estimate the vaccination effects of the 2011 ACIP recommendation for the age 16booster dose of MCV4, I take advantage of the fact that this policy, while implemented at the national level, applied only to the MCV4 vaccine and not to other adolescent vaccines. Specifically, I estimate the following difference-in-differences model, in which I compare the probability a 16 or 17 year old receives the MCV4 vaccine versus the Tdap vaccine, in the period before the 2011 ACIP booster recommendation versus after:

$$\mathbf{(2)} \qquad Y_{istb} = \beta_1 + \tau_t + \beta_2 MCV_{ib} + \beta_3 (MCVxPOST2011)_{tb} + \beta_4 (MCVxZ)_{stb} + \varepsilon_{istb}$$

where Y_{istb} is a dummy variable equal to one if individual *i* in state *s* who is age 17 in year *t* received a dose of vaccine *b* at age 16 or 17 and is equal to zero otherwise. MCV is an indicator variable that is equal to 1 if vaccine *b* is the MCV vaccine; the variable MCVxPOST2011 is the interaction between MCV and an indicator variable equal to one if the adolescent was 17 years old in 2012 or later.[116] In this specification β_3 is the coefficient of interest, as it captures the differential effect of exposure to the ACIP meningococcal booster recommendation on the probability of receiving a dose of MCV4 at age 16 or 17, compared to the probability of receiving a dose of the Tdap vaccine at those same ages. Notably, if the ACIP recommendation for the MCV4 booster dose had spillover effects to the probability of receiving a Tdap vaccine, then β_3 will underestimate the true effect of the ACIP recommendation.

In this specification $\boldsymbol{\tau_t}$ is a vector of year fixed effects. By including year fixed effects I am able to control for any potential policies or changes in attitudes which may generally affect the probability individuals in a given year receive either vaccine. Some state policies, however, may differentially affect the probability an individual receives a dose of MCV4 relative to Tdap. In order to allow for this, I include the interaction between a vector of state-level characteristics, Z_{st}, and the indicator variable MCV (which is equal to one if the outcome variable is receipt of the MCV4 vaccine). The vector Z_{st} captures the following state policies and characteristics: effective high school MCV4 booster mandates; post-secondary meningococcal education, waiver, and vaccine mandates; secondary school meningococcal education mandates; separate indicator variables for if the individual's cohort was exposed to a middle school MCV4 mandate, or by a middle school TD-containing vaccine mandate; and measures of meningococcal and pertussis (protected against by the Tdap vaccine) disease incidence in the state in the previous

[116] In this baseline specification I assume a 1-year lag in the effects of the recommendation. I relax that assumption in the event-study model presented later in equation 2.

year.

In some specifications I further include measures of state insurance policies in the Z_{st} vector, as the out-of-pocket cost of MCV4 is markedly higher than the out-of-pocket cost of the Tdap vaccine, and so a change in insurance access may differentially affect the probability of receiving one vaccine relative to the other.[117] Specifically, I additionally include indicator variables for if the state has insurance mandates for the coverage of well-child visits and immunizations, lagged state Medicaid/CHIP income thresholds, and an indicator variable for if a state had implemented Medicaid expansion by June of the survey year. Finally, to allow for differential linear trends in vaccination rates of the two vaccines, in some specifications I additionally include vaccine-specific linear time trends. All regressions include NIS-Teen provider-sample weights, and standard errors are clustered at the state level.

This estimation strategy relies on the assumption that observed vaccination rates of a non-routinely recommended adolescent vaccine (Tdap) serves as a valid counterfactual for how MCV4 vaccination rates would have evolved in the absence of the ACIP recommendation. I focus on the Tdap vaccine as the counterfactual vaccine for two main reasons: one, both MCV4 and Tdap vaccines were first approved for use in the United States in the same year (2005), and second, within a year of approval both vaccines were recommended for routine administration to 11-12 year old, with catch-up vaccination recommended through age 18. In Figure 3 I show national level trends in the probability of receiving a dose of the Tdap vaccine or MCV4 at age 16 or 17; visual inspection of these trends confirms that prior to the 2011 ACIP recommendation, trends in vaccination rates for these two vaccines were very similar.

To further test the assumption that vaccination rates were following parallel trends in the

[117] As of April 2018, the out of pocket cost of a Tdap vaccine at Walgreens was listed as $63.99, compared to the meningococcal vaccine, which was $133.99 per dose. https://www.walgreens.com/topic/healthcare-clinic/price-menu.jsp

pre-period and to allow for dynamic treatment effects, I re-estimate equation 1 and replace the single POST2011 indicator variable with a series of indicator variables that separately capture each calendar year:

$$\mathbf{(3)} \quad Y_{istb} = \beta_1 + \tau_t + \beta_2 MCV_{ib} + \sum_{j \in J} \beta_j (YEARj \times MCV)_{tb} + \beta_4 (MCV \times Z)_{stb} + \varepsilon_{istb}$$

where J={2008, 2009, 2011, 2012,…,2016}, with 2010 as the omitted year, and all other variables are as described in equation 1. In this specification, β_j is the change in the relative probability of receiving a dose of the MCV4 vaccine, in year *j* compared to the omitted base year. In addition to this specification allowing for more rigorous examination of the parallel trends assumption, it also has the advantage of allowing for dynamic treatment effects.

Morbidity model

Unfortunately, while the above difference-in-differences strategy is useful for estimating the vaccination effects of the ACIP meningococcal booster recommendation, the same strategy cannot be implemented to estimate the resulting morbidity effects, as the disease analogs of the Tdap vaccine (tetanus, diphtheria, and pertussis) follow very different trends relative to meningococcal disease in the pre-period.[118] Given this, I modify my estimation strategy and instead identify morbidity effects of the vaccination recommendation by comparing meningococcal disease incidence rates among the directly targeted age group (15-24 year olds) to disease incidence among other age groups. As mentioned previously, this strategy also allows me to estimate morbidity effects of the 2005 ACIP recommendation which recommended routine vaccination of 11-12 year olds. Specifically, I estimate the following difference -in-differences model:

[118] Specifically, tetanus and diphtheria are very rare in the United States, with 34 and 0 cases, respectively, reported to the CDC in 2016. Pertussis, while more common in the United States, is extremely cyclical, unlike meningococcal disease.

(4) $\mathbf{Y_{sta} = \beta_1 + \tau_t + AGE\ GROUP_a + \beta_2(15\text{-}24yrolds\ xPOST2011)_{ta}}$

$\mathbf{+ \beta_3(5\text{-}14yrolds\ xPOST2005)_{ta} + \beta_4(AGE\ GROUP\ xZ)_{sta} + \varepsilon_{ist}}$

where $\mathbf{Y_{sta}}$ is a measure of meningococcal disease incidence in state *s*, at year *t*, among age group *a*. I specify the outcome variable as either an incidence rate, in which the measure is the number of reported cases per 100,000 population, or as the natural log of (number of cases + 1). Specifications in which ln(meningococcal cases + 1) is the outcome variable additionally include the natural log of the age group-specific population in state *s* and time *t* as a control variable. As in equation 1, $\boldsymbol{\tau_t}$ is a vector of year fixed effects. In this specification **AGE GROUP** is a vector of age group fixed effects, and **15-24yrolds xPOST2011** and **5-14yrolds xPOST2005** are the interactions between the stated age group fixed effect and an indicator variable that is either equal to one for years after 2011 or for years after 2005, respectively. Thus, in this specification $\boldsymbol{\beta_2}$ and $\boldsymbol{\beta_3}$ are the coefficients of interest, as they capture the extent to which the difference in disease incidence between the directly targeted groups (15-24 year olds for the 2011 recommendation, and 5-14 year olds for the 2005 recommendation) and other age groups changes after a given ACIP recommendation. This differencing strategy accounts for secular trends in meningococcal disease incidence, as well as controls for any potential shocks at the year level that may have generally affected meningococcal disease incidence. As in equation 1, to additionally control for state policies that may have differentially affected the treatment versus control group, I include the interaction between a vector of state vaccination and insurance policies, **Z**, and the age group fixed effects. In some specifications I also include age group-specific linear time trends. I weight each observation by the state-year-age group population and cluster standard errors at the state level.

As with the vaccination model, in order to test for dynamic treatment effects and to

empirically check for parallel trends in outcomes in the pre-period, I additionally estimate an event study model, in which the POST variables are replaced by a series of indicator variables that capture the specific year, with the year prior to the given recommendation as the omitted year. All other variables are as specified in equation 3.

3.4.3. Estimation of Effects of State Meningococcal Vaccine Mandates

To estimate the effects of state laws requiring receipt of the meningococcal vaccine prior to entry into 11th or 12th grade I use difference-in-differences models in which I compare vaccination rates in adopting states versus non-adopting states, before versus after adoption. Specifically, I estimate the following model:

$$\textbf{(5)}\quad Y_{ist} = \beta_0 + \beta_1 X_{ist} + \beta_2(\text{HIGH SCHOOL MCV4 MANDATE})_{st} + \beta_3 Z_{st} + \beta_4 S_s + \beta_5 T_t + \varepsilon_{ist}$$

where Y_{ist} is a specified vaccine outcome for individual *i* in state *s* who was age 17 in year *t*. HIGH SCHOOL MCV4 MANDATE is the policy variable of interest, as it is an indicator variable that is equal to one if there is an 11th or 12th grade MCV4 mandate in effect in an individual's state of residence in year *t*. Because of ambiguity in the implementation of MCV4 mandates in Indiana and D.C., I drop them from analyses of the effects of the high-school booster mandates.[119]

X_{ist} is a vector of individual characteristics available in the NIS-Teen, including: child's gender, child's race/ethnicity (Hispanic, white, black, with other as the excluded category), number of other children under 18 years old living in the home (only 1 child, 2 to 3 children, with 4 or more children as the excluded category), maternal education (less than high school, high school, some college, with college or above as the excluded category), maternal age group

[119] I do verify, however, that all baseline estimates are robust to the inclusion of these two states.

(34 years old or younger, 35 to 44 years old, with 45 years or older as the excluded category) and an indicator variable for whether the mother is married. In this specification $\mathbf{Z_{st}}$ represents a vector of other state policies that may plausibly affect the probability that an individual decides to vaccinate. Specifically, it captures exposure to middle school vaccine mandates for the vaccines routinely recommended for administration at ages 11 or 12 (Tdap, MCV4, and HPV),[120] as well as exposure to binding `catch-up' mandates for vaccines that are routinely recommended to be administered during early childhood;[121] lagged measures of state laws requiring educational materials on the HPV or MCV4 vaccine to be distributed to students, parents, or through awareness campaigns; state non-medical exemption policies for vaccine mandates; contemporaneous measures of all childcare, kindergarten, and post-secondary school vaccine mandates that are changing over the sample period; state insurance policies as previously discussed (state laws requiring insurance coverage of well-child visits or immunizations for 16 year olds, lagged state Medicaid/CHIP income thresholds, and state Medicaid expansion); state pharmacist authority to administer vaccines to 16 year olds; lagged state pertussis and meningococcal disease incidence; lagged state unemployment rates from the Bureau of Labor Statistics; and lagged state demographic characteristics as measured by the Current Population Survey (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). S_S and T_t represent state and year fixed effects, respectively. I cluster standard errors at the state level, and

[120] I consider an individual to have been exposed to a middle school mandate if there was an effective mandate in their state of residence when they were 12 years of age.

[121] A number of states have 'catch-up' mandates in place for high school students and middle school students, in which they require students to have received a vaccine that is recommended for routine administration at a younger age. These vaccines are also mandated for receipt in either middle or elementary school, and thus I only consider a catch-up mandate to be binding for a given cohort if they were not exposed to the vaccine mandate at a younger age due to the timing of the implementation. I control for measles, varicella, hepatitis B, and hepatitis A catch-up mandates.

all specifications are weighted by NIS-Teen provider-sample weights.

For estimates of the morbidity effects of the high school meningococcal mandates I estimate a variant of equation 4, in which the outcome variable is the rate of meningococcal disease per 100,000 population in state *s* and year *t*, and regressions are weighted using state population estimates. In this aggregate level model, all policies are considered in effect at the start of the calendar year following implementation. I also estimate an event study model variant of equation 4, for both vaccination and morbidity outcomes, in which the indicator variables for each of the MCV4-specific policies are replaced with a series of indicator variables capturing years relative to policy implementation.[122] In these models the period prior to implementation of the mandate (t=-1) is the omitted base period.

3.5. Main Results

3.5.1. Vaccination Effects of Recommendations

I first estimate the effects of the ACIP meningococcal booster recommendation on the probability of receiving the MCV4 vaccine, using the difference-in-differences model with state-by-year fixed effects that is presented in equation 1. Results in Table 1 show that the ACIP booster recommendation increased the probability that an individual received a dose of the MCV4 vaccine at ages 16-17 (column 1) by 20.6 percentage points, relative to their probability of receiving a dose of the Tdap vaccine at the same ages. Results in columns 2 and 3 show the estimates are robust to allowing changes in state insurance policies to have differential effects on the probability of receiving the MCV4 versus Tdap vaccines, and to the inclusion of vaccine-specific linear time trends, respectively. Compared to the pre-2011 mean MCV4 vaccination

[122] Given that there was staggered roll-out of these policies across states, relative event time in this model is distinct from calendar year, unlike in equation 2.

rate, these estimates suggest the ACIP recommendation caused a 129 (.206/.161 * 100) percent increase in MCV4 vaccination at ages 16-17. Notably, if this ACIP recommendation also had the effect of increasing receipt of the Tdap vaccine, these estimates understate the true effect of the recommendation on vaccination rates.

I further explore the effects of the recommendation by estimating the event study model specified in equation 2, the results of which are presented graphically in Figure 4. These estimates show that there are important dynamics of the recommendation effect that are not captured by the baseline difference-in-differences specification. First, the results suggest that there is a lag period of approximately one year before there is a significant detectable effect of the recommendation on MCV4 vaccination rates, and, second, they show that the magnitude of the effect grows consistently over time, with estimated effects five years after implementation as large as 38.5 percentage points. The estimated coefficients for the years prior to the ACIP recommendation also show that there were not pre-existing differential trends in the probability that an individual received an MCV4 vaccine compared to the Tdap vaccine, as they are all relatively small in magnitude, and only one coefficient is even marginally significant at the 10 percent level. This provides further evidence that the trend in Tdap vaccination is an appropriate counterfactual for how MCV4 vaccination rates would have evolved in the absence of the ACIP recommendation.

3.5.2. Vaccination Effects of High School Mandates

I next examine the vaccination effects of high school vaccine mandates, using the state-level difference-in-differences model specified in equation 4. The results from these analyses are presented in columns 4 and 5 of Table 1. The results in column 4 indicate that the high school meningococcal booster mandates increase the probability of receiving a dose of the MCV4

vaccine between the ages of 16 and 17 by approximately 19.0 percentage points, and this result is robust to the inclusion of state-specific linear time trends (column 5). Note that because all high school mandates are implemented *after* the ACIP recommendation, this effect captures the marginal effect of a mandate given the presence of a recommendation.

Event study estimates, presented graphically in Figure 5, show that the mandates resulted in an immediate increase in vaccination rates among 16 and 17 year olds, and that this effect was even larger in the first and second years following implementation. Given how recent the identifying variation is for these mandates, it is not possible to more comprehensively trace out policy dynamics over time. Importantly, however, pre-implementation coefficients are consistently small in magnitude and generally not statistically significant, supporting the validity of the identifying parallel trends assumption and reducing concerns of endogenous policy implementation in response to particularly low vaccination rates.

3.5.3. Morbidity results

I next analyze the extent to which the large increases in meningococcal vaccination rates caused by the ACIP recommendation and high school mandates translated into reductions in disease incidence. I first focus on the effects of the ACIP recommendation, and present in Table 2 the results of estimating equation 3. Observations in this model are at the state-year-age group level, and the sample includes observations from all age groups. The outcome variable is the natural log of (age group-specific count of meningococcal cases +1).[123] I graphically present trends over time in ln(meningococcal cases+1) in Figure 6A for 5-14 year olds versus all other age groups, and in Figure 6B for 15 -24 year olds versus all other age groups.

[123] For these models, the specifications in which the outcome variable is the age group-specific disease incidence *rate* consistently fail to demonstrate parallel trends in the pre-period, and so I do not present results from these specifications.

The difference-in-differences estimates in column 1 of Table 2 suggest the 2005 ACIP recommendation significantly reduced meningococcal incidence among 5-14 year olds by 30.6 percent relative to all other age groups, while the 2011 ACIP recommendation significantly reduced meningococcal disease incidence among 15-24 year olds relative to all other age groups by17.5 percent.[124] When I additionally allow for state insurance policies to have differential effects on disease incidence across the age groups (column 2) and include age group-specific linear time trends (column 3), the estimated effects of the 2005 recommendation on disease incidence among 5-14 year olds remains large and statistically significant at the one percent level. Estimated effects of the 2011 recommendation, however, are sensitive to the inclusion of these additional controls, and are no longer statistically significant at conventional levels. The point estimates, however, remains negative and the large standard errors mean I am unable to rule out potentially large reductions in disease incidence among 15-24 year olds.

I present the accompanying event studies in Figure 7A, for 5-14 year olds, and Figure 7B, for 15-24 year olds. These event study estimates shows that the dynamics of the morbidity effects are broadly consistent with the dynamics of the vaccination effects of the ACIP recommendation. Specifically, there appears to be a substantial lag in the effects on disease incidence, with the largest effects occurring several years after implementation.

I present in Table 3 the estimated morbidity effects of the high school vaccine mandates, obtained from estimation of equation 4. The outcome variable in columns 1 and 2 is the rate of meningococcal disease incidence among 15-24 year olds per 100,000 population, and in columns

[124] Additional analyses not presented here suggest that the resulting reductions in meningococcal disease were largest in states that had average incidence above the median during the pre-period, although I find no differential effects of the ACIP recommendation on vaccination rates along this same dimension. This indicates that there are potentially important nonlinearities in the effects of vaccination on meningococcal disease incidence.

3 and 4 I present estimates using full population incidence rates. In general these estimates are not very conclusive: although most estimates are negative and the large standard errors mean I am unable to rule out potentially large reductions in disease incidence, only one estimate is even marginally significant (column 3).[125] Estimates from the event study model are presented in Figures 8A and 8B for 15-24 year olds and for population rates, respectively, and show that the mandates potentially did lead to large and significant reductions in meningococcal disease incidence, but that the reductions occurred with a lag relative to the timing of mandate implementation. Specifically, these estimates suggest that 2 years after implementation, there was a reduction in disease incidence among 15-24 year olds of a marginally significant 0.253 cases per 100,000 population, and a significant reduction in the entire population of .169 cases per 100,000 population. Relative to mean incidence rates in state-years in which there was not an effective mandate, these respectively represent a reduction of approximately 57 (0.281/0.489) and 45 (0.154/ 0.346) percent.

3.6. Additional Results

In this section I do a number of additional analyses to further explore the effects of the meningococcal vaccine policies. First, I test for potential heterogeneity in the vaccination effects across subgroups by separately estimating the models for different groups. I next consider potential spillover effects of the mandates to receipt of other preventive care, and finally I examine the effects on Google searches for meningococcal-related terms.

3.6.1. Heterogeneity

To explore potential heterogeneity in the vaccination effects of the meningococcal

[125] Results from models with ln(meningococcal disease cases+1) as the outcome variable are similarly inconclusive: the estimates are never statistically significant and standard errors are extremely large.

policies I estimate the baseline difference-in-difference models separately for different demographics subgroups. Results from these analyses are presented in Table 4, where each row represents a separate subgroup. For estimated effects of the ACIP recommendation (columns 1 and 2) I re-estimate equation 1 and report the coefficient on **MCVxPOST2011**; for estimated effects of the high school meningococcal booster mandates (columns 3 and 4) I re-estimate equation 4 and report the coefficient on the indicator variable for a state having an effective high school mandate. Each reported coefficient is from a separate regression. To help contextualize the results, I also report the relevant sub-group mean MCV4 vaccination rate among 16 and 17 year olds from states and years in which the given policy of interest was not in effect.

In general, these results demonstrate that there are heterogeneous responses to the meningococcal disease policies. Across both policies I find that effects are generally smaller for males relative to females, and for low income and low maternal-education households, relative to households with higher income or higher maternal education. Notably, the estimated effects of the ACIP recommendation strongly suggest that this policy potentially exacerbates disparities in health across different socioeconomic groups: lower-educated and lower- income households are less likely to be vaccinated prior to, and are also less likely to increase vaccination rates in response to, the ACIP recommendation.

I caution, however, that the heterogeneity in the effects of the MCV booster mandate should be interpreted carefully. As in the main analyses, a limitation of analyses of the effect of the meningococcal booster mandates on vaccination rates at age 17 is that I am unable to observe what grade the individual currently is in, and therefore am unable to determine if they have entered the grade for which the mandate is binding. In particular, if there are different patterns across the calendar year in timing of consumption of health care for different subgroups (e.g. if

low income households are more time-constrained, and therefore wait to get their child vaccinated closer to the start of the school year when the mandate becomes binding), then these differing time patterns may explain some portion of the observed heterogeneity in the effects of the booster mandate.

3.6.2. Non-mandated preventive care

I next examine the extent to which the vaccine mandates increased receipt of non-mandated preventive care among the age-targeted group. I first examine effects on the probability of having a preventive care visit. The NIS-Teen survey asks how old the teen was at their most recent check-up, and using this information I construct an indicator variable that is equal to one if an individual reported that their most recent check-up was at ages 16 or 17.

Results of these analyses are presented in columns 1 and 2 of Table 5, without and with state specific linear trends, respectively. I find that the high school meningococcal vaccine mandates significantly increase the probability that an individual has a preventive care visit at ages 16 or 17 by 6.2-6.9 percentage points. Notably, this effect is approximately twice as large as the preventive care visit spillover effect of *middle school* vaccine mandates found in Carpenter and Lawler (2018). This is consistent with the fact that older teens have lower rates of contact with health care providers than middle school-aged adolescents, and thus there is more room for change through policy intervention.

I examine further potential spillovers of the increased receipt of preventive care on several other measures of adolescent health and receipt of health care that are included in the NIS-Teen: indicator variables for initiation and completion of the HPV vaccine series by age 17, indicator variables for receiving any doses of the HPV vaccine or the Tdap vaccine at ages 16 or

17, an indicator variable for receipt of the flu vaccine within the past 3 years, an indicator variable that is equal to 1 if an adolescent has ever been diagnosed with any of a group of health conditions,[126] and an indicator variable that is equal to 1 if the adolescent has ever been diagnosed with asthma. My results suggest that the high school booster mandate significantly increased the probability of receiving a dose of the HPV vaccine at age 16 or 17 (columns 9 and 10), although estimates are sensitive to the inclusion of state-specific linear trends. These additional doses seem to have been administered to individuals who had already received at least one dose of the HPV vaccine series, as I find no evidence of increased initiation of the HPV series (columns 11 and 12) but do find a marginally significant increase in completion rates (receipt of at least 3 doses) in specifications that include state-specific linear time trends (column 14). The estimates in columns 15 and 16 also suggest significant spillovers to the uptake of a dose of the Tdap booster vaccine at ages 16 or 17, with effect sizes ranging from 3.8 to 5.4 percentage points. I find no evidence, however, of spillovers to the uptake of the flu vaccine in the past 3 years (columns 3 and 4), or to the probability of being diagnosed with any of the specified health conditions (columns 5 through 8).

In Appendix Table 2 I examine potential heterogeneity in the outcomes for which I find significant spillover effects: check-ups and receipt of doses of the HPV and Tdap vaccines. In general, I find spillover effects to be largest for the households with lower income and lower-educated mothers, even though these are the sub-groups for which the first-stage increase in the probability of receiving a dose of the meningococcal vaccine was the smallest. Notably however, the low socioeconomic status (SES) sub-groups are less likely to receive a 16-17 year old check-

[126] The listed health conditions are as follows: "A lung condition other than asthma, a heart condition, diabetes, a kidney condition, sickle cell anemia or other anemia, or a weakened immune system caused by chronic illness or by medicines taken for a chronic illness" (DHHS 2016).

up or to be up-to-date with the HPV or Tdap vaccine in the absence of the high school booster mandate, and therefore have the largest potential for improvements along these margins.

3.6.3. Google trends

As an additional measure of the effects of the high school meningococcal vaccine mandates I estimate their effects on Google searches for meningococcal- related terms, using Google trends data from 2005-2016. Google trends data provide state-month level measures of relative search popularity for a given search term. Relative search popularity is standardized within each state such that the month with the highest search volume is equal to 100; if overall searches in a state are below a certain (non-disclosed) threshold, Google will not release the data disaggregated to the state level. As a result, for some of the less common search terms (e.g. `Meningitis vaccine'), data are missing for several states.

Results from these analyses are presented in Table 6. The reported coefficients are from difference-in-difference models that include state and month-year fixed effects, as well as contemporaneous measures of all state-level policies and demographic characteristics previously discussed, including current and lagged measures of meningococcal disease incidence. Estimates consistently show that high school meningococcal vaccine mandates increase Google searches for a range of meningococcal-related terms. These results suggest that beyond increasing vaccination rates among targeted age groups, these mandates may have also resulted in the broader dissemination of information about meningococcal disease.

Given the spillover effect of the meningococcal booster mandate to receipt of a dose of the HPV vaccine and the Tdap vaccine at ages 16 or 17, I also test if the mandate increased HPV or Tdap-related Google searches. These results are presented in Appendix Table 7; estimates

show that there is no evidence that the meningococcal booster mandates increased searches for "hpv," the "HPV vaccine" search topic, or for "tdap." The null HPV result is consistent with the fact that the mandates did not affect overall *initiation* into the HPV vaccine series, and may suggest that the meningococcal booster mandate did not have spillover effects to knowledge regarding the HPV vaccine.

3.7. Conclusion

Over the past several decades, new scientific advances have substantially increased the number of vaccines that are approved and recommended for receipt during adolescence. Policymakers have responded to these advances by implementing a broad range of policies aimed at increasing vaccination rates among adolescents. In this paper I provide the first quasi-experimental evidence on the effects of two commonly implemented policies, ACIP recommendations and school entry immunization mandates, on vaccination rates among high school-aged adolescents. My results show that both of these policies cause large and significant increases in the probability that individuals receive a dose of the meningococcal vaccine at age 16 or 17. Additional analyses suggest, however, that there is substantial heterogeneity in the effects of the policies across different demographic sub-groups. Most notably, I find that in the case of the meningococcal vaccine, ACIP recommendations may serve to exacerbate pre-existing disparities in the probability of being vaccinated, as households with higher socioeconomic status are most responsive to the recommendation, as well as most likely to have been vaccinated prior to the recommendation being issued.

I also provide suggestive evidence that these large increases in vaccination rates resulted in reductions in the incidence of meningococcal disease. Importantly, given that mortality rates of meningococcal infection range from 10 to 15 percent, and the fact that up to 20 percent of

individuals that survive suffer from permanent disabilities, even small reductions in disease incidence translates into large societal gains. Additionally, I find the dynamics of the morbidity effects to be important, as event study estimates suggest a lagged effect that continues to increase for up to several years following policy implementation.

Finally, my results show that the implementation of a high school immunization mandate significantly increases the probability that an individual has a preventive care visit at ages 16 or 17. I also find that after a mandate is implemented, teens are more likely to receive other non-mandated vaccines (HPV and Tdap) during those same ages. Given that many high-risk behaviors are initiated during the teenage years, it is possible that the increased provider contact resulting from the immunization mandate could have a number of further spillover effects to adolescent health and behavior that I am unable to identify in the datasets used here. Interestingly, these spillovers to other types of preventive care mainly occur in low socioeconomic status households, and actually serve to *reduce* pre-existing disparities across groups.

3.8. References

Abrevaya, Jason, and Karen Mulligan (2011). "Effectiveness of state-level vaccination mandates: Evidence from the varicella vaccine," *Journal of Health Economics*, 30: 966-976.

Ackerson, Bradley, Rulin Hechter, Margo Sidell, Lina S. Sy, Jeffrey Slezak, Chun Chao, Nilesh Patel, Hung-Fu Tseng, and Steven Jacobsen (2017). "Human papillomavirus vaccine series completion in boys before and after recommendation for routine immunization." *Vaccine* 35(6): 897-902.

Anderberg, Dan, Arnaud Chevalier, and Jonathan Wadsworth (2011). "Anatomy of a Health Scare: Education, Income and the MMR Controversy in the UK." *Journal of Health Economics*, 30(3): 515-530.

Bradford, W. David, and Anne Mandich (2015). "Some State Vaccination Laws Contribute To Greater Exemption Rates And Disease Outbreaks In The United States," *Health Affairs*, 34(8): 1383-1390.

Carpenter, Christopher S. and Emily C. Lawler (2018). "Direct and spillover effects of middle school vaccination requirements," working paper.

Centers for Disease Control and Prevention (2018). "Meningococcal Disease," National Center for Immunization and Respiratory Diseases. Available at: https://www.cdc.gov/meningococcal/index.html Accessed April 15, 2018.

----- (2016). "Use of a 2-Dose Schedule for Human Papillomavirus Vaccination – Updated Recommendations of the Advisory Committee on Immunization Practices," Morbidity and Mortality Weekly Report 65(49): 1405-1408.

----- (2015). “Epidemiology and Prevention of Vaccine-Preventable Diseases.” Eds: Hamborsky J, Kroger A, Wolfe S. 13th ed. Washington D.C. Public Health Foundation.

----- (2011). “Updated Recommendations for Use of Meningococcal Conjugate Vaccines --- Advisory Committee on Immunization Practices (ACIP), 2010,” Morbidity and Mortality Weekly Report 60(03): 72-76.

----- (2007). “Notice to Readers: Revised Recommendations of the Advisory Committee on Immunization Practices to Vaccinate All Persons Aged 11-18 Years with Meningococcal Conjugate Vaccine,” Morbidity and Mortality Weekly Report 56(31): 794-795.

----- (2005). “Prevention and Control of Meningococcal Disease,” Morbidity and Mortality Weekly Report 54(RR07): 1-21.

----- (2000). “Prevention and Control of Meningococcal Disease,” Morbidity and Mortality Weekly Report 49(RR07): 1-10.

----- (1999). “Achievements in Public Health, 1900-1999 Impact of Vaccines Universally Recommended for Children,” Morbidity and Mortality Weekly Report 48(12): 243-248.

Chang, Lenisa V. (2018, forthcoming). Information, education, and health behaviors: Evidence from the MMR vaccine autism controversy. *Health Economics*.

Cohn, Amanda C., Jessica R. MacNeil, Lee H. Harrison, Ruth Lynfield, Arthur Reingold, William Schaffner, Elizabeth R. Zell et al. (2017). "Effectiveness and Duration of Protection of One Dose of a Meningococcal Conjugate Vaccine." *Pediatrics*: e20162193

Gruber, Jonathan (2001). Risky Behavior Among Youths: An Economic Analysis. Chicago: University of Chicago Press.

Kaiser Family Foundation (2015). Medicaid/CHIP Upper Income Eligibility Limits forChildren.,

pp. 2000–2015 (24 August 2015) http://kff.org/medicaid/state-indicator/medicaidchip-upper-income-eligibility-limits-for-children-2000-2015/

Lawler, Emily C. (2017). “Effectiveness of vaccination recommendations versus mandates: Evidence from the hepatitis A vaccine,” *Journal of Health Economics,* 52: 45-62.

Luca, Dara Lee (2016). “The Effects of Mandatory Vaccination Laws on Childhood Health and Adult Educational Attainment,” working paper.

MacNeil, Jessica R., Amy E. Blain, Xin Wang, and Amanda C. Cohn (2018). "Current Epidemiology and Trends in Meningococcal Disease—United States, 1996-2015." *Clinical Infectious Diseases,* 66(8): 1276-81.

Malone, Kevin M. and Alan R. Hinman (2003). Vaccination mandates: the public healthimperative and individual rights. Law Public Health Pract., 262–284.

Moghtaderi, Ali and Scott Adams (2016). “The Role of Physician Recommendations and Public Policy in Human Papillomavirus Vaccinations,” *Applied Health Economics and Health Policy*, 14: 349-359.

National Council of State Legislatures (2017). States With Religious and Philosophical Exemptions from School Immunization Requirements. http://www.ncsl.org/research/health/school-immunization-exemption-state-laws.aspx . [April 9 2018].

----- (2012). 50 State Summary of Meningitis Legislation and State Laws. http://www.ncsl.org/research/health/meningitis-state-legislation-and-laws.aspx. [April 9 2018].

Oster, Emily (2016). "Does Disease Cause Vaccination? Disease Outbreaks and Vaccination Response," NBER Working Paper #22464.

Philipson, Tomas (2000). Economic epidemiology and infectious diseases. *Handbook of Health Economics*, 1: 1761-1799.

Schaller, Jessamyn, Lisa Schulkind, and Teny Maghakian Shapiro (2017). "The Effects of Perceived Disease Risk and Access Costs on Infant Immunization." National Bureau of Economic Research, No. w23923.

Trogdon, Justin, Paul Shafer, Parth Shah, and William A. Calo (2016). "Are state laws granting pharmacists authority to vaccinate associated with HPV vaccination rates?" *Vaccine*, 34(38): 4514-9.

Uddin SG, O'Connor KS, Ashman JJ. (2016). "Physician office visits by children for well and problem-focused care: United States, 2012." NCHS data brief, no 248. Hyattsville, MD: National Center for Health Statistics.

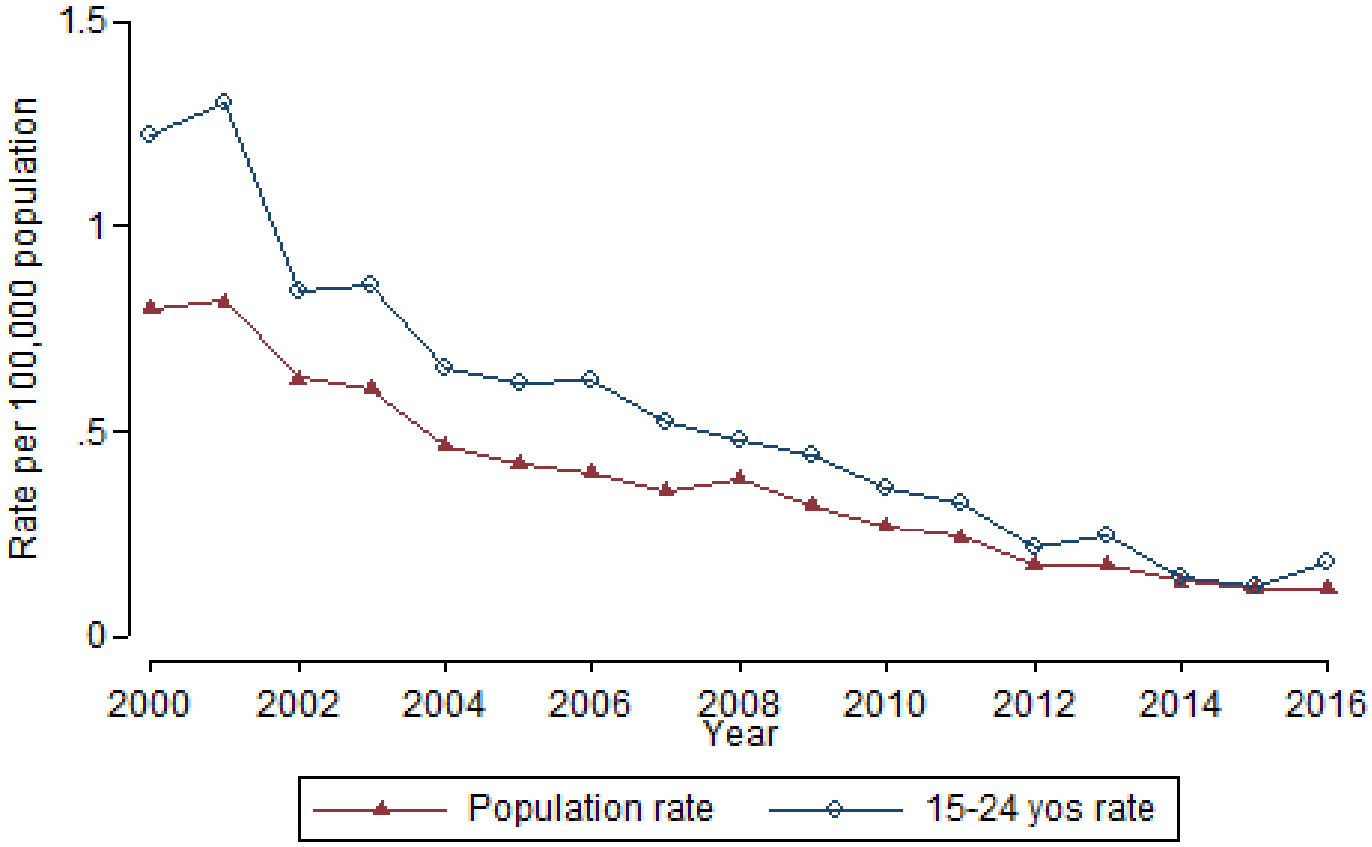
U.S. Department of Health and Human Services (DHHS) (2016). "National Immunization Survey-Teen." Hyattsville, MD: Centers for Disease Control and Prevention, National Center for Health Statistics.

Walgreens (2018). "Price Menu: Vaccines." Available at: https://www.walgreens.com/topic/healthcare-clinic/price-menu.jsp. Accessed April 9, 2018.

Ward, Courtney J. (2011). "The Effects of Immunization Mandates: Does Prenatal Exposure to State School Immunization Policy Impact Later Economic Well-Being?" Dalhousie University Working Paper.

White, Corey (2018). “Measuring the Social and Externality Benefits of Influenza Vaccination,” working paper.

Figure 1 : National Trend in Meningococcal Disease Incidence



Notes: Disease incidence data are from the CDC's Nationally Notifiable Disease Surveillance System, age group-specific population estimates are from the Surveillance and Epidemiologic End Results (SEER) system. Rates are calculated as number of reported cases per 100,000 population.

Figure 2: Timing of MCV4 Booster Mandate Across States

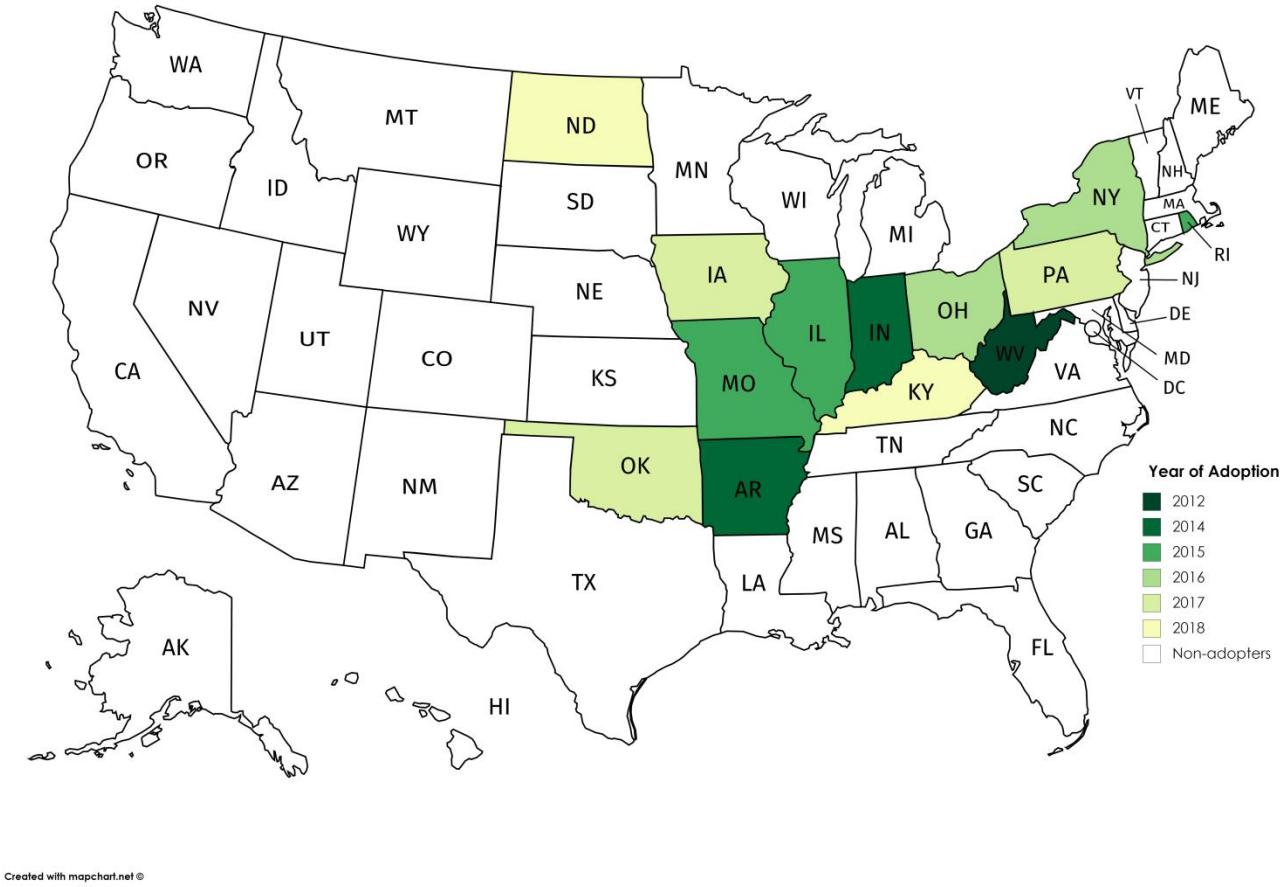
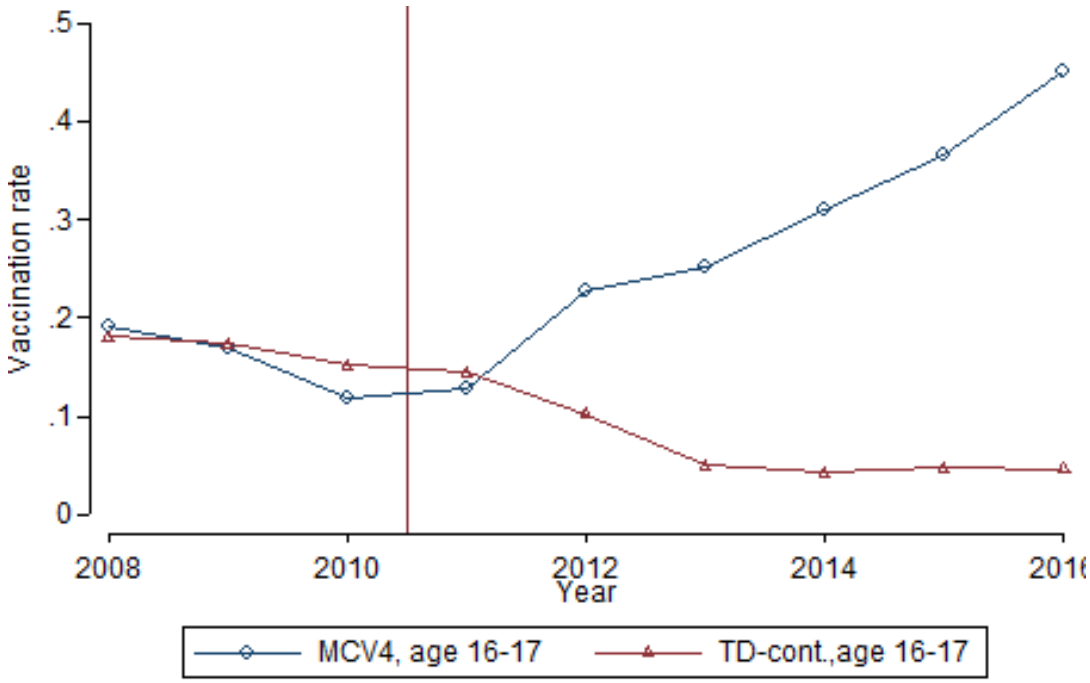
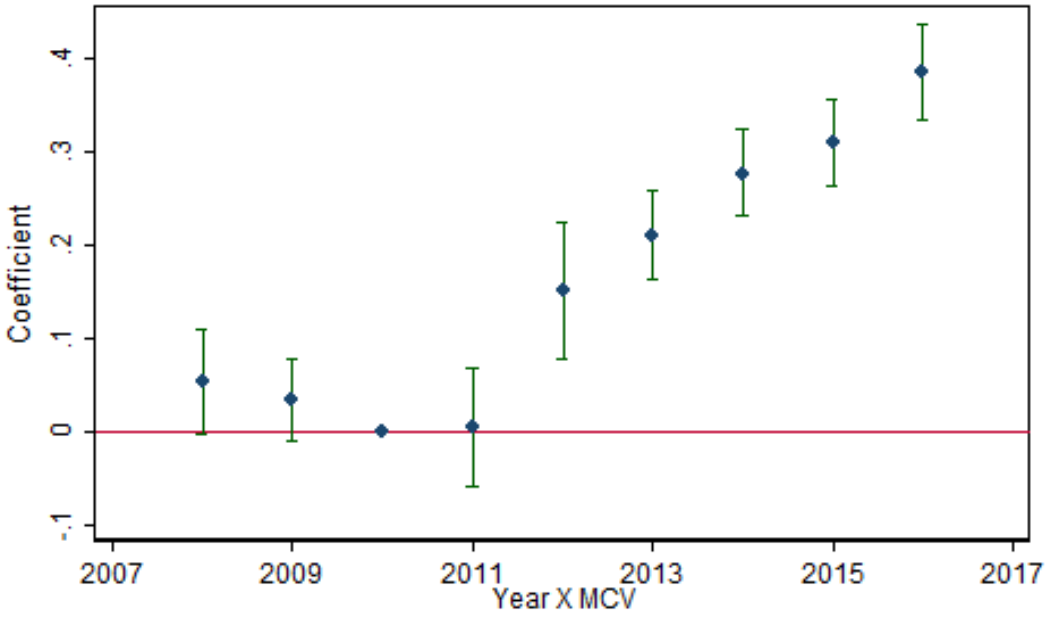


Figure 3: National Trends in Receipt of MCV4 and Tdap Vaccine, at ages 16-17



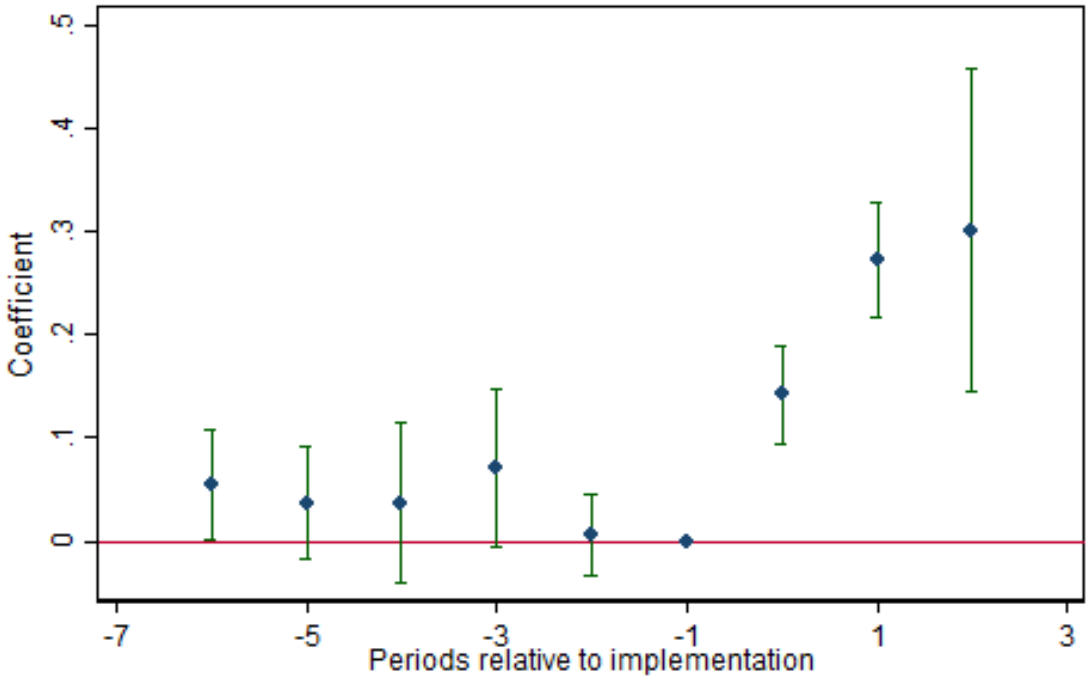
Notes: Data are from NIS-Teen, means are calculated using NIS-Teen provider weights. Sample is restricted to individuals who were 17 years old at the time of the survey.

Figure 4: Event Study Estimates of the Effect of the 2011 ACIP Recommendation On Meningococcal Vaccination Rates Among 16-17 Year Olds, Relative to Tdap Vaccination



Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for the MCV vaccine. Coefficients are relative to the excluded group of the year prior to the given ACIP recommendation, and are from the baseline specification that includes the interaction between the MCV indicator variable and a vector of state meningococcal and Tdap vaccination policies. Brackets represent the 95% confidence interval.

Figure 5: Event Study Estimates of the Effect of High School Immunization Mandates On Meningococcal Vaccination Rates Among 16-17 Year Olds Vaccination



Notes: Sample excludes DC & IN. Coefficients are relative to the excluded period of the year prior to mandate adoption. The coefficients presented for -6 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior. Estimated coefficient for three or more years post implementation is not reported, as it is identified by only one state. Brackets represent the 95% confidence interval.

Figure 6A: National Trends in ln(meningococcal cases +1), 5-14 year olds versus all other age groups

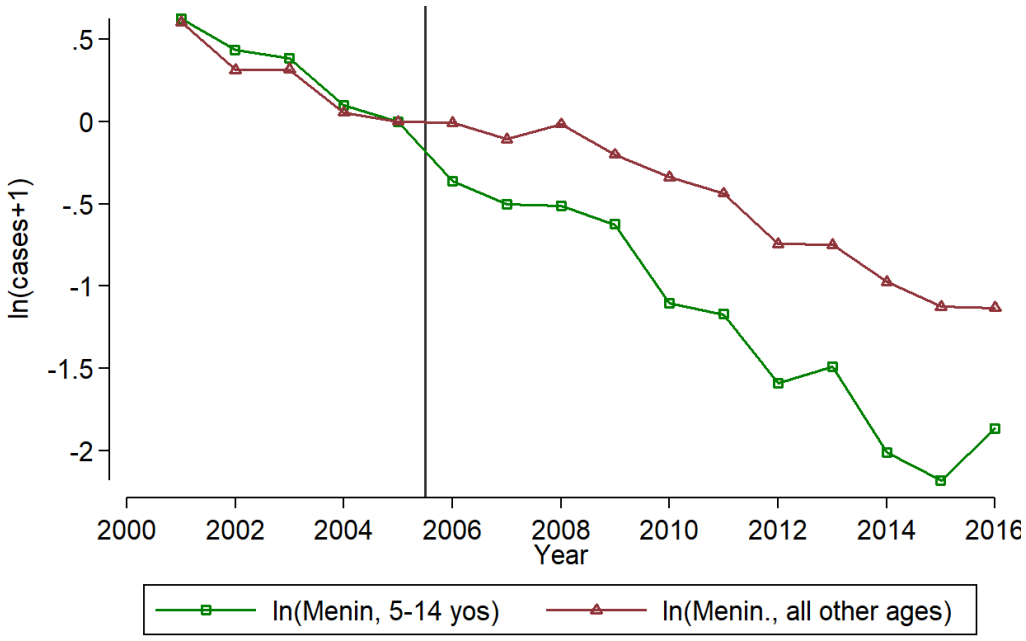
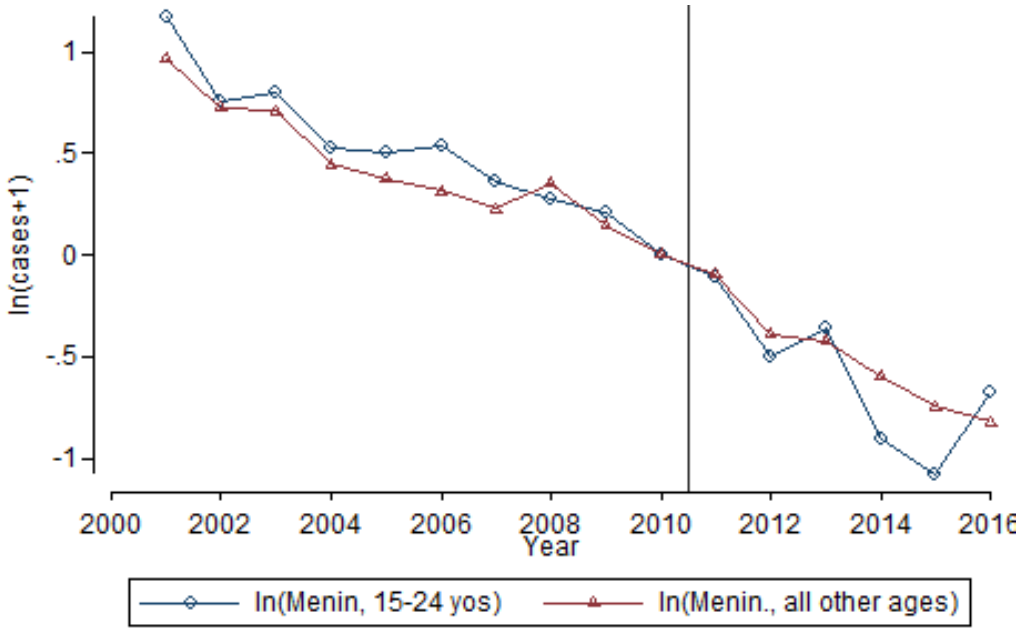


Figure 6B: National Trends in ln(meningococcal cases +1), 15-24 year olds versus all other age groups



Note: Data are from CDC NNDSS. In Figure A the series are each adjusted to be mean zero in 2004, in Figure B the series are adjusted to be mean zero in 2010.

Figure 7A: Event Study Estimates of the Effect of 2005 ACIP Recommendation on Disease Incidence Among 5-14 Year Olds, Relative to All Other Age Groups

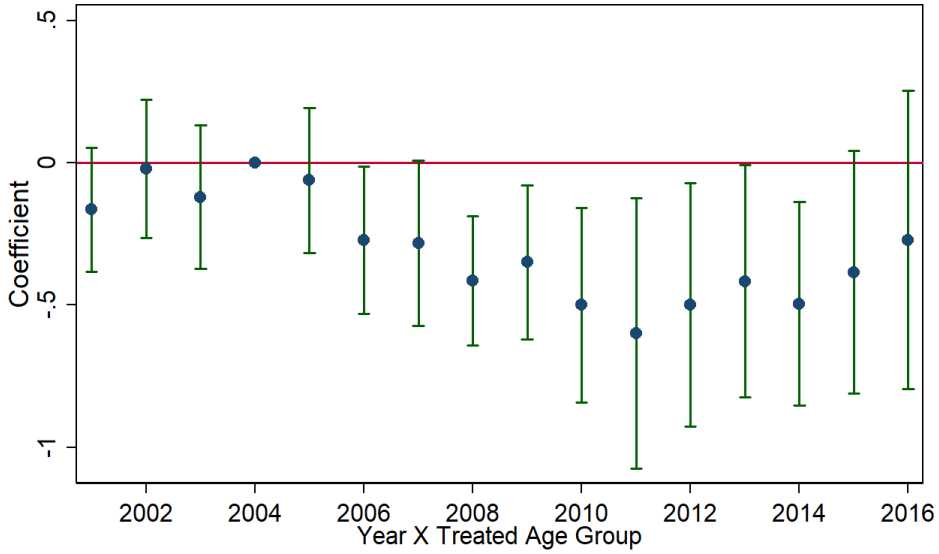
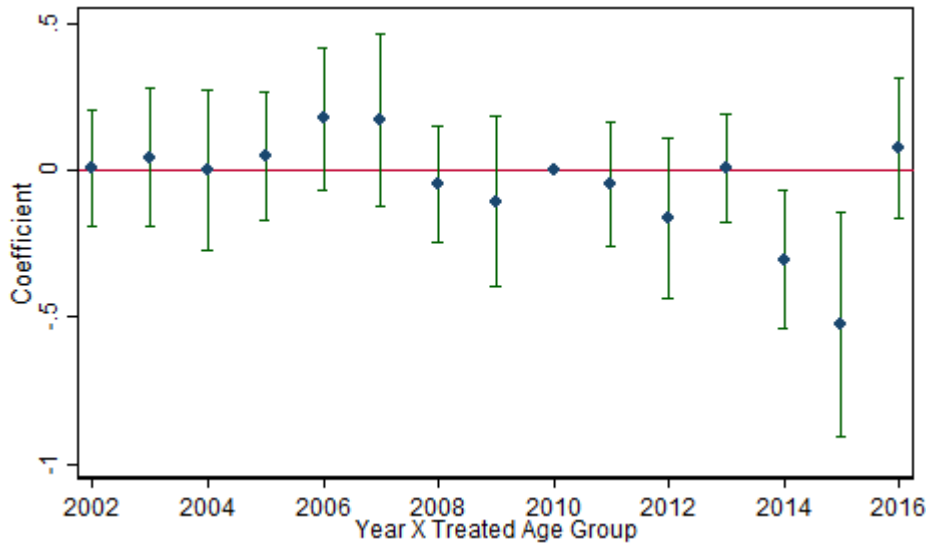


Figure 7B: Event Study Estimates of the Effect of 2011 ACIP Recommendation on Disease Incidence Among 15-24 Year Olds, Relative to All Other Age Groups



Notes: In Figure A, reported coefficients are from the interaction between the stated calendar year and the indicator variable for the 5-14 year old age group; in Figure B they are the coefficients on the interaction between the given calendar year and the indicator variable for the 15-24 year old age group. Both sets of coefficients are from the same regression, in which the outcome variable is ln(age group-specific meningococcal cases+1), and which includes the interaction between age group fixed effects and a vector of state meningococcal vaccination policies. Coefficients are relative to the excluded group of the year prior to the given ACIP recommendation; brackets represent the 95% confidence interval.

Figure 8A: Event Study Estimates of the Effect of High School Immunization Mandates on Disease Incidence Among 15-24 Year Olds

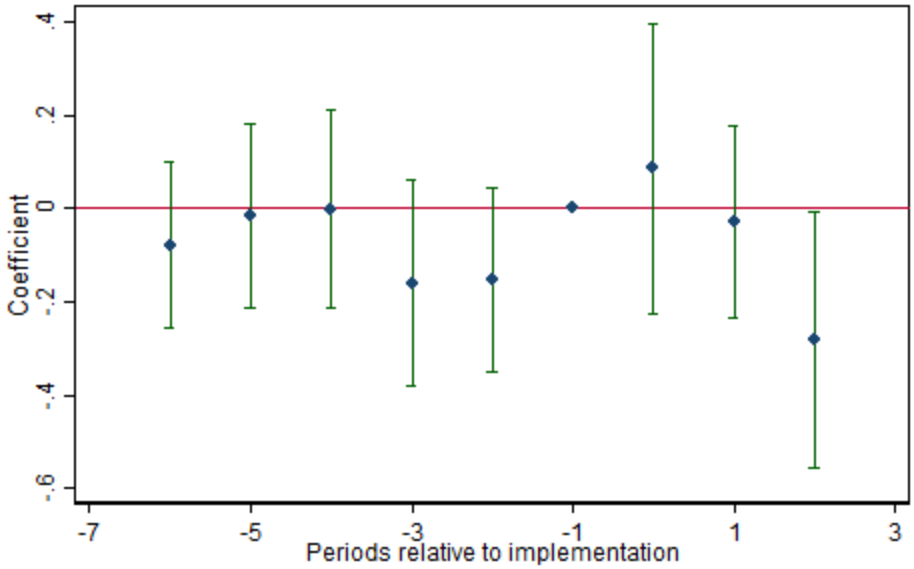
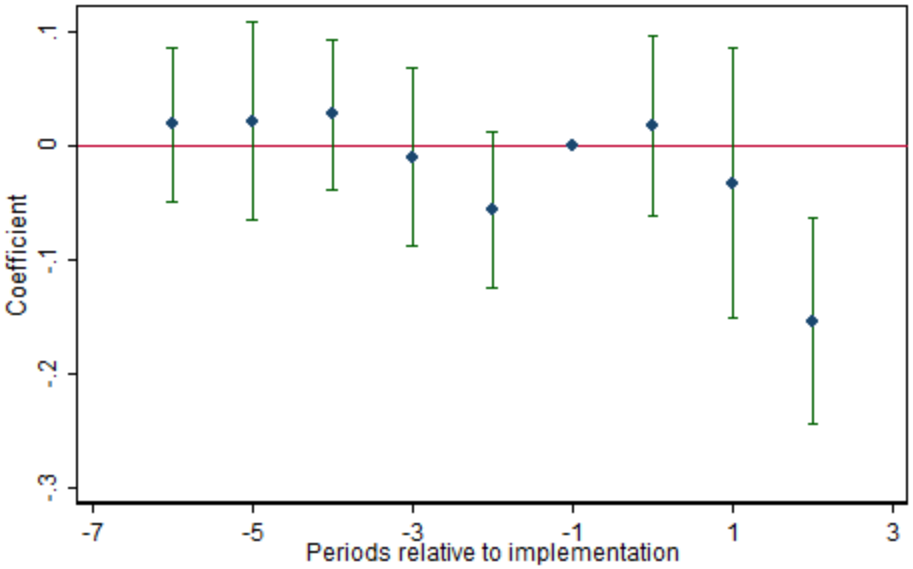


Figure 8B: Event Study Estimates of the Effect of High School Immunization Mandates on Population Disease Incidence



Notes: Sample excludes DC & IN. Coefficients are relative to the excluded period of the year prior to mandate adoption. The coefficients presented for -6 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior. Estimated coefficient for three or more years post implementation is not reported, as it is identified by only one state. Coefficients in Figures A and B are from separate regressions, in which the outcome variable is the rate of meningococcal disease per 100,000 population for 15-24 year olds, or for the total population, respectively. Brackets represent the 95% confidence interval.

Table 1: Age-targeted MCV4 Vaccination Policies Increased MCV4 Vaccination Rates at age 16-17, NIS-Teen (2008-2016)

	(1) Pr (Receive Vaccine Dose, age 16-17)	(2) Pr (Receive Vaccine Dose, age 16-17)	(3) Pr (Receive Vaccine Dose, age 16-17)	(4) 1 dose MCV4, age 16-17	(5) 1 dose MCV4, age 16-17
Post- 2011 ACIP X MCV	0.206***	0.257***	0.202***		
	(0.0179)	(0.0133)	(0.0220)		
High school MCV Mandate				0.190***	0.212***
				(0.0244)	(0.0242)
State and vaccine fixed effects?	Y	Y	Y	N	N
Includes MCVxState Insurance policies?	N	Y	Y	N	N
Vaccine-specific linear trend?	N	N	Y	N	N
State and year fixed effects?	N	N	N	Y	Y
Linear state trends?	N	N	N	N	Y
Observations (unique individuals)	33386	33386	33386	31585	31585
R-squared	0.108	0.112	0.113	0.0945	0.0999
Mean MCV4 vacc. rate	0.247	0.247	0.247	0.244	0.244

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models and use NIS-Teen sampling weights. The sample in all columns is restricted to individuals who were 17 year old at the time of survey, columns 4 and 5 additionally exclude observations from Indiana and DC. The coefficients in columns 1-3 are from the estimation of equation 1, in which the outcome variable is an indicator for whether the individual received a dose of the specified vaccine (either MCV4 or Tdap) at age 16 or 17. These models include vaccine and year fixed effects and include a vector of controls for state policies and disease incidence (state college and high school immunization and education requirements for MCV; state middle school immunization mandates for Tdap and MCV; lagged state pertussis and meningococcal disease incidence) interacted with an indicator variable for the MCV vaccine. Column 2 additionally includes the interaction between state insurance policies (state mandates for insurance coverage of well-child visits and vaccines; state children's Medicaid/CHIP income eligibility thresholds; indicator variable for if the state expanded Medicaid) and the MCV indicator variable, and column 3 adds vaccine specific linear trends. The coefficients in columns 4 and 5 are from the estimation of equation 4; the outcome variable is an indicator for if the individual received a dose of the MCV4 vaccine between ages 16 and 17. In addition to controls for the state immunization policy, disease incidence and insurance variables listed above, models in columns 4 and 5 additionally include controls for individual demographic characteristics (gender, race, number of children in the household, and mother's age, education level, and marital status); state and year fixed effects; state HPV policies (see text for details); state immunization mandates for child care/kindergarten entry; state catch-up vaccination mandates; state pharmacist vaccination authority; state unemployment rates; and state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). Column 5 also includes linear state-specific trends. All standard errors are clustered at the state level.

Table 2: Effects of ACIP Recommendations on Disease Incidence, CDC Data (2001-2016)

	(1) Ln(Meningococcal cases +1), age-group specific *control group:* all other ages	(2) Ln(Meningococcal cases +1) , age-group specific *control group:* all other ages	(3) Ln(Meningococcal cases +1) , age-group specific *control group:* all other ages
Post-2005 ACIP X 5-14 yr olds	-0.306***	-0.300***	-0.427***
	(0.0895)	(0.0904)	(0.121)
Post-2011 ACIP X 15-24 yr olds	-0.175*	-0.151	-0.0712
	(0.0889)	(0.117)	(0.125)
State and age-group fixed effects?	Y	Y	Y
(Age group FE) x Insurance policies?	N	Y	Y
Age group-specific linear trend?	N	N	Y
Observations	4080	4080	4080
R-squared	0.895	0.896	0.899
Mean	1.951	1.951	1.951

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models and are weighted by state age-specific population. The sample in columns 5-8 exclude observations from Indiana and DC. The coefficients in columns 1-4 are from the estimation of equation 3, where the outcome variable and control age group are listed in the column header. Each of these models include age-group and year fixed effects. The coefficients in columns 5-8 are from the estimation of a variant of equation 4. See the notes to Table 1 for more information on the controls included in each model. Standard errors are clustered at the state level.

Table 3: Effects of Meningococcal Vaccination Policies On Disease Incidence, CDC Data (2001-2016)

	(1)	(2)	(3)	(4)
	Meningococcal Incidence Rate, 15-24 year olds	Meningococcal Incidence Rate, 15-24 year olds	Population Meningococcal Incidence Rate	Population Meningococcal Incidence Rate
High-school MCV Mandate	-0.0291	0.00189	-0.0747*	-0.0277
	(0.0805)	(0.145)	(0.0441)	(0.0525)
State and year fixed effects?	Y	Y	Y	Y
Linear state trends?	N	Y	N	Y
Observations	734	734	734	734
R-squared	0.582	0.628	0.825	0.850
Mean	0.436	0.436	0.314	0.314

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models and are weighted by state age-specific population. The sample in columns 5-8 exclude observations from Indiana and DC. The coefficients are from the estimation of a variant of equation 4. See the notes to Table 1 for more information on the controls included in each model. Standard errors are clustered at the state level.

Table 4: Heterogeneous Effects of Vaccination Policies on Receipt of MCV4

	Effect of the 2011 ACIP Recommendations			Effect of High School Booster Mandates		
		(1)	(2)		(3)	(4)
	Pre-2011 mean MCV4 vacc. rate	1 Dose, Age 16-17	1 Dose, Age 16-17	Pre-Mandate mean MCV4 vacc rate	1 Dose MCV4, Age 16-17	1 Dose MCV4, Age 16-17
Sub-group						
Females	0.165	0.203***	0.220***	0.243	0.225***	0.279***
		(0.0189)	(0.0203)		(0.0384)	(0.0624)
Males	0.152	0.209***	0.187***	0.229	0.157***	0.151***
		(0.0193)	(0.0330)		(0.0369)	(0.0480)
Mom ed: ≤HS	0.148	0.190***	0.191***	0.217	0.0945***	0.0946**
		(0.0225)	(0.0294)		(0.0333)	(0.0407)
Mom ed: Any College	0.163	0.214***	0.198***	0.248	0.251***	0.299***
		(0.0209)	(0.0228)		(0.0294)	(0.0263)
Inc: <$40k	0.141	0.173***	0.168***	0.220	0.134***	0.111**
		(0.0228)	(0.0382)		(0.0357)	(0.0430)
Inc: $40-75k	0.158	0.190***	0.176***	0.215	0.257***	0.289***
		(0.0223)	(0.0350)		(0.0825)	(0.0903)
Inc: +$75k	0.169	0.245***	0.248***	0.260	0.242***	0.323***
		(0.0238)	(0.0345)		(0.0392)	(0.0436)
Linear trends?		No	Yes		No	Yes

* significant at 10%; ** significant at 5%; *** significant at 1%. Each estimate is from a separate regression. In columns 1 and 2 the reported estimate is the coefficient on the interaction term POST-2011XMCV; in columns 3 and 4 reported estimates are the coefficient on the indicator variable for if a state has an effective high school MCV4 booster mandate. Specifications in columns 1 and 2 include vaccine and year fixed effects, estimates in column 2 are from the fully saturated model that additionally include vaccine-specific linear trends and the interaction between state insurance policies and the MCV indicator. Specifications in columns 3 and 4 include year and state fixed effects; column 4 estimates additionally include state-specific linear trends. The sample in columns 3 and 4 also exclude observations from DC and Indiana.

Table 5: Effects of the Mandate on Contact with Health Care Provider and Health Outcomes, NIS-Teen 2008-2016

	(1) Check-up, Age 16-17	(2) Check-up, Age 16-17	(3) Flu vaccine, past 3 years	(4) Flu vaccine, past 3 years	(5) Ever diagnosed with group of conditions	(6) Ever diagnosed with group of conditions	(7) Ever diagnosed with asthma	(8) Ever diagnosed with asthma
MCV Booster Mandate	0.0686***	0.0624***	-0.00630	-0.0254	0.00565	-0.0215	-0.0482	-0.0746
	(0.0252)	(0.0196)	(0.0186)	(0.0261)	(0.0119)	(0.0227)	(0.0378)	(0.0538)
N	30968	30968	31585	31585	31553	31553	31543	31543
R-squared	0.0435	0.0477	0.0866	0.0881	0.0114	0.0142	0.0187	0.0212
Mean	0.840	0.840	0.337	0.337	0.0756	0.0756	0.202	0.202
Linear state trends?	N	Y	N	Y	N	Y	N	Y
	(9) HPV dose, Age 16-17	(10) HPV dose, Age 16-17	(11) Initiated the HPV series, by age 17	(12) Initiated the HPV series, by age 17	(13) Completed the HPV series, by age 17	(14) Completed the HPV series, by age 17	(15) TD-containing vaccine, age 16-17	(16) TD-containing vaccine, age 16-17
MCV Booster Mandate	0.0471***	0.00948	0.0144	-0.00827	0.0332	0.0553*	0.0536**	0.0379**
	(0.0166)	(0.0174)	(0.0175)	(0.0187)	(0.0321)	(0.0307)	(0.0236)	(0.0174)
N	31585	31585	31585	31585	31585	31585	31585	31585
R-squared	0.0431	0.0466	0.275	0.277	0.213	0.215	0.0590	0.0674
Mean	0.186	0.186	0.409	0.409	0.268	0.268	0.105	0.105
Linear state trends?	N	Y	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. See notes to Table 1 for details on the specification and control variables. All samples exclude Indiana and DC.

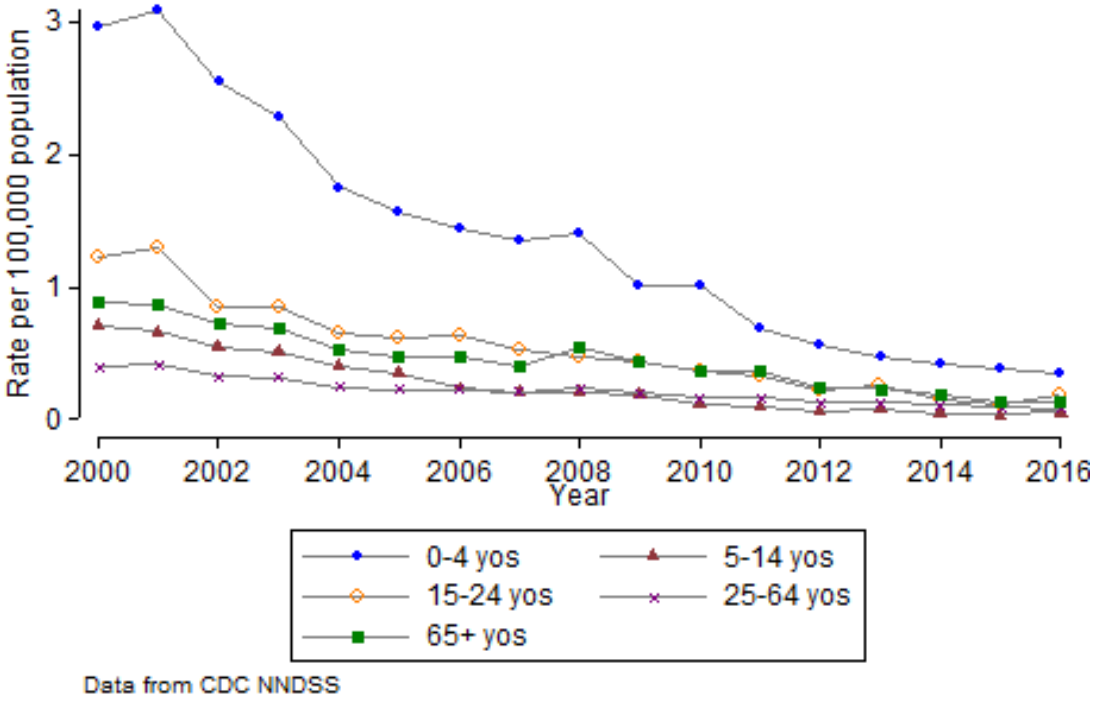
Table 6: Effects of the Mandate on Google Search Behavior, Google Trends 2005-2016

	(1) Relative Google search popularity for 'Meningococcal'	(2) Relative Google search popularity for 'Meningococcal'	(3) Relative Google search popularity of the 'Meningococcal vaccine' topic	(4) Relative Google search popularity of the 'Meningococcal vaccine' topic	(5) Relative Google search popularity for 'Meningitis'	(6) Relative Google search popularity for 'Meningitis'	(7) Relative Google search popularity for 'Meningitis vaccine'	(8) Relative Google search popularity for 'Meningitis vaccine'
MCV booster Mandate	7.949***	11.43***	12.35***	10.29***	1.623*	2.467**	9.565***	10.93***
	(2.883)	(2.504)	(4.178)	(3.296)	(0.821)	(1.067)	(3.366)	(2.714)
Meningococcal rate	4.199	2.031	-0.132	-3.624	6.297***	6.454***	5.089	3.714
	(2.849)	(2.953)	(3.965)	(4.178)	(1.486)	(1.722)	(4.212)	(4.203)
N	7488	7488	6992	6992	7644	7644	6552	6552
R-squared	0.323	0.332	0.535	0.561	0.573	0.581	0.332	0.349
Mean	16.99	16.99	26.78	26.78	21.86	21.86	16.92	16.92
Linear state trends?	N	Y	N	Y	N	Y	N	Y

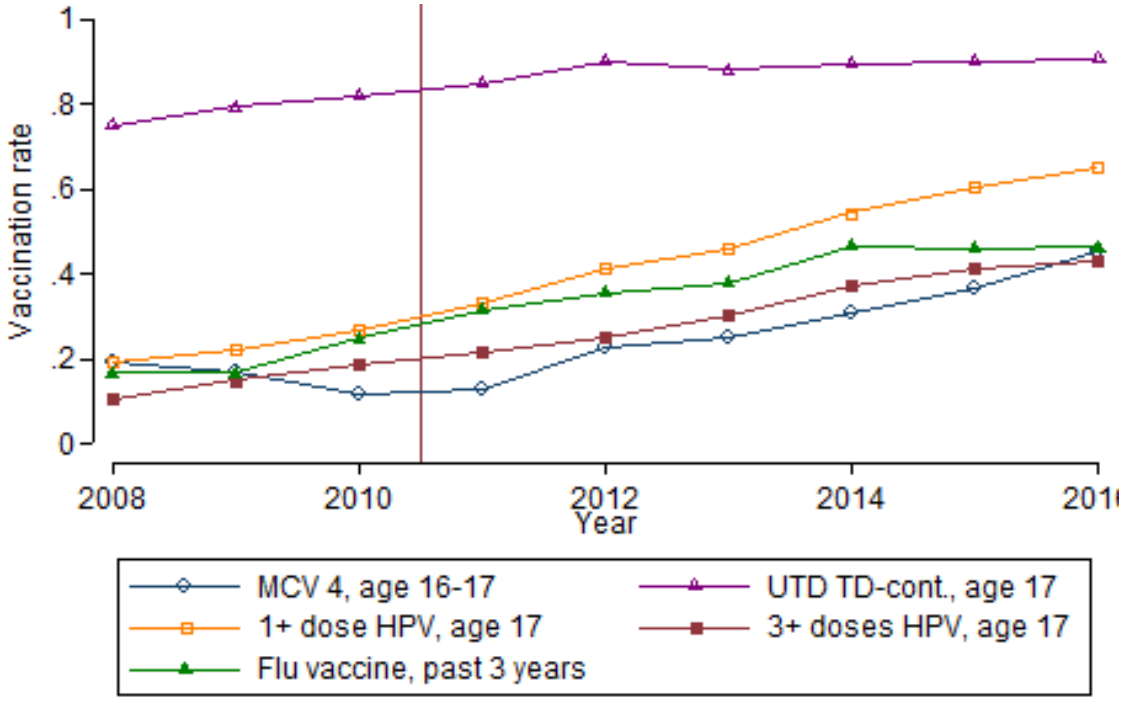
* significant at 10%; ** significant at 5%; *** significant at 1%. The outcome variable is a measure of the popularity of a given search term or topic, in which, for each state, the month of peak search volume is normalized to 100. Samples exclude Indiana and DC. All models include the state policy controls and state demographics as described in the notes to Table 1 as well as fixed effects for each state and for each month-year. Columns 2, 4, and 6 also include linear state trends.

3.9. Appendix

Appendix Figure 1: Trends in Meningococcal Disease Incidence Rate, by Age Group



Appendix Figure 2: National Trends in Receipt of Adolescent Vaccines



Notes: Data are from NIS-Teen, means are calculated using NIS-Teen provider weights.

Appendix Table 1: Descriptive Statistics, NIS-Teen 2008-2016

	(1) Full sample	(2) Pre-ACIP Recommendation (2008-2010)	(3) Post-ACIP Recommendation (2011-2016)	(4) Individuals in states w/ booster mandate by 2016	(5) Individuals in states w/o booster mandate by 2016
Dose of MCV4, age 16-17	0.244	0.160	0.288	0.240	0.245
Dose of Tdap vaccine, age 16-17	0.105	0.169	0.071	0.112	0.104
Dose of HPV vaccine, age 16-17	0.186	0.157	0.201	0.188	0.185
Influenza vaccine (past 3 years)	0.337	0.196	0.411	0.312	0.342
Child's characteristics					
Female	0.486	0.491	0.483	0.485	0.486
Hispanic	0.195	0.163	0.212	0.130	0.209
White	0.581	0.620	0.561	0.639	0.569
Black	0.142	0.147	0.139	0.154	0.139
Other ethnicity	0.082	0.069	0.088	0.077	0.083
Preventive care visit, age 16 or 17	0.840	0.817	0.852	0.882	0.831
Mother's characteristics					
Less than high school	0.126	0.124	0.126	0.117	0.128
High school	0.255	0.283	0.241	0.281	0.250
Some college	0.264	0.53	0.270	0.248	0.267
College degree or above	0.355	0.340	0.363	0.354	0.355
Married	0.684	0.746	0.651	0.667	0.687
Age: <35 yrs	0.036	0.027	0.041	0.027	0.038
Age: 35-44 yrs	0.396	0.409	0.389	0.391	0.398
Age: 45+ yrs	0.568	0.564	0.569	0.582	0.564
Morbidity Rates per 100,000 pop.					
Meningococcal, population rate	0.216	0.424	0.160	0.310	0.316
Meningococcal, age 15-24 rate	0.436	0.593	0.207	0.390	0.446
Observations	31,585	10,069	21,516	5,519	26,066

Notes: All values are weighted means calculated by the authors from NIS-Teen 2008-2016 data, using provided sample weights. For morbidity rates, the sample in column (2) is 2001-2010. Means exclude Indiana and D.C.

Appendix Table 2: Heterogeneous Spillover Effects of MCV4 High School Booster Mandates

	Preventive Care Check-Up			Receipt of HPV Vaccine			Receipt of TD-cont. vaccine		
		(1)	(2)		(3)	(4)		(5)	(6)
	pre-mandate mean	Check-up, Age 16-17	Check-up, Age 16-17	UTD, pre-mandate mean	1 dose, Age 16-17	1 dose, Age 16-17	UTD, pre-mandate mean	1 Dose, Age 16-17	1 Dose, Age 16-17
Sub-group									
Females	0.858	0.0576**	0.0614**	0.426	0.0774**	0.0141	0.863	0.0513	0.0453
		(0.0275)	(0.0266)		(0.0308)	(0.0320)		(0.0400)	(0.0358)
Males	0.819	0.0767*	0.0653**	0.109	0.0165	0.00241	0.841	0.0543***	0.0276
		(0.0435)	(0.0280)		(0.0200)	(0.0212)		(0.0159)	(0.0186)
Mom ed: ≤HS	0.806	0.0920**	0.0669*	0.245	0.0829***	0.0108	0.816	0.0845**	0.0552*
		(0.0412)	(0.0385)		(0.0233)	(0.0274)		(0.0325)	(0.0314)
Mom ed: Any College	0.858	0.0488	0.0521**	0.275	0.0250	0.0181	0.874	0.0345	0.0234
		(0.0301)	(0.0210)		(0.0212)	(0.0274)		(0.0232)	(0.0142)
Inc: <$40k	0.809	0.0563	0.0368	0.262	0.128***	0.103*	0.837	0.0856***	0.0468**
		(0.0393)	(0.0484)		(0.0291)	(0.0580)		(0.0231)	(0.0223)
Inc: $40-75k	0.833	0.107**	0.128*	0.227	-0.00114	-0.0344	0.827	0.0700**	0.0889***
		(0.0511)	(0.0639)		(0.0442)	(0.0453)		(0.0309)	(0.0307)
Inc: +$75k	0.870	0.0576	0.0749***	0.296	0.0217	-0.00671	0.882	0.0268	0.0184
		(0.0391)	(0.0263)		(0.0294)	(0.0399)		(0.0306)	(0.0327)
Linear trends?		N	Y		N	Y		N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. Each estimate is from a separate regression, and is the coefficient on indicator variable for if a state has an effective high school MCV4 booster mandate. The outcome variable is as given in the column header. All specifications include year and state fixed effects; specifications in the even numbered columns additionally include state-specific linear trends.

Appendix Table 3: Google Trends 2005-2016

	(1) Relative Google search popularity for 'HPV'	(2) Relative Google search popularity for 'HPV'	(3) Relative Google search popularity of the 'HPV vaccine' topic	(4) Relative Google search popularity of the 'HPV vaccine' topic	(5) Relative Google search popularity for 'tdap'	(6) Relative Google search popularity for 'tdap'
MCV booster Mandate	0.0273	-1.342	1.571	-0.585	-1.080	1.391
	(1.953)	(2.056)	(2.948)	(2.462)	(4.412)	(3.261)
Meningococcal rate	3.143**	0.519	2.554	0.977	-1.412	-6.917
	(1.427)	(1.743)	(3.097)	(3.149)	(3.856)	(4.139)
N	7448	7448	7448	7448	7448	7448
R-squared	0.788	0.803	0.660	0.679	0.778	0.815
Mean	47.72	47.72	25.55	25.55	30.50	30.50
Linear state trends?	N	Y	N	Y	N	Y

* significant at 10%; ** significant at 5%; *** significant at 1%. The outcome variable is a measure of the popularity of a given search term or topic, in which, for each state, the month of peak search volume is normalized to 100. Sample excludes Indiana and DC. All models include the state policy controls and state demographics as described in the notes to Table 1 as well as fixed effects for each state and for each month-year. Columns 2, 4, and 6 also include linear state trends.