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ABSTRACT

We study the direct and spillover effects of state requirements that middle school youths obtain a tetanus, diphtheria, and pertussis (Tdap) booster prior to middle school entry. These mandates increased vaccine take-up by 29 percent and reduced pertussis (whooping cough) incidence in the population by a much larger 53 percent due to herd immunity effects. We also document cross-vaccine spillovers: the mandates increased adolescent vaccination for meningococcal disease and human papillomavirus (which is responsible for 98 percent of cervical cancers) by 8-34 percent, with particularly large effects for children from low SES households.

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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), three doses of human papillomavirus (HPV) vaccine, and an annual influenza vaccine. Of these, only the Tdap booster vaccination rates currently meet their HP2020 target of 80 percent.[1] 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.[2] 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.

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[1] 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 28.1 percent of girls and 6.9 percent of boys had received all three doses of the HPV vaccine by 2012, far below of the HP2020 target of 80 percent.

[2] As of January, 2015, nineteen of those 46 states also require 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.

The primary outcomes we consider are receipt of vaccinations by the age of 13 for Tdap (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 (protected by the Tdap booster) and salmonellosis (which is not vaccine-preventable) in the population and by five-year age groups. These morbidity analyses allow us to disentangle the extent to which population morbidity effects are due to adolescents being directly targeted by vaccine mandates versus herd immunity effects accruing to infants, younger children, adults, and 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.[3] Second, there is substantial latitude for further improvements if the middle school mandates are found to be effective at

[3] 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 the anti-vaccination movement has gained popularity in the United States.

increasing vaccination and reducing morbidity. In addition to the remaining states adopting any vaccination requirements, states with existing requirements could strengthen them (for example by requiring other vaccines in addition to Tdap).

Third, 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.[4]

To preview, we find clear evidence that state laws requiring youths to obtain a Tdap booster prior to middle school entry were extremely 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 13.4-13.6 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, with an effect on population-wide pertussis incidence that is much larger (53 percent reduction) than the effect on vaccination (29 percent increase). Additional analyses using age-specific morbidity data from the CDC confirm that the middle school vaccination requirements significantly reduced pertussis morbidity not only for the age group directly affected (10-14 year olds) but also for nearly all other age groups: infants, younger children, adults, and the elderly. We also show that there are no systematic effects of the middle school vaccination requirements on age-specific morbidity for salmonellosis (which is not vaccine-preventable).

Finally, we find evidence of cross-vaccination spillovers: in the 27 states where the middle school requirement included only the Tdap booster and not the MCV vaccine, we estimate that the Tdap booster requirement increased MCV vaccination rates by 2.1-2.9 percentage points. Even more striking, we find that the Tdap booster requirement significantly increased HPV vaccination initiation

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[4] In fact, one reason why HPV-promoting public policies have been controversial is that some

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 extremely 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-caused cancers in both men and women, especially cervical cancer.

Our paper proceeds as follows: Section I provides institutional background on the mandates and conditions we study, and Section II provides a brief literature review. Section III describes the data and outlines the empirical approach. Section IV presents the results, and Section V discusses and concludes.

I. 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.[5]

A. 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

believe the HPV vaccine promotes sexual promiscuity.

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. 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 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

[5] The Appendix provides more detailed information on each condition we study.

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.

B. 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.[6] Although all states presently mandate the receipt of some vaccines, there is considerable variation in the set required for school attendance in each state

[6] 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.

(Malone and Hinman 2003).[7] As of January 2015, forty-six states have adopted middle school entry requirements for the Tdap booster (Figure 2).

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.[8] Currently the ACIP recommends that 11-12 year olds receive an annual influenza vaccination, one dose of Tdap, three doses of HPV vaccine, and a single dose of quadrivalent meningococcal conjugate vaccine.[9]

C. 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 (10-14 year olds), but we are also interested in two types of spillover

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

[8] 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.

[9] Out-of-pocket cost for this bundle of vaccines is potentially high. Walgreens, for example, currently charges $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,

effects. First, we examine the effects of the reduced disease transmission of the 10-14 year olds on the morbidity rates of younger and older individuals in the state. In medical and public health literatures, this is termed the 'herd immunity' effect or the 'community' effect of the increased vaccinations induced by the state Tdap mandates. 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 if the vaccine mandates cause increased contact with health care providers who 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.[10]

II. 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

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and several states adopted laws requiring private insurance plans in the state to cover the vaccines (see Chang 2016a for evidence on these).

[10] 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.

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, with effect sizes that are too large to reflect actual changes in disease risk. She interprets these findings in a model where perceived disease risk is a function of whether the agents are aware of any cases of the disease. 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).[11]

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 (2016, forthcoming) 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

[11] Numerous subsequent studies have failed to confirm a link between the MMR vaccine and

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.[12]

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

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autism, and the original study that purported the connection was retracted in 2010.

[12] 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 2008-2014 and also

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.

III. Data Description and Empirical Approach

Data on adolescent vaccination come from the 2008-2013 waves of the National Immunization Survey – Teen (NIS-Teen).[13] This survey targets adolescents between 13 and 17 years of age and includes provider-verified immunization histories and basic household sociodemographic characteristics. 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 month and year) 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 disease incidence were obtained directly from the CDC. These data consist of counts of cases of a subset of nationally notifiable diseases

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

by state, year, and five-year age group.[14] 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 salmonellosis (a control condition not protected by any vaccine) from 2002-2013.

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:

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

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

[13] 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 an Appendix table described below.

[14] 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 reported cases and thus represent a substantial undercount of true disease incidence. For

excluded category), maternal education (less than high school, high school, some college, relative to the excluded category of college or above), 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.[15]

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 year olds in year *t-1* or for 11 year olds in year *t-2* in state *s*.[16] This vector captures vaccination mandates for the tetanus, diphtheria, and pertussis booster (Tdap),[17] 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

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example, they do not include cases where the individual did not go to a health care provider or misdiagnosed cases.

[15] 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.

[16] 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.

[17] 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.

additionally recommended annually for 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.[18]

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 '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).[19]

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[18] 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.

[19] 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*).

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;[20] nonmedical exemption policy (Bradford and Mandich 2015);[21] 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 2016, forthcoming); and income eligibility thresholds for the state Medicaid/Children's Health Insurance Program.[22] 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

[20] 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.

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

[22] 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 pharmacists with respect to prescribing authority for the HPV vaccine (Trogdon et al. 2016)

line).[23] In order to best capture the state characteristics that would have feasibly been relevant to the vaccination decisions considered 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, year of survey, and birth cohort fixed effects. In some models we further control for state-specific linear time trends where we interact each state fixed effect with a variable TREND that equals 1 in 2004, 2 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).[24]

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

[23] 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.

[24] 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. We verify that none of the main results is sensitive either to this decision or to the exclusion of weights.

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 100,000 population. 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, all policies are considered in effect at the start of the calendar year following implementation, and we include the state unemployment rate and state-level demographic controls from year *t-1*. These models use age-specific state population weights.

IV. Results

A. 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 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.

B. Direct Effects of Tdap Mandates for Middle School Entry

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 13.4 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.[25] 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 mandates induced large, immediate, and significant increases in Tdap booster take-up, and there is no evidence of systematic trends prior to Tdap

[25] 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). State mandates 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).

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. The estimates in columns 3 and 4 of Table 1 show clear 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 significantly reduced pertussis morbidity by 3.7-4.7 cases per 100,000 population, or by at least 53 percent relative to the sample mean. We additionally present event-study estimates of the effect of the Tdap mandates on population-wide pertussis morbidity in Figure 4 (coefficient estimates are presented in Appendix Table 3).[26] These results demonstrate that the mandate effect on disease incidence was immediate and sustained, and also provide evidence that the mandates were not implemented in response to particularly high rates of disease in the state.

The estimated size of the population-wide pertussis morbidity reduction is striking given that the mandates we study here only directly applied to middle

[26] 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 3).

school age youths. They suggest the presence of large herd immunity effects, which we directly examine in Table 2. Specifically, Table 2 makes use of age-specific morbidity data for two diseases: pertussis and salmonellosis (which is not vaccine-preventable). 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 strong evidence that the middle school vaccination requirements for the Tdap booster were extremely effective at reducing morbidity among the targeted group: 10-14 year olds. We estimate that a Tdap mandate reduced pertussis cases of 10-14 year olds by 16.54 cases per 100,000 population. Perhaps more strikingly, however, the Tdap mandates for middle school entry are also estimated to significantly reduce pertussis morbidity for every other age group, consistent with the possibility of large herd immunity effects induced by the increased vaccination of disease transmitters (adolescents). These reductions are statistically significant for nearly every age group and are insensitive to the inclusion of linear state trends. Moreover, they are large, both absolutely and proportionally. The estimates for 0-4 year olds are nearly as large in absolute terms as the direct reductions for 10-14 year olds whose vaccine behaviors were directly affected, and the effects for the older adults relative to their lower rate of pertussis morbidity are also very large in proportional terms.[27] Large spillover effects to infant pertussis morbidity is not surprising, as infants cannot be vaccinated against pertussis until two months of age, and it takes multiple doses over several months for them to fully develop immunity.

As a robustness/falsification analysis we also estimate the effects of the Tdap mandates on age-specific salmonellosis morbidity, the only other disease for which we were able to obtain age-specific morbidity data at the state/year level from the CDC. Salmonellosis is a relatively common infection caused by salmonella bacteria, and humans are typically infected by eating contaminated food.[28] Symptoms include diarrhea, fever, and abdominal cramps, and the morbidity consequences are most significant for infants and the elderly. Salmonellosis is not vaccine-preventable; thus, if we observed effects of the Tdap booster mandates on salmonellosis morbidity for 10-14 year olds (or for other age

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[27] We show this visually in Appendix Figure 2 which shows the estimated proportional pertussis morbidity reduction attributable to the Tdap mandates (relative to the age-group specific 2005 mean) across the life course. Appendix Figure 2 confirms that the effects of the Tdap mandates for middle school entry were large across all age groups but were particularly effective for babies, young children, 30-39 year olds (who are potentially the parents of the directly targeted adolescents and their siblings), and the elderly.

[28] The mean rate of salmonellosis during our sample period was 12.6 cases per 100,000 population.

groups), this would be suggestive of a model misspecification or an omitted variables problem. We present the estimates of the Tdap mandates on salmonellosis morbidity in columns (3) and (4) of Table 2. The estimates are small and statistically insignificant in all models. Thus, overall we find strong evidence that the Tdap mandates for middle school entry generated large reductions in pertussis morbidity that extended well beyond the directly targeted age group (10-14 year olds).[29]

C. 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, nearly 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

[29] The cross-age morbidity spillovers documented in Table 2 might not be herd immunity effects of there were cross-age *behavioral* spillovers to increased vaccination rates of non-targeted age groups. We tested this possibility directly in Appendix Table 4 using 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. This suggests that the vast majority of the 53 percent reduction in population-wide pertussis morbidity is driven by the 29

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.[30] 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 2.1-2.9 percentage points, and these estimates are statistically significant in models with linear state trends.[31] The Tdap mandate effect in these models is identified from the 27 states that adopted Tdap requirements but *not* MCV requirements, as well as from the small number

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percent increase in Tdap booster vaccination rates of 11-12 year olds (i.e. due directly to the reduced transmission of the directly targeted 10-14 year olds).

[30] 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.

[31] In results not reported but available upon request, we also found a large direct effect of MCV mandates on take-up of the MCV vaccine. This effect was similar in magnitude to the direct take-up effect for the Tdap booster mandates.

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). 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 highly 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, and these estimates are not sensitive to inclusion of state trends.[32] 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

[32] Appendix Table 5 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 6 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 7 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 8 shows that the spillover effects to MCV and HPV are largely driven by years in which the

the start of the school year – the same is not true for seasonal influenza. Typically seasonal flu vaccines become available in 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.[33]

D. 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

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.

[33] 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.

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 gradient could reflect that the children with lower educated mothers have a lower vaccination rate in the absence of the mandate and thus have further to go to achieve compliance.[34]

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

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[34] 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.

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.[35] Finally, it could be an income effect: if 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.

E. Mechanisms

Our final sets of analyses attempt to disentangle mechanisms for the cross-vaccination spillovers observed in Tables 3 and 4. We think of the possible mechanisms in two broad categories: patient (here, parent) behavior versus

[35] In results not reported but available upon request, we additionally considered heterogeneity in mandate effects by type of provider; 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.

provider behavior. 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 of the Tdap mandates on these last two outcomes – receipt of a physician recommendations 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). 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.[36]

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. 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

[36] 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.

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.[37]

V. Discussion and Conclusion

We provide a variety of analyses showing that state mandates requiring Tdap vaccination prior to middle school entry were extremely effective at significantly increasing Tdap vaccine uptake between the age of 10 and 12 by 13.4-13.6 percentage points, or by about 29 percent of the sample mean. Event study analyses show that there are not systematic pre-trends in vaccination outcomes prior to mandate adoption and that the direct vaccination effects of the mandates occur immediately. Similarly specified models of population-wide morbidity show even larger effects of Tdap mandates on whooping cough: we estimate a reduction on the order of 53 percent. Disaggregated pertussis morbidity data by five year age group confirm that the Tdap mandates for middle school entry substantially reduced pertussis rates among 10-14 year olds (whose vaccination rates were directly affected) but also induced extremely large

[37] We also note that the fact we find any effect of state Tdap mandates on completion of the HPV vaccine series – which requires 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 (2016, forthcoming)

reductions in pertussis morbidity for infants, younger children, older children, young adults, adults, and the elderly. These effects occurred due to herd immunity, or the reduced transmission attributable to 10-14 year olds.

We also find clear evidence of cross-vaccination spillovers: state requirements that middle school youths obtain the Tdap booster resulted in sizable and statistically significant increases in MCV vaccination even in 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 parent 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 suggest that they reduced population-wide pertussis cases by 3.3 per 100,000 population. This translates to approximately 10,500 fewer cases of whooping cough that were avoided each year due to increased vaccination of 10-

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who finds in the context of a different vaccine (hepatitis A) that vaccination recommendations are

12 year olds (320 million people in the US * 3.3/100,000 cases). For children, this means reduced days missed from school; for parents, it translates to reduced days missed from work (both to care for sick kids and due to reduced adult illness as documented in Table 2). Lost work days due to illness at childcare centers and schools likely fell by much larger amounts. There are also the direct health consequences of pertussis: a study of hospital discharge databases in four states found that the mean length of stay for infants (who constitute 90% of all pertussis cases) was 6 days at a cost of $9,586 per stay (O'Brien and Caro 2005). Average costs for children and adolescents/adults were $4,729 and $5,683 per hospitalization, respectively. In less than one percent of cases, pertussis will result in death.

Our spillover estimates, however, suggest even larger returns, particularly for HPV. 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 all 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

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effective at inducing initiation but not completion of a vaccine series in young children.

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.[38]

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 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 for 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.

[38] 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).

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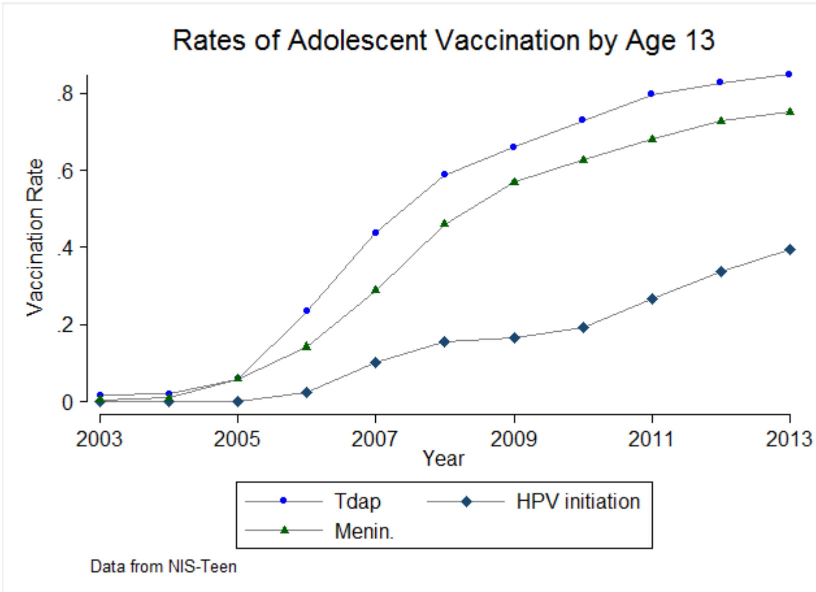
Figure 1:
Trends in Adolescent Vaccination Rates for ACIP-Recommended Vaccines



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:
Timing of Tdap Mandate Policy Adoption

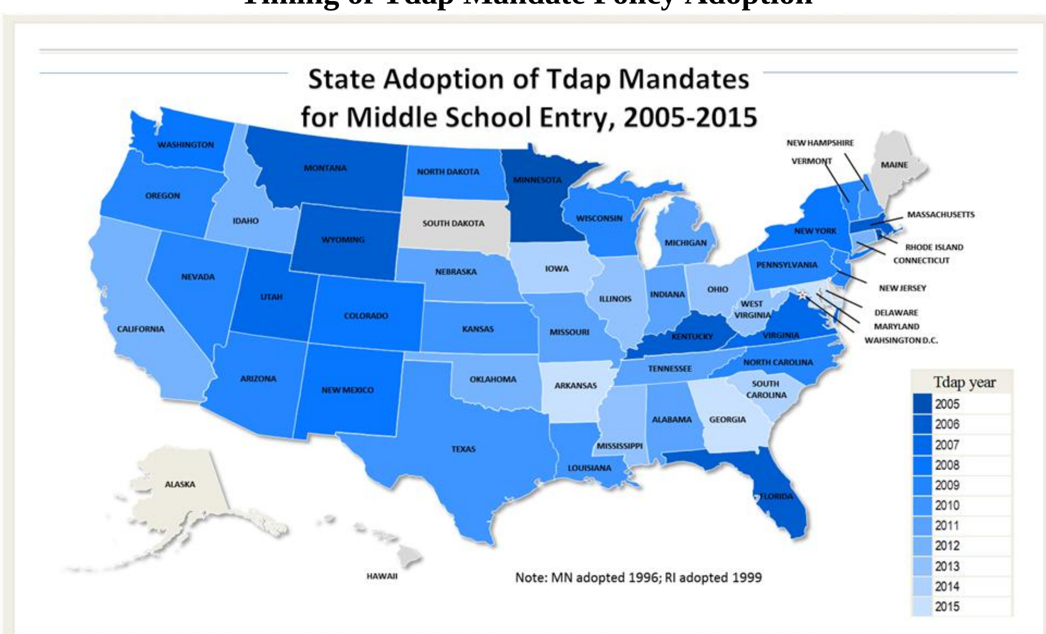
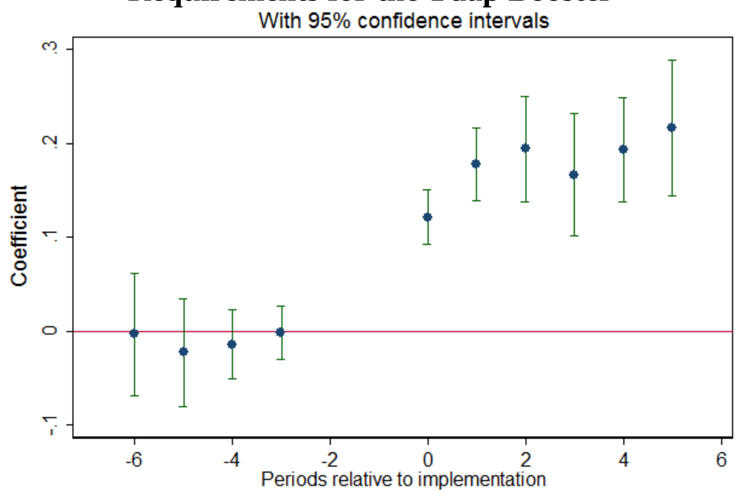
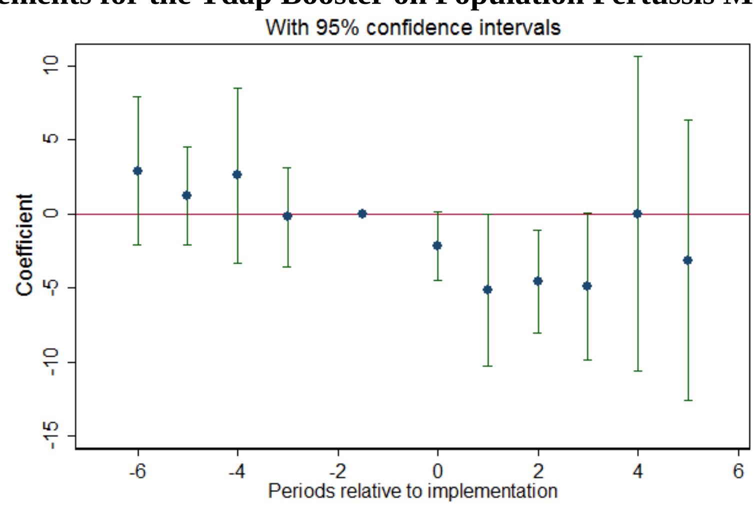


Figure 3:
Event Study Estimates of the Direct Effects of Middle School Vaccination Requirements for the Tdap Booster



Notes: Coefficients are relative to the excluded group of the two years 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 4:
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 two years 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-Wide* Pertussis Morbidity
NIS-Teen (2008-2013) and CDC Data (2002-2013)

	(1) 1 dose Tdap booster	(2) 1 dose Tdap booster	(3) Pertussis morbidity	(4) Pertussis morbidity
Sample mean	0.449	0.449	6.955	6.955
Tdap Mandate for Middle School Entry	0.134***	0.136***	-3.720**	-4.705**
	(0.015)	(0.017)	(1.749)	(1.910)
R-squared	0.335	0.338	0.458	0.534
N	116304	116304	611	611
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%. Sample means are calculated over the full period. 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 Across the Life Course, CDC Data 2002-2013
Each entry is the coefficient on the Tdap mandate

	(1) Pertussis morbidity	(2) Pertussis morbidity	(3) Salmonellosis morbidity	(4) Salmonellosis morbidity
Direct effect:				
Age 10-14	-16.54 (7.423)**	-20.82 (8.598)**	0.050 (0.684)	0.434 (0.757)
Herd immunity effects:				
Age 0-4	-14.91 (6.666)**	-17.65 (7.299)**	-6.061 (4.467)	-3.044 (4.429)
Age 5-9	-10.24 (4.307)**	-13.08 (4.938)**	-0.350 (1.047)	0.496 (1.218)
Age 15-19	-5.326 (3.028)*	-6.484 (2.788)**	-0.041 (0.625)	0.381 (0.638)
Age 20-24	-1.207 (0.615)*	-1.419 (0.585)**	-0.076 (0.609)	0.257 (0.717)
Age 25-29	-1.197 (0.554)**	-1.394 (0.541)**	0.619 (0.554)	0.320 (0.751)
Age 30-34	-1.346 (0.619)**	-1.751 (0.678)**	0.363 (0.726)	0.204 (0.957)
Age 35-39	-1.428 (0.666)**	-1.881 (0.755)**	-0.169 (0.562)	-0.398 (0.642)
Age 40-44	-1.151 (0.715)	-1.285 (0.752)*	-0.138 (0.615)	-0.168 (0.745)
Age 45-49	-1.082 (0.614)*	-1.194 (0.613)*	0.213 (0.860)	0.480 (1.057)
Age 50-54	-0.970 (0.506)*	-1.270 (0.526)**	-0.125 (0.649)	-0.041 (0.780)
Age 55-59	-0.727 (0.458)	-1.067 (0.476)**	-0.320 (0.806)	-0.125 (0.971)
Age 60-64	-0.703 (0.361)*	-0.917 (0.393)**	-0.165 (0.873)	0.043 (0.991)
Age 65+	-0.524 (0.291)*	-0.759 (0.356)**	-0.956 (0.868)	-0.511(0.958)
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 for five year age groups (reported in each row). Each entry is from a separate regression. 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	0.099	0.099	0.122	0.122
Tdap Mandate for Middle School Entry	0.0214	0.0285*	0.0489***	0.0419***	0.0248***	0.0334***	0.0130	0.0075
	(0.0157)	(0.0143)	(0.0150)	(0.0153)	(0.0089)	(0.0106)	(0.0081)	(0.0066)
R-squared	0.285	0.289	0.111	0.114	0.065	0.067	0.176	0.178
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
Each entry is the coefficient on the Tdap mandate

	(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:	0.136 (0.017)***	0.029 (0.014)*	0.042 (0.015)***	0.033 (0.011)***
2. Girls, mean	0.448	0.355	0.265	0.117
Tdap mandate effect:	0.152 (0.018)***	0.039 (0.019)**	0.035 (0.015)**	0.037 (0.013)***
3. Boys, mean	0.449	0.358	0.123	0.028
Tdap mandate effect:	0.121 (0.018)***	0.018 (0.013)	-0.061 (0.048)	0.032 (0.052)
4. White, mean	0.453	0.343	0.205	0.095
Tdap mandate effect:	0.148 (0.019)***	0.037 (0.018)**	0.044 (0.017)**	0.034 (0.011)***
5. Black, mean	0.412	0.347	0.238	0.078
Tdap mandate effect:	0.152 (0.041)***	0.075 (0.024)***	0.046 (0.034)	0.061 (0.023)**
6. Hispanic, mean	0.456	0.389	0.303	0.118
Tdap mandate effect:	0.129 (0.016)***	0.032 (0.020)	0.102 (0.037)***	0.048 (0.019)**
7. Mother has at least BA, mean	0.509	0.403	0.206	0.094
Tdap mandate effect:	0.110 (0.021)***	0.005 (0.020)	0.029 (0.019)	0.032 (0.011)***
8. Mother has less than BA, mean	0.418	0.333	0.252	0.101
Tdap mandate effect:	0.149 (0.019)***	0.039 (0.014)***	0.048 (0.017)***	0.035 (0.014)**

* 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)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ever heard of HPV	Ever heard of HPV	Ever heard of cervical cancer vaccine, genital warts vaccine, HPV shot, Gardasil, or Cervarix	Ever heard of cervical cancer vaccine, genital warts vaccine, HPV shot, Gardasil, or Cervarix	Doctor recom-mended HPV vaccine	Doctor recom-mended HPV vaccine	Had an 11-12yo well child visit	Had an 11-12yo well child visit
Sample mean:	0.939	0.939	0.904	0.904	0.454	0.454	0.909	0.909
Tdap Mandate for Middle School Entry	-0.0084	0.0234	0.0247*	0.0390	0.0228	0.0053	0.0232**	0.0413***
	(0.0148)	(0.0187)	(0.0131)	(0.0244)	(0.0158)	(0.0341)	(0.00919)	(0.0132)
R-squared	0.0646	0.0734	0.0997	0.106	0.0997	0.104	0.0374	0.0404
N	12063	12063	12063	12063	27100	27100	37788	37788
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 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 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 2005-2014

	(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	27.46	27.46	27.84	27.84	49.76	49.76
Tdap Mandate for Middle School Entry	3.585**	6.733***	2.016	3.318**	2.011**	1.449**
	(1.609)	(1.374)	(1.739)	(1.566)	(0.877)	(0.691)
Pertussis rate in the state	0.126*	0.214**	0.0032	0.0136	-0.0320	-0.0310
	(0.0670)	(0.0862)	(0.0254)	(0.0254)	(0.0245)	(0.0272)
R-squared	0.661	0.731	0.614	0.656	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

APPENDIX
FOR ONLINE PUBLICATION ONLY

This Appendix describes in greater detail the diseases under study.

1.1 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.[39]

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.[40] 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.

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[39] 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.

[40] 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 $\leq$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.

Pertussis is a highly contagious respiratory disease,[41] 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.

1.2 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.[42] 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.[43]

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[41] 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).

[42] 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.

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

Older teens are recommended to receive a second booster shot of MCV4 when they are 16 years old.

1.3 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.[44] In the United States, rates of cervical cancer incidence and mortality are substantially higher among blacks and Hispanics (American Cancer Society 2015).[45]

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,

[44] 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).

[45] 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

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).

1.4 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.

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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.

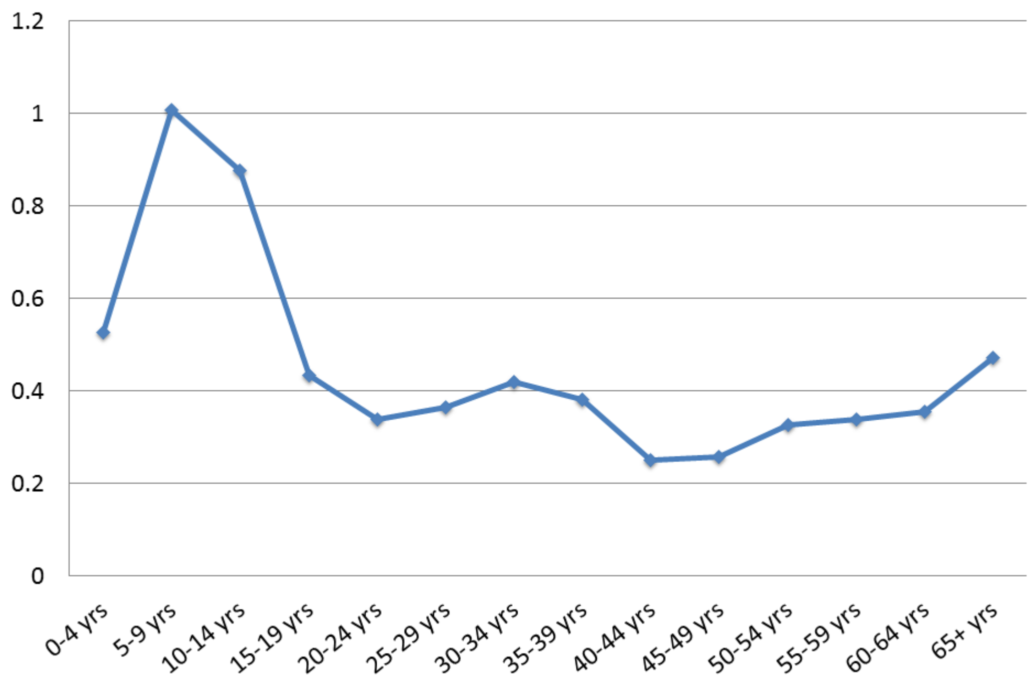
9. Are there any other vaccines that are recommended for my adolescent?

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:
Estimated Effect Sizes of Direct and Herd Immunity Effects of Tdap Mandates on Pertussis Incidence Across the Life Course (relative to 2005)



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 2005. 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) 1 dose Tdap booster	(1) 1 dose Tdap booster
Sample mean	0.449	0.449
6+ years before Tdap mandate	-0.003 (0.032)	-0.063 (0.058)
5 years before Tdap mandate	-0.022 (0.029)	-0.061 (0.047)
4 years before Tdap mandate	-0.014 (0.018)	-0.049 (0.033)
3 years before Tdap mandate	-0.002 (0.014)	-0.026 (0.023)
Year of Tdap mandate	0.122 (0.014)***	0.127 (0.018)***
1 year after Tdap mandate	0.178 (0.019)***	0.191 (0.038)***
2 years after Tdap mandate	0.194 (0.028)***	0.217 (0.066)***
3 years after Tdap mandate	0.166 (0.032)***	0.191 (0.075)**
4 years after Tdap mandate	0.193 (0.028)***	0.208 (0.104)**
5+ years after Tdap mandate	0.216 (0.036)***	0.201 (0.163)
N	116304	116304
R-Squared	0.336	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:
Event Study Estimates of the Direct Effect of Middle School Vaccination Requirements, CDC Data 2002-2013**

	(1) Pertussis Morbidity	(2) Pertussis Morbidity
Sample mean	6.955	6.955
6+ years before Tdap mandate	2.886 (2.477)	1.284 (3.989)
5 years before Tdap mandate	1.192 (1.642)	1.383 (2.922)
4 years before Tdap mandate	2.600 (2.943)	3.122 (2.665)
3 years before Tdap mandate	-0.227 (1.650)	0.347 (1.783)
Year of Tdap mandate	-2.174 (1.140)*	-1.871 (1.491)
1 year after Tdap mandate	-5.106 (2.545)*	-5.671 (2.982)*
2 years after Tdap mandate	-4.566 (1.726)**	-4.969 (2.806)*
3 years after Tdap mandate	-4.894 (2.456)*	-6.226 (4.048)
4 years after Tdap mandate	-0.013 (5.285)	-0.187 (7.113)
5+ years after Tdap mandate	-3.120 (4.697)	-2.704 (7.822)
N	611	611
R-Squared	0.481	0.554
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 4:
Cross-Age Morbidity Effects Were Disease-Related, Not Vaccination-Related
(i.e., Herd Immunity Effects, not Behavioral Spillover Effects)
NIS 2003-2015, 19-35 month olds

	(1)	(2)	(3)
	Up-to-date, 4 doses of DTaP	Up-to-date, 4 doses of DTaP other children in HH	Up-to-date, 4 doses of DTaP, no other children in HH
Sample mean:	0.846	0.834	0.882
Tdap Mandate for Middle School Entry	-0.0088	-0.0071	-0.0131
	(0.0055)	(0.0069)	(0.0084)
R-squared	0.0419	0.0444	0.0288
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 5:
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	0.099	0.099
Years relative to Tdap mandate:						
6+ years before	-0.060 (0.028)**	-0.071 (0.038)*	-0.035 (0.035)	0.069 (0.063)	0.003 (0.021)	0.051 (0.045)
5 years before	-0.037 (0.023)	-0.043 (0.029)	-0.046 (0.026)*	0.051 (0.043)	-0.020 (0.015)	0.035 (0.033)
4 years before	-0.055 (0.019)***	-0.067 (0.026)***	-0.044 (0.019)**	0.013 (0.027)	-0.016 (0.016)	0.017 (0.027)
3 years before	-0.009 (0.015)	-0.022 (0.015)	-0.025 (0.013)*	-0.009 (0.019)	-0.018 (0.008)**	-0.008 (0.013)
Year of	0.026 (0.018)	0.032 (0.018)*	0.040 (0.015)**	0.039 (0.017)**	0.024 (0.014)*	0.027 (0.015)*
1 year after	0.067 (0.019)***	0.084 (0.024)***	0.056 (0.025)**	0.058 (0.035)	0.020 (0.012)	0.016 (0.017)
2 years after	0.074 (0.022)***	0.098 (0.038)**	0.044 (0.023)*	0.070 (0.045)	0.026 (0.015)*	0.028 (0.024)
3 years after	0.056 (0.032)*	0.097 (0.051)*	0.040 (0.035)	0.077 (0.063)	0.020 (0.019)	0.016 (0.029)
4 years after	0.103 (0.034)***	0.139 (0.057)**	0.056 (0.038)	0.115 (0.077)	0.024 (0.026)	0.022 (0.038)
5+ years after	0.099 (0.043)**	0.119 (0.080)	-0.007 (0.053)	0.091 (0.109)	0.008 (0.037)	0.008 (0.045)
N	116304	116304	57133	57133	57133	57133
R-Squared	0.287	0.289	0.112	0.114	0.066	0.068
Linear state 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.

Appendix Table 6:
Other Ways to Measure Cross-Vaccine Spillover Effects of Tdap Mandates: Combinations of Outcomes, NIS-Teen 2008-2013

	(1) Had 1 dose Tdap AND 1 dose MCV	(2) Had 1 dose Tdap AND Initiated HPV vaccine	(3) Had 1 dose Tdap AND Completed HPV vaccine	(4) Had 1 dose Tdap AND 1 dose MCV AND Initiated HPV vaccine	(5) Had 1 dose Tdap AND 1 dose MCV AND Completed HPV vaccine
Sample mean	0.303	0.170	0.076	0.150	0.068
Tdap Mandate for Middle School Entry	0.0454***	0.0459***	0.0506***	0.0490***	0.0462***
	(0.0122)	(0.0163)	(0.0161)	(0.0146)	(0.0134)
R-squared	0.297	0.161	0.081	0.145	0.074
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 7:
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
Tdap Mandate for Middle School Entry	0.136***	0.154***	0.0326**	0.0365**	0.0331***	0.0157	0.0181***	0.0152**
	(0.0142)	(0.0155)	(0.0136)	(0.0147)	(0.0120)	(0.0130)	(0.0052)	(0.0073)
R-squared	0.339	0.342	0.300	0.302	0.117	0.118	0.060	0.062
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 8:
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
Tdap Mandate for Middle School Entry	-0.0525* (0.0313)	0.00230 (0.0264)	0.0204 (0.0141)	0.0053 (0.0067)
Tdap Mandate ✕ ACIP recommendation for MCV	0.0807*** (0.0249)			
Tdap Mandate ✕ ACIP recommendation for HPV		0.0469** (0.0197)	0.0154 (0.0117)	
Tdap Mandate ✕ ACIP recommendation for Flu				0.0250* (0.0136)
R-squared	0.289	0.114	0.067	0.178
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.