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Giving Teens a Boost? Effects of Adolescent Meningococcal Vaccine Recommendations

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This study provides the first quasi-experimental evidence on the effects of non-binding vaccine recommendations targeted at high school-aged adolescents. Using data from the National Immunization Survey-Teen and the CDC's disease surveillance system, I find that these simple recommendations significantly increased meningococcal vaccination rates among the targeted population by 21 percentage points, or 133% relative to the baseline mean, and substantially reduced meningococcal disease incidence in the population. I also provide evidence that the recommendations primarily affected vaccination rates through changes in provider behavior, and show that they exacerbated pre-existing disparities in receipt of preventive care. In particular, lower SES groups, which had lower rates of vaccination and provider contact prior to the recommendation, were also less responsive to the policy.

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Increased availability and utilization of vaccines is often considered to be one of the key reasons why the United States has experienced dramatic reductions in disease incidence in the past century (CDC 1999). Historically, immunization programs have primarily targeted young children, as they are a particularly vulnerable population and have typically faced the highest burdens of morbidity and mortality from vaccine-preventable diseases, and immunization rates among this age group now typically exceed 90 percent. Only within the past couple of decades have adolescents also become part of the focus of immunization programs, since a number of new vaccines have been developed which are targeted towards this older age group.[1] Uptake of vaccines among adolescents, however, has increased relatively slowly, and in general their immunization rates remain persistently low.

Adolescents are considered to be a particularly challenging group to vaccinate, given their low rates of attachment to the healthcare system and the fact that they typically see providers only for acute care or sports physicals (Humiston and Rosenthal 2005). Recently, in an attempt to overcome potential barriers to adolescent vaccination, a broad set of national and state policies have been implemented; as of January 2019, nearly all states have an adolescent immunization policy of some form in effect. In spite of the growing number of immunization policies targeted towards adolescents, however, very little is known about their effectiveness.

In this paper I analyze one the most widely implemented vaccination policies, non-binding national vaccination recommendations, and provide the first evidence on their effects when they are targeted at high school-aged adolescents. These recommendations are issued by the Advisory Committee on Immunization Practices (ACIP) and form the basis for the

[1] For example, in 2004 only one vaccine, the tetanus and diphtheria (Td) vaccine, was recommended by the CDC for children over the age of 6. As of this writing, there are 5 separate vaccines recommended for receipt between the ages of 11 and 18.

recommended vaccination schedule in the United States. Prior work on the effects of such recommendations has focused on recommendations targeted towards very young children (Lawler 2017). For a number of reasons, discussed in more detail below, we may expect the effects of those recommendations to differ from the effects of recommendations that are targeted towards adolescents.

Specifically, I examine the 2011 ACIP recommendation that 16-year-olds receive a booster dose of the quadrivalent meningococcal conjugate vaccine (referred to as MenACWY or MCV4). This vaccine was originally approved for use in the United States in 2005, and provides protection against four serogroups (strains) of meningococcal disease. Meningococcal disease is a severe and deadly disease with high rates of mortality (10 to 15 percent of cases) and long-term disability (approximately 20 percent of cases); vaccination is targeted towards adolescents due to a peak in incidence among 16- to 21-year-olds (CDC 2011b).

In my analyses I first estimate the effects of the MCV4 booster recommendation on vaccination rates among the targeted age group (16- to 17-year-olds) and on meningococcal disease incidence. My results show that this policy significantly increased uptake of the vaccine, thus broadly demonstrating that adolescents (and their parents) are responsive to simple non-binding recommendations for preventive care. I also find resulting reductions in meningococcal disease incidence. Given the severity of meningococcal disease, these morbidity reductions translate into substantial reductions in lives lost and rates of permanent disability. Importantly, back-of-the-envelope calculations demonstrate that for the MCV4 vaccine this policy generates substantial social benefits: I estimate that every dollar spent on additional vaccine doses (and associated administration costs) generated more than two dollars in social savings.

Additionally, I provide new evidence on the mechanisms through which ACIP

recommendations affect vaccination rates. These recommendations, while publicly disseminated through CDC publications, are largely intended to change the vaccination behavior of physicians and health care providers (CDC 2011a).[2] My results are consistent with this provider mechanism and, furthermore, they show that ACIP recommendations disproportionately benefit higher socio-economic groups, which also have higher rates of preventive care visits. This finding is particularly important for policymakers, as it demonstrates that, due to differential rates of provider contact across socio-economic groups, policies of this type may exacerbate pre-existing disparities in the probability of receiving preventive care.

To estimate the effects of the MCV4 booster dose recommendation I use difference-in-differences and triple-difference identification strategies. Given that the recommendation was implemented nationally, in order to identify suitable control groups and outcomes I leverage the fact that the recommendation applied only to MCV4 and that it was targeted at individuals who were at least 16 years of age. Specifically, I estimate vaccination effects by comparing changes in vaccination rates for a non-targeted vaccine (the tetanus, diphtheria, and pertussis, or Tdap, vaccine) to the changes in the targeted vaccine (MCV4), for both non-targeted (14- to 15-year-olds) and targeted (16- to 17-year-olds) age groups. Morbidity effects are similarly estimated by comparing changes in incidence for serogroups of meningococcal disease that are protected against by the vaccine to changes for serogroups that are not, and by comparing changes for different age groups.

Using data from the National Immunization Survey-Teen, I first show that the ACIP recommendation increased the probability that 16- and 17-year-olds received a dose of MCV4 by approximately 21 percentage points, or 133 percent relative to the pre-period mean; 14- and 15-

[2] This intention is evidenced by the CDC imploring health care providers to "ensure that they are following the most up-to-date schedules" and to "adhere as closely as possible to recommended vaccination schedules" (CDC 2011a).

year olds, who are slightly too young to be targeted by the recommendation, experienced no similar increase in uptake. The fact that there is no spillover to the slightly younger age group is consistent with the narrow targeting of the vaccine recommendation: it explicitly states that even if a previous dose of MCV4 is received at age 15, the booster dose should still be administered at age 16. This increase in vaccination also resulted in substantial reductions in the incidence of meningococcal disease: using CDC surveillance data I estimate that incidence was reduced by 28 to 45 percent relative to the baseline mean.

I next provide a collage of evidence suggesting that the recommendation affects vaccination rates primarily through changes in provider behavior. Specifically, my results show that the recommendation caused no change in the probability that 16- and 17-year-olds had a preventive care visit following the implementation of the recommendation. In other words, I am able to rule out the possibility that the recommendation increased vaccination rates by changing the doctor-going behavior (for preventive care) of adolescents along the extensive margin. I also verify that my results are driven by the group which should be most affected by changes in provider behavior: those adolescents that had a preventive care visit in the past year. Although there is a small increase in vaccine uptake among adolescents who do not report having had a preventive care visit, this increase occurs much more gradually and is not statistically different from zero until three years after the recommendation is issued.

In additional analyses I also show that the recommendation did not cause any increase in Google searches for terms related to the meningococcal vaccine or meningitis. This finding is quite striking, especially when compared to previous literature that shows Google searches are responsive to disease incidence and school vaccination policy (Oster 2018, Carpenter and Lawler 2019). I argue that this null result on internet search behavior is broadly consistent with the

MCV4 booster recommendation affecting vaccination outcomes primarily through changes in physician behavior.

Finally, I explore heterogeneity in the vaccination effects of the ACIP recommendation across sub-groups. I show that adolescents in households that are lower-educated, lower-income, or non-privately insured have lower rates of provider contact *and* lower MCV4 vaccination rates in the period prior to the recommendation, and also experience the smallest increases in uptake of MCV4 following the recommendation. This finding suggests that although the MCV4 booster recommendation saves lives and generates substantial social savings, it may also have the unintended consequence of exacerbating pre-existing disparities and increasing inequality across groups. Furthermore, given the evidence that the recommendation likely affects vaccination rates primarily through changes in provider behavior, this also suggests that the degree to which recommendations exacerbate disparities may depend on the baseline level of provider contact in a given population.

This paper makes a number of contributions to the economics literature on infectious disease and the causal determinants of vaccination (Philipson 2000). First, by studying the determinants of vaccination among adolescents, this paper contributes to an under-developed area of this literature, as the vast majority of articles to date have focused on the determinants among infants and young children (see, for example, Abrevaya and Mulligan 2011, Chang 2018, Lawler 2017, or Oster 2018) and comparatively very little is known about the determinants among high school-aged adolescents.[3] As the number of vaccines targeted towards adolescents

[3] Notably, however, several recent papers have examined the effects of HPV vaccine policies targeted at adolescents. Trogdon et al. (2016) examine the effects of expanding pharmacist scope of practice on receipt of the HPV vaccine among adolescents and find no effect. Moghtaderi and Adams (2016) examine the effects of state laws requiring receipt of the HPV vaccine or the distribution of information about it, and they similarly find no effect on adolescent HPV vaccination rates. Smith et al. (2015a, 2015b) examine the effects of free provision of the HPV vaccine at school based clinics in Canada and finds large increases in uptake. Carpenter and Lawler (2019) estimate

has steadily increased over the past several decades, this has become an increasingly important population to study. Moreover, given that infants and young children have much higher rates of health care utilization and a very different pre-existing vaccine policy environment relative to 16- and 17-year-olds, *a priori* it is unclear the extent to which the findings from studies of infants may apply to the adolescent population.

Second, this paper provides important new evidence on the effects of one of the most widely implemented vaccination policies: ACIP recommendations. Although there are a number of papers in the medical and public health literatures that have examined vaccination rates before versus after an ACIP recommendation (see for example MacNeil et al. 2018, Ackerson et al. 2017), to the best of my knowledge only one other study has estimated the vaccination effects in a quasi-experimental framework (Lawler 2017), [4] and no other study has provided evidence on the potential mechanism through which ACIP recommendations may affect vaccine uptake. Additionally, while Lawler (2017) finds ACIP recommendations for the hepatitis A vaccine to be very effective at increasing vaccination rates, those recommendations were targeted towards 2- and 3-year-olds and so, for reasons previously discussed, it is unclear the extent to which those findings may be applicable to 16- and 17-year-olds.

More broadly, this paper is informative regarding the manner in which adolescents (or their parents) respond to age-targeted health policies. The teen years are a period of the life course when rates of provider contact are low and when many high-risk behaviors are initiated,

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the effects of state laws requiring that 11- to 12-year-olds receive the Tdap vaccine prior to middle school entry; they find large effects on the uptake of the Tdap vaccine, as well as spillover effects to the uptake of other vaccines.

[4] There are a number of papers, however, in the closely related literature that examines the effects of information shocks on the vaccination decision. The types of information shocks considered in this literature, such as awareness campaigns, education mandates, and media coverage of the vaccine-autism controversy (see, for example, Moghtaderi and Adams 2016, Anderberg et al. 2011, and Chang 2018) may not be informative in this context given the evidence that the information from the ACIP recommendation primarily flows through health care providers, as opposed to popular press or schools.

and yet comparatively little is known about the effectiveness of public policies targeted at this age group (Gruber 2001, Uddin et al. 2016). My results suggest that simple non-binding recommendations have substantial potential to increase the receipt of the recommended preventive care among this age group. They also demonstrate, however, that policies of this form may primarily affect outcomes among the set of adolescents that are already in regular contact with health care providers, and therefore may serve to exacerbate pre-existing health disparities.

Finally, this paper is the first to estimate the effects of meningococcal disease-targeted vaccination policies on vaccination rates and disease incidence in a quasi-experimental framework. Given differences in transmission, contagion, and morbidity across diseases, disease-specific analyses are necessary in order for policy makers to estimate the cost-effectiveness of a given vaccination policy. Notably, these findings will be directly informative for a number of policy makers, as the implementation of MCV4-specific policies is currently ongoing: in 2016 alone over 15 states introduced legislation aimed at increasing MCV4 immunization rates (ASTHO 2016).

The rest of this paper proceeds as follows: Section I provides background on meningococcal disease and ACIP recommendations and Section II describes the data and outlines the empirical approach. I present the main set of results in Section III, with evidence on mechanisms and heterogeneous effects of the policy presented in Section IV. Finally, Section V discusses and concludes.

I. BACKGROUND

I.A. Meningococcal Disease and Vaccination

Meningococcal disease encapsulates the set of infections caused by the bacteria *Neisseria meningitidis* and most commonly presents as an infection of the lining of the brain and spinal cord

(meningitis) or of the bloodstream (septicemia). Both meningococcal meningitis and meningococcal septicemia are characterized by sudden onset of fever and vomiting; symptoms of meningitis frequently also include headache and stiff neck, while septicemia is more frequently additionally associated with fatigue, chills, and a rash. Although standard treatment for meningococcal disease is a course of antibiotics, the severity of the illness is such that individuals with acute cases are hospitalized for an average of 8 to 9 days and mortality rates, even with treatment, range from 10 to 15 percent (CDC 2015, Davis et al. 2011). Additionally, up to 20 percent of people who recover from meningococcal disease have permanent disabilities, including nervous system damage, hearing loss, and cognitive impairment (CDC 2018).[5]

Transmission of meningococcal disease occurs through close person-to-person contact and the communicability of the disease is considered to be limited, with household contacts suffering secondary infections at a rate of only 3 to 4 percent (CDC 2015). Crowded living conditions and smoking are both considered to be environmental risk factors for meningococcal disease. Infection rates peak before age 5, and again between ages 16 and 21.

There are numerous different serogroups (variations) of the *N. meningitdis* bacteria; serogroups A, B, C, W, and Y are the most significant causes of invasive meningococcal disease. Clinical presentation and transmission mechanisms are consistent across types, although the relative importance of each serogroup varies across age groups. In particular, serogroups C, W, and Y account for 73 percent of meningococcal disease cases among individuals over the age of 10, whereas serogroup B is relatively more prevalent among infants and young children, and accounts for 60 percent of cases among children under the age of 5 (CDC 2015). This paper focuses

[5] Although these estimates are for the entire population, estimates for those who have meningococcal disease as an adolescent or young adult are similar: for individuals between the ages of 15to 24, mortality rate estimates range from 11 to 20 percent, and among survivors, the estimated rate of severe long-term disability ranges from 20 to 23 percent (Erickson et al. 2001**;** Clarke and Mallonee 2009).

specifically on vaccination against the A, C, W, and Y serogroups, for which a vaccine has been licensed in the United States since 1981.[6] Although a vaccine that provides protection against serogroup B now also exists, it was not approved in the United States until 2014.

The current vaccine, the quadrivalent A, C, W, and Y conjugate vaccine (MCV4), was first approved in the United States in 2005. Relative to the earlier meningococcal vaccines, this new vaccine was expected to generate a better and more long-lasting immune response and to be more effective at reducing transmission of the bacteria in the community (CDC 2005). Specifically, at the time of licensure, available evidence suggested that a dose of MCV4 would provide protection for at least 10 years. Subsequent studies, however, suggest that immunity may significantly decline within 3 to 7 years (CDC 2011b; Cohn et al. 2017).

I. B. Meningococcal Vaccination Recommendations

In the United States recommendations on the use of vaccines are set by the Advisory Committee on Immunization Practices (ACIP). The ACIP is a 15-member committee composed of doctors and public health professionals and was established in 1964. The recommendations issued by the ACIP are potentially very influential both because they serve as the *de facto* standard of care, and because they are directly tied to a number of state and national health laws.[7]

Routine vaccination against meningococcal disease was recommended by ACIP for the first time in 2005, following the approval of the first quadrivalent conjugate vaccine (MCV4) in January of that year. At that time ACIP recommended routine administration of 1 dose of MCV4 at ages 11 or 12, with the expectation that the vaccine would provide protection through the high-

[6] An earlier vaccine, approved for use in the U.S. in 1974, provided protection only against serogroup C.

[7] 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.

risk ages of 16 to 21. They also recommended routine vaccination of other high- risk groups, including college freshmen residing in dormitories and military recruits (CDC 2013).[8] Catch-up vaccination was recommended for all adolescents through age 15; this recommendation was extended through age 18 in 2007.[9]

In January 2011, based on new data that suggested declines in the persistence of antibodies within 3 to 7 years after vaccination, ACIP updated their recommendations once again to include a booster dose at age 16 (even if the first dose had been received at age 15), with catch-up vaccination for the booster recommended through age 18 (CDC 2011b).[10] Notably, the minutes from the October 2010 ACIP meeting, during which the decision was made to recommend the age 16 MCV4 booster dose, show that there was *not* a clear consensus at the time for the need to add the booster dose to the immunization schedule, and the recommendation was passed by a very narrow margin, with 6 affirmative votes, 5 negative votes, and 3 abstentions (ACIP 2010).[11] Evidence also suggests that the opinions of the broader medical community were similarly split at that time: results from a 2010 physician survey show that only 24 percent of pediatricians and 32 percent of family doctors were very or moderately concerned about immunity wearing off for adolescents that were immunized at ages 11 and 12 (ACIP 2010). This lack of broad consensus supports the interpretation that the effects I identify are being driven by the adoption of the ACIP recommendation itself, as opposed to being driven by the availability of new evidence on the

[8] Other high-risk groups include microbiologists who are routinely exposed to *N. meningitidis*, persons who travel to countries in which there is high incidence of meningococcal disease (primarily sub-Saharan Africa), and individuals with certain medical conditions (persistent complement component deficiencies and asplenia).
[9] When MCV4 was first approved in 2005 there were concerns about there being sufficient vaccine supply to vaccinate all adolescents up to age 18. This supply issue was resolved in 2007 (CDC 2007).
[10] Note that at the time of the January 2011 ACIP recommendation, MCV4 was already covered for eligible adolescents under the VFC program and by all private insurance with no cost sharing under the preventive care provision of the ACA, since it had previously been recommended as a catch-up vaccine for children through age 18.
[11] Discussion during the ACIP meeting highlighted that the existing evidence on duration of immunity was from very small scale studies, with multiple committee members noting the wide confidence intervals of those results (page 29).

effectiveness of the vaccine.

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

II. DATA AND EMPIRICAL STRATEGY

II. A. Data Sources

I utilize several different data sources for these analyses. Data on vaccination and preventive care visits are from the National Immunization Survey – Teen (NIS-Teen), 2008-2016. NIS-Teen is a random digit dialing survey that targets 13- to 17-year-olds, and consists of both a household survey and a survey of the adolescent's healthcare provider(s). Information on the adolescent's most recent preventive care visit is reported by parents during the household survey; all vaccination outcomes used in my analyses are obtained from the provider reports. Because the ACIP recommendations target adolescents that are at least 16 years old, I restrict my sample to individuals who were 17 years old at the time of survey and focus on vaccine doses received at ages 16 or 17. My primary vaccination outcome of interest is receipt of the quadrivalent meningococcal conjugate vaccine (MCV4), at ages 16 or 17.[13] As a falsification test, in some

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

[13] Due to changes in the coding of variables across survey waves, in some years individuals who received a meningococcal vaccine that provided protection against serogroups A,C,W, and Y, but for whom the vaccine subtype is unknown (i.e, if it is a conjugate vaccine or a polysaccharide vaccine), are unable to be distinguished

specifications I additionally estimate the effects of the ACIP recommendation on adolescents who are slightly too young to have been targeted by the recommendation. In these analyses I restrict the sample to individuals who were 15 years old at the time of the survey and focus on vaccine doses received at ages 14 or 15.

Data on disease incidence were obtained from the CDC for the years 2000-2016, as reported by states to the Nationally Notifiable Disease Surveillance System.[14] These data consist of counts of meningococcal cases, and are available at two separate levels of aggregation: counts of meningococcal cases (of any serogroup) at the state-year-age group level (0- to 4-year-olds, 5- to 14-year-olds, 15- to 24-year-olds, 25- to 64-year-olds, and 65 and older), or counts of meningococcal cases at the state-year-serogroup level (ACWY, B, other serogroup, and unknown serogroup). Notably, information on serogroup was not recorded prior to 2005, and is incompletely reported across years, with more than 60 percent of cases being of unknown type in some years.

I present in Appendix Figures 1 and 2 trends in adolescent vaccination rates and meningococcal disease incidence, respectively, and I show summary statistics on key variables from the NIS-Teen and CDC disease surveillance data in Appendix Table 1. In column 1 I present the statistics for the full sample of states and years; columns 2 and 3 respectively summarize the data for the years prior to and after the 2011 ACIP booster recommendation.

from individuals who received a dose of a meningococcal vaccine that provided protection only against serogroup B. Therefore, for my main outcome variable, I require individuals to have documented receipt of a dose of MCV4. As a robustness check I re-estimate all models with the outcome variable of "receipt of any meningococcal-containing vaccine," which includes receipt of unknown subtype A,C, W, and Y serogroup vaccines, but also includes serogroup B vaccines. My results are robust to this alternative definition of the outcome variable.

[14] Although these data represent the most comprehensive measure of meningococcal disease in the United States, they are limited in that they rely on physician diagnosis and therefore necessarily represent an underestimation of true disease incidence. This underestimation is expected to be much smaller for meningococcal disease relative to other diseases, however, given that the severity of the disease essentially necessitates provider contact.

These statistics show that vaccination rates among 16- and 17-year-olds are increasing over time for the MCV4, HPV, and influenza vaccine. Rates among 16- and 17-year-olds for the Tdap vaccine are actually decreasing, which is consistent with the fact that the Tdap vaccine is routinely recommended for 11- to 12-year-olds, but was more commonly received by older cohorts as a catch-up dose in the initial years following introduction of the vaccine.

Appendix Figure 2 shows that meningococcal disease incidence has declined substantially over time, and this decline actually began prior to the introduction of MCV4 in 2005. The summary statistics show that a decline in incidence occurred over the sample period for 15- to 24-year olds (targeted by the 2011 recommendation), as well as for 5- to 14-year olds (targeted by the original 2005 recommendation). Additionally, declines are observed both for the serogroups that are directly treated by the vaccine (serogroups ACWY) and for the serogroup that is not (serogroup B). Given this strong secular downward trend in meningococcal incidence, the extent to which increased vaccination among adolescents contributed to the decline is an empirical question.

II. B. Estimation Strategy

I estimate the effects of the 2011 ACIP recommendation using a difference-in-differences strategy in which I compare the treated group (or outcome) to the control group (or outcome), in the years prior-to versus the years after the issuing of the recommendation. I identify groups and outcomes that should have been unaffected by the implementation of the recommendation by leveraging the fact that the recommendation applied only to MCV4, and that it was targeted to individuals who were at least 16 years of age. When the data allow, I leverage both of these dimensions of the recommendation policy simultaneously to implement a triple-difference strategy.

Specifically, I make the following comparisons between treatment and control: To estimate the effects on MCV4 vaccination rates, I first compare the change in vaccination rates for the targeted vaccine (MCV4) to the change in vaccination rates for a non-targeted vaccine (Tdap), separately for the targeted age group (16- and 17-year-olds) and for a non-targeted age group (14- and 15-year-olds). I then combine these two specifications by taking the third difference between the two age groups. Differencing out the change in MCV4 and Tdap vaccination rates for a non-targeted age group (14- and 15-year-olds) serves to control for potential differential changes in MCV4 and Tdap vaccination rates that would have commonly occurred for adolescents in the absence of the recommendation.

To estimate the effects of the recommendation on disease incidence rates, I again make two comparisons, although data limitations do not allow for them to be combined into a single triple-difference specification. First, I compare changes in disease incidence for the meningococcal serogroups that are protected against by the vaccine (serogroups A, C, W, and Y) to changes in incidence of serogroup B, which is not protected against. I then separately compare changes in meningococcal disease incidence (of all serogroups) for the targeted age group (15- to 24-year-olds) relative to a non-targeted age group (5- to 14-year-olds). I note that although some of these comparisons are between treatment and control *groups*, and others are between treated and control *outcomes* within the treatment group, to simplify exposition I refer to control groups and control outcomes interchangeably throughout the rest of the article.

The identifying assumption in the difference-in-differences models is that each of the control outcomes represent a valid counterfactual for how the treated outcome would have evolved in the absence of the recommendation. As an example, this implies that we must assume that in the absence of the recommendation, meningococcal serogroups A, C, W, and Y incidence

would have evolved in the same manner as meningococcal serogroup B incidence. For the triple-difference model the identifying assumption is somewhat weaker: it requires simply that the *difference* between MCV4 and Tdap vaccination rates would have followed the same trends for 16- and 17-year-olds as for 14- and 15-year-olds in the absence of the recommendation. Notably, if the ACIP recommendation had spillover effects to any given control group or outcome then this strategy will underestimate the true effect of the ACIP recommendation. I discuss these assumptions in more detail and provide evidence in support of them below.

In order to allow for dynamic treatment effects over time and to test for parallel trends between my treatment and control in the years prior to the ACIP recommendation, my baseline model is a dynamic difference-in-differences (event study) model that can be described as follows:

$$\textbf{(1)} \quad \boldsymbol{Y_{jst} = \beta_0 + \beta_1 \tau_t + \beta_2 TREAT_j + \sum_{k \in K} \beta_3^k (TREAT \times YEAR)_{jt}^k + \beta_4 (TREAT \times Z)_{jst} + \varepsilon_{jst}}$$

where $\boldsymbol{Y_{jst}}$ is the outcome variable for group *j* (treatment or control) in state *s* in year *t*. $\boldsymbol{TREAT_j}$ is an indicator variable that is equal to 1 if group *j* is the treated group and is zero otherwise; $\boldsymbol{\tau_t}$ represents a vector of year fixed effects; and $\boldsymbol{TREAT \times YEAR}$ is a vector of interactions between the indicator for being treated and a set of year fixed effects, in which $K = \{2008, 2009, 2011, 2012, \ldots 2015, 2016\}$, with the year prior to the ACIP recommendation (2010) as the omitted year.[15] In this specification β_3^k is the vector of coefficients of interest, as they capture the differential change compared to 2010 in the treated outcome relative to the counterfactual outcome in a given calendar year.

[15] For specifications with CDC surveillance data at the state-year-age group level, $K = \{2001, 2002, \ldots, 2008, 2009, 2011, 2012, \ldots 2015, 2016\}$, for specifications with surveillance data at the state-year-serogroup level, $K = \{2005, 2006, 2007, 2008, 2009, 2011, 2012, \ldots 2015, 2016\}$.

Inclusion of a treatment group fixed effect controls for time invariant differences between the treatment and control; inclusion of year fixed effects flexibly controls for any common shocks, such as the implementation of the ACA preventive care provision, that may have occurred in a given calendar year and affected both treatment and control. Some policies, however, may differentially affect the two groups, and so to allow for this, I include the interaction between a vector of state-level policies, Z_{st}, and the indicator variable $TREAT$. Specifically, the vector Z_{st} captures the following policies: state-level MCV4- or Tdap-specific vaccine policies (high school MCV4 booster mandates; post-secondary meningococcal education, waiver, and vaccine mandates; secondary school meningococcal education mandates; and separate indicator variables for if the individual's cohort was exposed to a middle school MCV4 mandate or to a middle school TD-containing vaccine mandate), and indicators for if the state has insurance mandates for the coverage of well-child visits and immunizations (separately specified for coverage of children through age 15, and through age 18), as these may vary across ages within a state.[16] Information on these policies was compiled from the Immunization Action Coalition (2018), the National Council of State Legislators (2012), and independent review of state statutes and regulations.

For all models I also estimate a standard difference-in-differences specification, in which the vector of $\boldsymbol{TREAT \times YEAR}$ interactions is replaced by the single interaction $\boldsymbol{TREAT \times Post2010}$, where $\boldsymbol{Post2010}$ is an indicator variable equal to 1 if the year is 2011 or later. All

[16] Insurance mandates may also differentially affect the probability of receiving the Tdap vaccine compared to the MCV4, as the out-of-pocket price of MCV4 is markedly higher than the out-of-pocket price of the Tdap vaccine (at Walgreens as of April 2018, the prices were listed as $133.99 versus $63.99 per dose, respectively https://www.walgreens.com/topic/healthcare-clinic/price-menu.jsp). See Chang (2016) for evidence on the effects of insurance coverage mandates on uptake of immunizations among young children. Notably, once the Affordable Care Act (ACA) preventive care mandate became effective in September, 2010, well-child visits and ACIP recommended immunizations were covered with no cost sharing for all age groups and across all states. I also verify that all vaccination results are robust to the inclusion of lagged measures of state pertussis and meningococcal disease incidence, as Oster (2018) and Schaller et al. (2016) show vaccination rates to be responsive to disease incidence.

regressions estimated using NIS-Teen data are weighted using provided sample weights, and regressions estimated using CDC surveillance data are weighted using state population measures obtained from the Surveillance and Epidemiologic End Results (SEER) system for the relevant age group. To address within-state serial correlation in the outcome variables, all standard errors are clustered at the state level (Bertrand, Duflo, and Mullainathan 2004).

Since treatment in these models occurs at a more aggregate level than the unit of observation, I also verify that all of my main results are robust to clustering standard errors at the treatment group-by-year level (Abadie et al. 2017). Notably, at this level there are relatively few clusters (e.g., for specifications using NIS-Teen, in which there are nine years of data, this implies a total of 18 clusters); to adjust for this limitation I use the wild cluster bootstrap procedure with 1000 replications (Cameron, Gelbach and Miller 2008). In all main results tables I report the resulting bootstrapped p-value, as standard errors are difficult to back out from this procedure.

As mentioned previously, the vaccination data are such that they allow for the estimation of a triple-difference model in which the vaccination effect is identified by comparing the change in uptake of MCV4 to the change in uptake of the Tdap vaccine, for the targeted age group (16- to 17-year-olds) versus a non-targeted age-group (14- to 15-year-olds). Specifically, I estimate the following:

$$\textbf{(2)}\quad \boldsymbol{Y_{ajst} = \beta_0 + \beta_1 \tau_t + \beta_2 MCV4_j + \beta_3 Age17_a + \beta_4 (Post2010 \times MCV4)_{jt} + \beta_5 (Post2010 \times Age17)_{at} + \beta_6 (MCV4 \times Age17)_{aj} + \sum_{k \in K} \beta_7^k (MCV4 \times Age17 \times YEAR)_{ajt}^k + \beta_8 (MCV4 \times Z)_{jst} + \beta_9 (Age17 \times Z)_{ast} + \varepsilon_{ajst}}$$

where $\boldsymbol{Y_{ajst}}$ is an indicator variable equal to 1 if an individual, who is age *a* (17 or 15 years) at the time of survey in year *t* and resides in state *s*, has received a dose of vaccine *j* (MCV4 or Tdap) at

age *a* or *a*-1. In this model $\boldsymbol{\tau_t}$ represents a vector of year fixed effects, $\boldsymbol{MCV4_j}$ is an indicator variable that is equal to 1 if the outcome variable measures receipt of the MCV4 vaccine and is zero if it measures receipt of the Tdap vaccine, and $\boldsymbol{Age17_a}$ is an indicator variable that is equal to 1 for individuals that were 17 at the time of survey and is zero for those that were age 15. The model includes the main effects of these indicator variables, as well as all two- and three-way interactions. In this specification the coefficients of interest are $\boldsymbol{\beta_7^k}$, for K={2008, 2009, 2011, 2012, …, 2015, 2016}, as they capture the differential change in the probability of receiving the MCV4 vaccine relative to the Tdap vaccine, for 17-year-olds compared to 15-year-olds, in a given calendar year relative to the omitted base year (2010). As in equation (1), $\boldsymbol{Z_{st}}$ represents a vector of state policies, and I allow the effects of these to vary flexibly across vaccine types ($(\boldsymbol{MCV4 \times Z})_{\boldsymbol{jst}}$) and ages ($(\boldsymbol{Age17 \times Z})_{\boldsymbol{ast}}$). As before, all specifications are weighted using NIS-Teen provider weights, and I cluster standard errors at the state level.

III. MAIN RESULTS

III. A. Vaccination Effects of Recommendations

I first estimate the effects of the ACIP meningococcal booster recommendation on the probability of receiving the MCV4 vaccine. Using the dynamic difference-in-differences model specified in equation (1), in which my treated and control outcomes, respectively, are receipt of a dose of MCV4 and of a dose of Tdap at ages *a* or *a-1*, I separately estimate the effects for 17-year-olds and for 15-year-olds (as a falsification test). This estimation strategy relies on the assumption that observed vaccination rates of an adolescent vaccine not targeted by the 2011 ACIP recommendation (Tdap vaccine) serves as a valid counterfactual for how MCV4 vaccination rates would have evolved in the absence of the ACIP recommendation. I focus on the Tdap vaccine as the counterfactual vaccine for two main reasons: one, both MCV4 and Tdap

vaccines were first approved for use in the United States in the same year (2005), and second, within a year of approval both vaccines were recommended for routine administration to 11- to 12-year-olds, with catch-up vaccination recommended for older adolescents. Additionally, visual inspection of the trends in vaccination rates, presented in Appendix Figure 3, confirms that prior to the 2011 ACIP recommendation, immunization rates for these two vaccines were very similar in terms of both trends *and* levels for 16- and 17-year-olds (Appendix Figure 3A) as well as for 14- and 15-year-olds (Appendix Figure 3B).

The results from estimation of the event study models are presented in Figure 1 and show that the ACIP booster recommendation led to a large increase in the probability that an individual received a dose of the MCV4 at ages 16 or 17, relative to their probability of receiving a dose of the Tdap vaccine at the same ages, and that there was no similar differential increase among 14- and 15-year-olds. The null effect on vaccination rates among 14- and 15-year-olds is expected given the narrow targeting of the ACIP recommendation, which explicitly states that even if a dose of MCV4 is received at age 15, the booster dose should still be administered at age 16.

Notably, these results suggest that there are important dynamics to the effect of the recommendation: First, they show that the magnitude of the effect is increasing over time, with estimated effects five years after implementation as large as 37.0 percentage points. The estimates also suggest that there is no statistically significant effect on the vaccination rates of 17-year-olds in the year the recommendation was issued (2011). I note, however, that a portion of this observed lag is likely due to the fact that some 17 year olds, surveyed in year *t*, likely received their MCV booster dose in year *t-1* (at age 16 or 17), which then implies that some of the doses that were administered in 2011 (as a result of the new ACIP recommendation) are not

observed until 2012. Finally, these results also show that for both 17- and 15-year-olds there were not pre-existing differential trends in the probability that an individual received an MCV4 vaccine compared to the Tdap vaccine, as the estimated coefficients for the years prior to the ACIP recommendation are all relatively small in magnitude and none are statistically significant. This is important for my identification strategy, as it provides further evidence that Tdap vaccination rates represent an appropriate counterfactual for how MCV4 vaccination rates would have evolved in the absence of the ACIP recommendation.

I present in Figure 2 the estimates from the triple-difference model specified in equation (2). Consistent with the findings in Figure 1, these estimates also show that the ACIP booster recommendation had a large and significant effect on the probability that 16- to 17-year-olds received a dose of MCV4, and that the magnitude of the effect similarly increased substantially over time.

I summarize this set of results in Table 1, in which I report the single difference-in-difference (columns 1 through 4) or triple-difference coefficient (columns 5 and 6) that captures the average effect of the ACIP recommendation on MCV4 immunization rates. The estimate from the triple-difference specification shows that on average the ACIP recommendation increased MCV4 vaccination rates among 16- and 17-year-olds by approximately 21.4 percentage points (column 6). Compared to the pre-2011 mean MCV4 vaccination rate, these estimates suggest the ACIP recommendation caused a 133 (.214/.161 × 100) percent increase in MCV4 vaccination at ages 16 or 17. Additionally, these results show that the estimates are not sensitive to excluding state-level policy controls (columns 1, 3, and 5), and are robust to clustering at the treatment group-year level (wild bootstrapped p-values reported in brackets).

III. B. Morbidity Effects of Recommendations

The ACIP's primary motivation for issuing the age 16 MCV4 booster recommendation was to reduce the burden of meningococcal disease among 16- to 21-year-olds. In this section I provide evidence on the morbidity effects of the ACIP booster recommendation by estimating two separate versions of the difference-in-differences model specified in equation (1). In the first version I compare the change in the rate of meningococcal serogroups A, C, W, and Y incidence, which is protected against by the MCV4, to the change in the rate of meningococcal serogroup B incidence, which is not protected against by the MCV4. In the second version I compare the change in the rate of meningococcal disease incidence (of all serogroups) between targeted (15- to 24-year-olds) and non-targeted (5- to 14-year-olds) age groups.[17] The outcome variable in these specifications is measured as number of cases (of a given serogroup or among a given age group), per 100,000 population. I show that although each of these comparisons face slightly different limitations and require different identifying assumptions, the results across the two strategies is remarkably consistent.

The event study results from comparing changes across serogroups and across age groups are presented in Figures 3 and 4, respectively. Both sets of comparisons provide evidence that the ACIP recommendation resulted in a significant reduction in meningococcal disease incidence. Importantly, both strategies show a similar pattern of effects, with a one-year lag before the reduction in disease incidence is statistically significant, after which the magnitude of the reduction is generally increasing. Furthermore, this pattern is consistent with the dynamics of the effects on vaccination rates.

For interpretation of the magnitude of these morbidity reductions I focus on the single difference-in-differences estimate for each of the models, which are presented in Table 2. The

[17] Due to the level of aggregation in the disease surveillance data I am unable to combine these two sets of comparisons into a single triple-difference specification.

estimate from the cross-serogroup comparison suggests that the ACIP recommendation resulted in a reduction of 0.063 cases of meningococcal ACWY per 100,000 population (column 2), while the estimate from the cross-age group comparison suggests a reduction of 0.182 meningococcal cases per 100,000 population of 15- to 24-year-olds (column 4). These results are robust to the exclusion of controls for state policies (columns 1 and 3), and to clustering standard errors at the treatment-group-year level.

Scaling these estimates by the size of the relevant underlying population implies 203 fewer serogroup A,C, W, and Y cases per year (scaled by the size of the entire U.S population: 322.2 million, as of 2016), and 79 fewer cases among 15- to 24-year-olds (scaled by the size of the 15- to 24-year-old population: 43.5 million, as of 2016). Although these estimates differ in absolute magnitude, this is to be expected given that the reduction in incidence for the 15- to 24-year-old subset of the population must necessarily be smaller than the total reduction in cases for the entire population. Moreover, due to potential herd immunity spillovers to younger individuals, the estimates from the cross-age group comparison are also more likely to be downwardly biased.

The identifying assumption for the comparison across different serogroups is that incidence of the control serogroup, serogroup B, would have evolved in a similar manner to incidence of the treated serogroups, A, C, W, and Y. There are several reasons to believe this to be true. First, although there are differences in the polysaccharide (sugar) capsule across the different serogroups, they share transmission mechanisms and clinical symptoms. This suggests that any changes in factors that may generally affect transmission of meningococcal disease, such as reduced sharing of drinks or food, or changes in the probability of physician diagnosis of meningococcal disease, should similarly affect all serogroups. Second, the event study

coefficients, which are all very small in magnitude and not statistically different from zero for the years prior to 2010, show that serogroup A, C, W, and Y and serogroup B incidence trends were similar in the years prior to the recommendation. Moreover, there was not a vaccine that provided protection against serogroup B until 2014, reducing concerns of potential spillovers of the ACIP recommendation to serogroup B incidence in terms of vaccination behavior, which would bias the estimated morbidity effects towards zero.

There are limitations to this comparison, however. Notably, there has been a substantial decline in the incidence of meningococcal B even in the absence of a vaccine against the disease, and there are also persistent differences in the risk factors for different serogroups (such as age and geography), both for reasons that are not well understood (CDC 2015). Additionally, in available surveillance data the serogroup information is missing for a large number of reported meningococcal cases.

The cross-age group comparison has the advantage of being able to overcome these limitations, as the relative incidence of serogroup B is similarly distributed across the two age groups, so any unexplained changes in incidence would equally affect both groups, and since age information included in the surveillance data is reported at a much higher rate than the serogroup information.[18] As previously, noted, however, for cross-age group comparisons there is a much greater chance of spillover effects from the treatment to the control group due to herd immunity, which would bias the estimates towards zero. I chose the 5- to 14-year-olds as the control group specifically to mitigate this bias as much as possible, since MCV4 vaccination rates among adolescents under the age of 15 were relatively high at the time of the booster recommendation,

[18] Specifically, in any given year age information is missing for less than 1% of reported cases.

presumably due to the 2005 ACIP recommendation that targeted this age group.[19] Additionally, the event study coefficients for the years prior to 2010 provide further evidence that meningococcal disease incidence was trending similarly between the two groups during the pre-period.[20]

IV. ADDITIONAL RESULTS

In this section I perform a number of additional analyses to further explore the effects of the ACIP booster recommendation. I first examine the hypothesis that ACIP recommendations affect vaccination rates primarily through changes in provider behavior.[21] To do so, I estimate the effects of the recommendation on the probability that an adolescent has a preventive care visit and on Google searches for terms related to the meningococcal vaccine. In the final set of analyses, I test for potential heterogeneity in the vaccination effects by separately estimating the triple-difference model specified in equation (2) for different sub-groups.

IV. A. Mechanisms: Preventive Care Visits

There are two key channels through which the recommendation may have affected vaccination rates: changes in patient behavior, in which the patient more actively seeks out the vaccine, or changes in provider behavior, in which the provider becomes more likely to offer and/or recommend the vaccine to a given patient. I argue that these two channels have differing

[19] MCV4 vaccination rates among 13- and 14-year-olds in 2010 were approximately 62.6 percent, as measured in the NIS-Teen.

[20] There is a notably large coefficient for the 2006 calendar year, which is significant at the 10 percent level and suggests that in 2006 there was a drop in incidence among 5- to 14-year-olds relative to 15- to 24-year-olds. This is consistent with the timing of the previous MCV4 ACIP recommendation, which was issued in 2005 and was targeted at 11- to 12-year-olds. The difference in disease incidence following that recommendation is likely not sustained since it included the provision that MCV4 should be received as a catch-up vaccine by adolescents up to the age 18, and so presumably it also led to temporary increases in vaccination rates among older teens. Unfortunately, I cannot empirically examine the effects of this recommendation on vaccination rates among adolescents, as NIS-Teen data do not start until 2008.

[21] Note that providers in this context could include non-physicians, as all states allow some subset of non-physician providers (e.g., advanced practice nurses, nurse practitioners, registered nurses, physician assistants, or pharmacists) to prescribe and/or administer vaccines (Stewart et al. 2016).

predicted effects on the probability that a patient has a preventive care visit: if patients are more actively seeking out the vaccine, we should see an increase in preventive care visits, whereas if the change is arising through changes in provider behavior, we should see no change in the rate of preventive care visits along the extensive margin.

To shed light on the mechanism through which the ACIP recommendation is affecting vaccination rates, I therefore estimate the effects of the ACIP recommendation on the probability of having had a preventive care visit at current age *a* or at age *a-1*, as reported by parents in the NIS-Teen. I rely on a cross-age comparison to identify these effects, in which I compare changes in the probability of having had a preventive care visit for the targeted age group (17-year-olds) relative to a non-targeted age group (15-year-olds). Specifically, I estimate equation (1), and set $\boldsymbol{TREAT}$ equal to 1 if the individual was age 17 at the time of survey.

The event study estimates from this analysis are presented graphically in Figure 5 and show no evidence that the ACIP recommendation had an effect on the probability that a 17-year-old had a preventive care visit at age 17 or 16, as the estimated coefficients are all small in magnitude and only one (2016) is statistically different from zero.[22] Moreover, the single difference-in-differences coefficients that correspond to $\boldsymbol{TREAT \times Post2010,}$ as reported in Table 3, columns 1 and 2, are similarly small in magnitude and statistically insignificant.

This null result on the probability of having a preventive care visit allows me to rule out the possibility that the recommendation increased vaccination rates by changing the doctor-going behavior (for preventive care) of adolescents or their parents along the extensive margin. As previously discussed, this is consistent with the idea that the recommendation primarily affects

[22] For completeness I also present in Figure 5 the event study coefficients from the same difference-in-differences specification, where 17-year-olds are being compared to 15-year-olds, in which the outcome variable is an indicator variable equal to 1 if the individual received a dose of MCV4 at age *a* or *a-1*.

vaccination rates through changes in provider behavior.

I further explore the potential mechanism by separately estimating the effects of the recommendation on MCV4 vaccination rates for the subset of adolescents that did and did not have a preventive care visit at ages 16 or 17. If a change in provider behavior is what is driving the observed vaccination increases, then it must be the case that the largest increases in vaccination rates should be occurring for the subset of adolescents who had a preventive care visit. For this set of analyses I re-estimate equation (1) separately for those 17-year-olds that did and did not have a recent preventive care visit, and identify the effects on vaccination rates by comparing changes in uptake of the MCV4 to changes in the uptake of the Tdap vaccine.

The event study estimates from these analyses are presented in Figure 6; I present the summary difference-in-difference coefficients in columns 3 through 6 of Table 3. These results show a stark difference in the rate of uptake of the MCV4 between teens that did and did not have a preventive care visit. Specifically, in the year following the recommendation, there is no statistically significant effect on MCV4 vaccination rates for teens that did not have a check-up, compared to a significant 15.6 percentage point effect for the subset of teens that did have one, and in subsequent years the magnitude of the effect is persistently around 15 percentage points higher among teens that had a visit. The difference-in-difference point estimates show that, on average, the effect was over two times larger for these teens relative to teens that did not have a preventive care visit. Moreover, the estimated effects among the group that did not have a visit are not statistically significant at conventional levels when standard errors are clustered at the treatment group-by-year level.

IV. B. Mechanisms: Google Searches

I next explore the effects of the ACIP booster recommendation on Google searches for

meningococcal- related terms, using Google Trends data from 2004-2016. If the recommendation is affecting vaccination rates through changes in patient behavior, we may expect an increase in Google searches for vaccine-related terms (e.g., increased searches for "where to get the meningococcal vaccine" or "cvs meningitis vaccine"). On the other hand, if the mechanism is changes in provider behavior, we may expect no change in Google searches.

Google Trends data provide measures of relative search popularity for a given search term at the state-month level. Relative search popularity is standardized within each state such that the month with the highest search volume is equal to 100; if overall searches in a state are below a certain (non-disclosed) threshold, Google will not release the data disaggregated to the state level. As a result, for some less common search terms (e.g., "Meningitis vaccine"), data are missing for several states. These data are increasingly being utilized in the economics literature, and in particular have recently been used by two related papers which examine determinants of vaccination in the United States (Oster 2018, Carpenter and Lawler 2019). These papers find that Google searches for terms related to a given vaccine responded significantly to changes in disease incidence (Oster 2018) and to the implementation of state mandates requiring children to receive a vaccine prior to school entry (Carpenter and Lawler 2019).

Unfortunately, the difference-in-differences strategy used to estimate the main effects of the ACIP recommendation is not well-suited for estimating the effects on Google searches, as the aggregate nature of the data does not allow for cross-age comparisons, and comparisons of trends between meningococcal-related search terms and potential control outcome searches (e.g., "Tdap" or "Tdap vaccine") show that the outcomes were trending differently in the pre-period. Given this, I instead adopt an identification strategy that leverages cross-state differences in the expected propensity of providers to adopt the ACIP recommendations, and compare Google

searches in states with high versus low rates of adoption.[23]

As a proxy for the expected propensity to adopt the ACIP recommendations I construct a state-level measure of provider participation in Immunization Information Systems (IIS, also referred to as immunization registries) using provider information in the NIS-Teen. IIS are computerized databases that allow for all of an individual's vaccination records to be consolidated into a single record that is accessible to their providers, thus improving a given provider's ability to administer appropriate vaccines. Evidence shows that provider participation is associated with increased receipt of on-time vaccinations (Groom et al. 2015) and improving provider participation rates in IIS has been a public health priority since the early 2000s (CDC 2002).

Provider participation rates in IIS can be viewed as a reasonable measure of expected adoption of the MCV4 ACIP recommendation for two reasons. First, participation in IIS broadly demonstrates a willingness to adopt vaccine-specific practice recommendations, and so states that have higher rates of provider participation in IIS may be expected to be more responsive to an ACIP recommendation. Second, since higher participation rates in IIS improves the quality of an individual's vaccination record, it should also improve provider ability to determine if the administration of the MCV4 vaccine is appropriate for a given patient.

Specifically, for these analyses I compare states with above- versus below-median rates of provider participation in IIS in the baseline year (2010),[24] and I estimate the following

[23] Geographic variation across space in rate of technology adoption has been well documented in other cases (e.g., Skinner and Staiger 2005).

[24] In 2010 the state-level IIS participation rate ranged from 25 percent to 98 percent, with the 25th, 50th, and 75th percentiles occurring at 62.6, 81.6, and 92.7 percent, respectively. I also estimate specifications in which I allow the treatment effect to vary based on the quartile of the state IIS participation rate in the baseline year, and in which I categorize states based on their average IIS participation rate for all sample years prior to the recommendation (2008-2010). Estimates from those models are similar and are available upon request.

equation:

$$\textbf{(3)} \quad \boldsymbol{Y_{st} = \beta_0 + \beta_1 \tau_t + \beta_2 S_s + \sum_{k \in K} \beta_3^k (ABOVE\ MEDIAN \times YEAR)_{st}^k + \beta_4 Z_{st} + \varepsilon_{st}}$$

where $\boldsymbol{Y_{st}}$ is the relative Google search volume for a given term in state *s* and month-year *t*; τ_t represents month-year fixed effects, and S_s is a vector of state fixed effects. In this specification $(\boldsymbol{ABOVE\ MEDIAN \times YEAR})_{st}^k$ is the vector of treatment variables of interest, as it captures the differential change in Google searches for states that were above the median in provider participation in IIS in 2010 relative to those states that were below the median. I also include in this specification a vector of time varying state characteristics, $\boldsymbol{Z_{st}}$. Since the recommendation effect in this model is being identified by comparing outcomes *across* states, I expand the set of state time-varying characteristics included in these specifications, although I verify my results are robust to including only the characteristics included in equation (1).[25] Regressions are weighted by state population and standard errors are clustered at the state level.

Before estimating effects on Google searches using this model, I first verify that states below versus above the median IIS participation rate in the baseline year had differential uptake of the vaccine following the recommendation.[26] I present the event study estimates from this

[25] Specifically, in addition to the state vaccine and insurance policy controls discussed previously, I also include indicator variables that capture the state's non-medical exemption policy for school vaccine mandates (NCSL 2017), an indicator variable for if the state has expanded Medicaid (Kaiser Family Foundation 2019), and variables that capture the state's race/ethnicity composition (percent black, percent Hispanic, and percent other), percent population female, state age distribution (percent under 21 years and percent 21-64), percent of population with high school degrees and percent with 4 year college degrees, state poverty rate, and state unemployment rate. Demographic controls were obtained from the Census Bureau, and state unemployment rates come from the Bureau of Labor Statistics.

[26] I also estimate the model in equation (3) with receipt of the Tdap vaccine at 16 or 17 as the outcome variable, to check for potential spillover effects to uptake of this non-targeted vaccine. The event study results are presented in Appendix Figure 4, and the single difference-in-differences coefficient is present in Appendix Table 2. These results show no significant effect of the 2011 ACIP recommendation on uptake of the Tdap vaccine, thus reducing concerns that spillovers of this type represent a meaningful source of bias in my baseline set of results. For completeness I also estimate equation (3) with check-up at age 16 or 17 as the outcome variable. Using this alternate model I continue to find no statistically significant effect of the ACIP recommendation on the probability of having a check-up at ages 16 or 17.

model in Figure 7 and the associated difference-in-differences coefficients in columns 1 and 2 of Table 4, with the baseline and expanded set of state controls, respectively. These results show that following the recommendation there was substantial differential uptake of the vaccine based on baseline IIS participation rates, with all event study point estimates being positively signed and statistically significant at the 10 percent level or better. The difference-in-differences coefficient suggests that, on average, uptake of MCV4 was approximately 8 percentage points higher in states that were above the median IIS participation rate in the baseline year.

I next estimate this same model with Google searches for meningococcal-related terms as the outcome variable, and present the results from these analyses in Figure 8 and in columns 3 and 4 of Table 4.[27] These estimates show that although there was substantial differential uptake of MCV4 between states that were above versus below the median IIS participation rate during the baseline year, there was no significant differential change in Google searches across that same margin.[28] This null effect on Google searches for the ACIP recommendation suggests that the recommendation did not cause patients to more actively seek out information about the vaccine through internet search engines, and therefore is consistent with the idea that the vaccination effect is being driven primarily through changes in provider behavior.

[27] Specifically, this measure includes searches that have the word "meningococcal" or searches that include both the words "meningitis" and "vaccine." For searches with the word "meningitis" I require them to also have the word "vaccine" due to a highly publicized outbreak of *fungal* meningitis in October 2012 that led to an extreme spike in searches for "meningitis." For completeness I present in Appendix Table 3 additional results in which I separately specify the outcome variable to be relative search volume for searches that include "meningococcal," or "meningitis," or "meningitis" and "vaccine."

[28] I also estimate specifications in which I instead allow the treatment effect to vary based on state MCV4 immunization rates in the baseline year. In this specification states that had MCV4 immunization rates *below* the median in the baseline year are considered to be more treated by the recommendation. Notably, places with *lower* MCV4 vaccination rates in the baseline year likely are the same places that are *more* responsive to health information, given the fact that the MCV4 vaccine was originally recommended in 2005 to be received at age 11 or 12, with catch-up vaccination for individuals through age 18. Therefore, in 2010, 16 and 17 year olds should only have been receiving a dose of MCV4 if they did not receive the vaccine at the recommended age of 11 or 12 *and* had not yet received a catch-up dose in the intervening years. Estimates from this model are similar and are presented in Appendix Table 4; event study estimates are presented in Appendix Figures 5 and 6.

IV. C. Heterogeneity

In my final set of analyses I explore potential heterogeneity in the vaccination effects of the ACIP booster recommendations. I estimate the triple-difference model specified in equation (2) separately for different subgroups and report the results in Table 5, in which each row represents a separate sub-group.[29] In column 2 I report the sub-group specific coefficient on the interaction term $\boldsymbol{MCV4 \times Age17 \times Post2010}$, and, in order to help contextualize the results, in column 1 I report the relevant sub-group mean MCV4 vaccination rate among 16- and 17-year-olds in the years prior to the recommendation being issued.

In general, these results demonstrate that there are heterogeneous responses to the ACIP booster recommendation, with 16- and 17-year-olds in higher-educated, higher-income, and privately insured households being much more likely to increase MCV4 vaccination rates in response to the recommendation. Notably, these same groups also have the highest rates of check-ups (reported in Appendix Table 5) *and* the highest vaccination rates in the pre-period. Overall, this finding suggests that the heterogeneous effects of the ACIP recommendation served to exacerbate disparities in receipt of MCV4 across different socioeconomic groups.

I additionally explore this heterogeneous response to the ACIP recommendation in two ways. First, in order to verify that the differential vaccination take-up effects are not being driven by heterogeneous changes in preventive care visits, I re-estimate equation (1) with receipt of a preventive care visit as the outcome variable. My results, presented in Appendix Table 5, show that the effect of the ACIP recommendation on check-ups is consistently a relatively precise zero

[29] I also explore potential heterogeneity in the effects of the ACIP recommendation based on the pre-existing state vaccine policy environment. Specifically, I considered the presence of the following policies: MCV education policies for secondary schools, MCV education policies for post-secondary schools, and post-secondary MCV waiver or mandate requirements. For this set of policies, I do not find there to be significant differences in the effect of the ACIP recommendation. These analyses are available upon request.

across all sub-groups considered. Second, I estimate if the heterogeneous effects of the ACIP recommendation across socioeconomic groups persists after conditioning on having had a preventive care visit. This analysis allows me to disentangle the extent to which the observed heterogeneity is explained by differential rates of provider contact as opposed to being driven by other factors, such differential willingness to be vaccinated. I present these results in Appendix Table 6. In general, these results show that conditional on a check-up the effect of the ACIP recommendation is similar across groups. I note, however, that the point estimates suggest that higher income and privately insured households potentially were more responsive relative to lower income and non-privately insured households, although the standard errors are large.

V. DISCUSSION AND CONCLUSION

In this paper I provide the first quasi-experimental evidence on the effects of non-binding vaccine recommendations that are targeted towards high school-aged adolescents. Using difference-in-differences and triple-difference models, my results show that the ACIP recommendation for an age 16 booster dose of MCV4 increased the probability that individuals receive a dose of the vaccine at age 16 or 17 by approximately 21 percentage points. I also provide evidence that these large increases in vaccination rates resulted in approximately 203 fewer meningococcal cases per year, or, equivalently, reduced incidence by 45 percent relative to the pre-period mean.

By using a quasi-experimental framework to estimate the effects of the ACIP recommendation on both vaccination rates and disease incidence, I am able to provide new estimates of the overall cost-effectiveness of the policy. Specifically, my results imply that the recommendation resulted in approximately 898,800 more doses of MCV4 being administered to 16-year-olds each year (0.214 × approximately 4.2 million 16-year-olds), at a total cost of

approximately $74.66 million per year (including costs of the vaccine dose plus costs of administration and resulting adverse events).[30] For estimates of social savings, I take into account costs of averted medical care (both for treatment during illness and for resulting permanent disabilities), work time lost due to acute illness, and the value of lives saved due to the reduction in cases of meningococcal disease. I estimate that on average the reduction in morbidity and mortality resulted in social savings of $159.9 million per year. Overall this implies that the social savings outweighs the costs associated with the policy, with each dollar spent generating more than two dollars in social savings.

These results fill an important gap in the literature on the effectiveness of vaccine policies targeted towards adolescents. While there is evidence that school-based vaccine mandates and free provision of vaccines at school clinics significantly increase vaccination rates among younger adolescents (Carpenter and Lawler 2019; Smith et al. 2015a), the evidence on the effects of other policies targeted at this age-group is more discouraging: pharmacist scope of practice expansions and school-based informational campaigns have both been shown to have no effect on adolescent vaccination rates (Trogdon et al. 2016, Moghtaderi and Adams 2016). Moreover, while Lawler (2017) shows that ACIP recommendations targeted at young children increase their vaccination rates by 27 to 34 percentage points, policymakers have expressed concern that the recommendations would be relatively ineffective for adolescents, given their low rates of provider contact (CDC 2004). My results show that while the ACIP recommendation may increase vaccination rates comparatively less for adolescents than for young children (21 percentage points versus 27 to 34 percentage points, respectively), they are still broadly effective at increasing vaccination rates for the targeted vaccine.

[30] I discuss the underlying calculations and associated sensitivity checks in detail in the Appendix.

My results also provide new evidence on the mechanism through which ACIP recommendations affect immunization rates. Specifically, I show that the recommendation had no significant effect on the probability of having a preventive care visit at ages 16 or 17 or on Google searches for terms related to the meningococcal vaccine, suggesting that the recommendation did not cause patients to more actively seek out the meningococcal vaccine or information about it. These results are consistent with the idea that the recommendation affected outcomes primarily through changes in provider behavior. A notable limitation of these analyses, however, is that I am unable to observe patient or provider behavior directly.

Understanding the mechanism through which the ACIP recommendation affects vaccination rates is important for several reasons. First, the underlying mechanism has substantial implications for the extent to which different subgroups are exposed to the treatment, which in turn has consequences in terms of the policy's effect on health inequality. Specifically, a policy that primarily relies on changes in provider behavior, as the evidence suggests this one does, will disproportionately benefit those groups with higher pre-existing rates of contact with the health care system. Accordingly, I find evidence that the ACIP recommendations exacerbated pre-existing disparities in the probability of receiving MCV4: my results show that lower-income and lower-educated households, who are less likely to report having had a check-up *and* less likely to have been vaccinated prior to the recommendation, are less likely to increase uptake of the vaccine following the recommendation.

Second, this evidence on the underlying mechanisms of the ACIP recommendation effects provides new insight regarding the responsiveness of health care providers to changes in recommendations and practice guidelines. While my results suggest a relatively large portion of providers changed their behavior in response to the ACIP recommendation, the findings on the

degree of provider responsiveness in other settings has been mixed.[31] I suspect that these differences in responsiveness can be explained by the relative cost of adopting new practices - both in terms of the infrastructure costs of adoption as well as the time and cognitive effort costs for the provider. In particular, there is reason to believe that incorporating a new vaccine into an adolescent preventive care visit would be relatively low cost. For example, given the importance of vaccination in well-child care and the fact that other vaccines are recommended (as catch-ups) for this age group, providers seeing adolescents in their practice likely have already integrated vaccine administration into their practice. Additionally, the practice guidelines for determining if an individual should receive a dose of MCV4 is relatively straightforward (based on age and prior receipt), and so the treatment decision likely has a low cognitive effort cost for providers.

Overall, although these analyses are specific to the meningococcal vaccine, I believe that the results are broadly informative for policymakers regarding the mechanisms through which ACIP recommendations affect vaccination rates, and also regarding the responsiveness of adolescents (and their parents) to simple non-binding recommendations for preventive care. In particular, since my results suggest that ACIP recommendations primarily affect vaccination rates through changes in provider behavior, we therefore should expect them to be relatively less effective when targeted towards populations that have lower rates of provider contact. Similarly, although I show that there is substantial potential to increase adolescent uptake of preventive care through recommendations, my results highlight that this type of policy may

[31] For example, Buchmueller and Carey (2018) find that Prescription Drug Monitoring Programs are only effective at reducing opioid abuse if providers are required to access them – implying that the recommendation for usage is insufficient to change provider behavior. In a different context, however, Alalouf et al. (2018) find that providers follow recommended diagnostic guidelines for diagnosing diabetes, as they observe a discontinuous jump in the probability of being diagnosed of between 11 and 29 percentage points at the relevant threshold. Much of the existing economics literature on the determinants of provider practice decisions focuses on financial incentives, such as pay-for-performance schemes (e.g., Konetzka et al. 2018, Eijkenaar et al. 2013) or insurance reimbursement structures (e.g., Domino 2012, Johnson and Rehavi 2016). The findings of this literature on the responsiveness of providers to financial incentives is similarly mixed.

disproportionately benefit higher socio-economic groups that are also in contact with health care providers at a higher rate.

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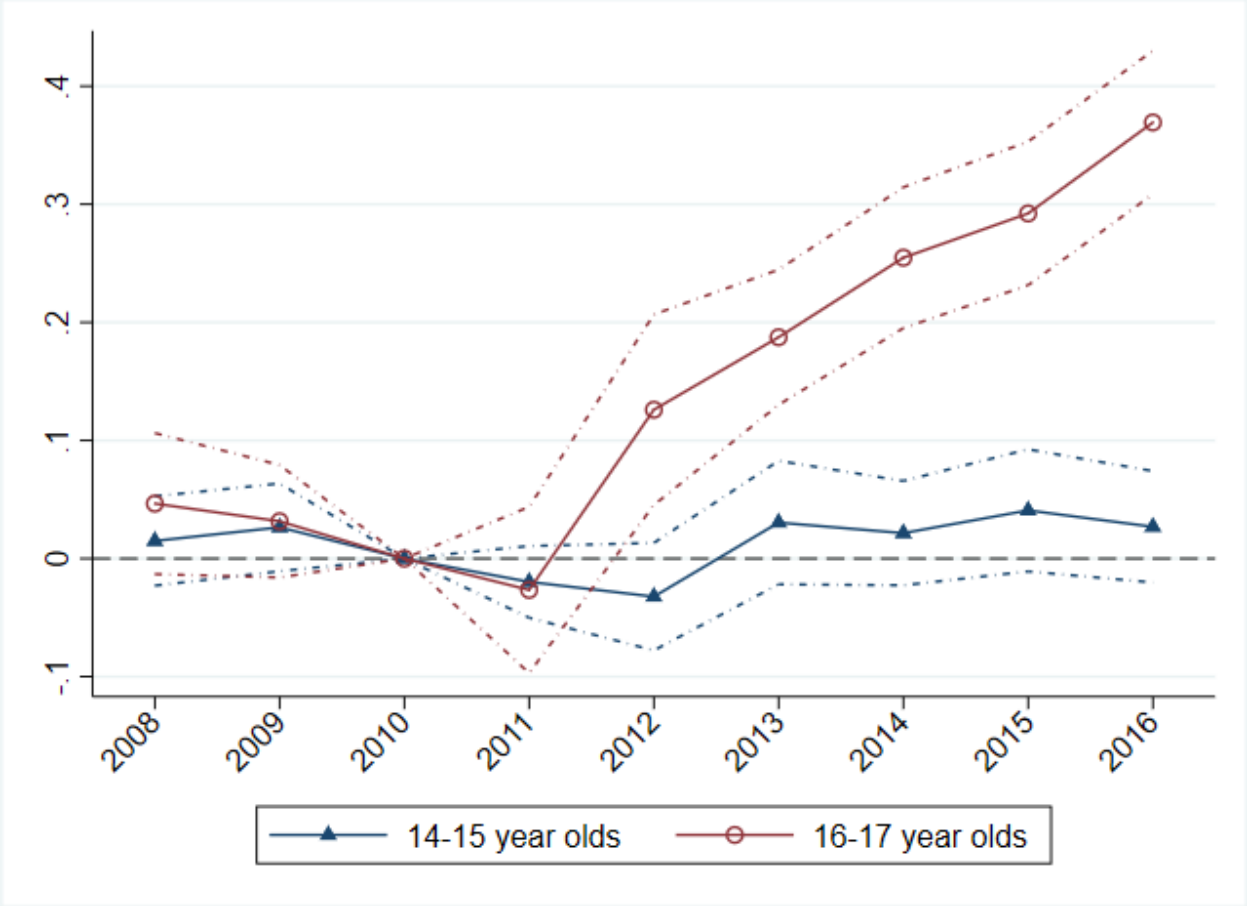
Figure 1:
Event Study Estimates of the Effect of the 2011 ACIP Recommendation On Vaccination Rates, Receipt of MCV4 vs. Tdap Vaccine

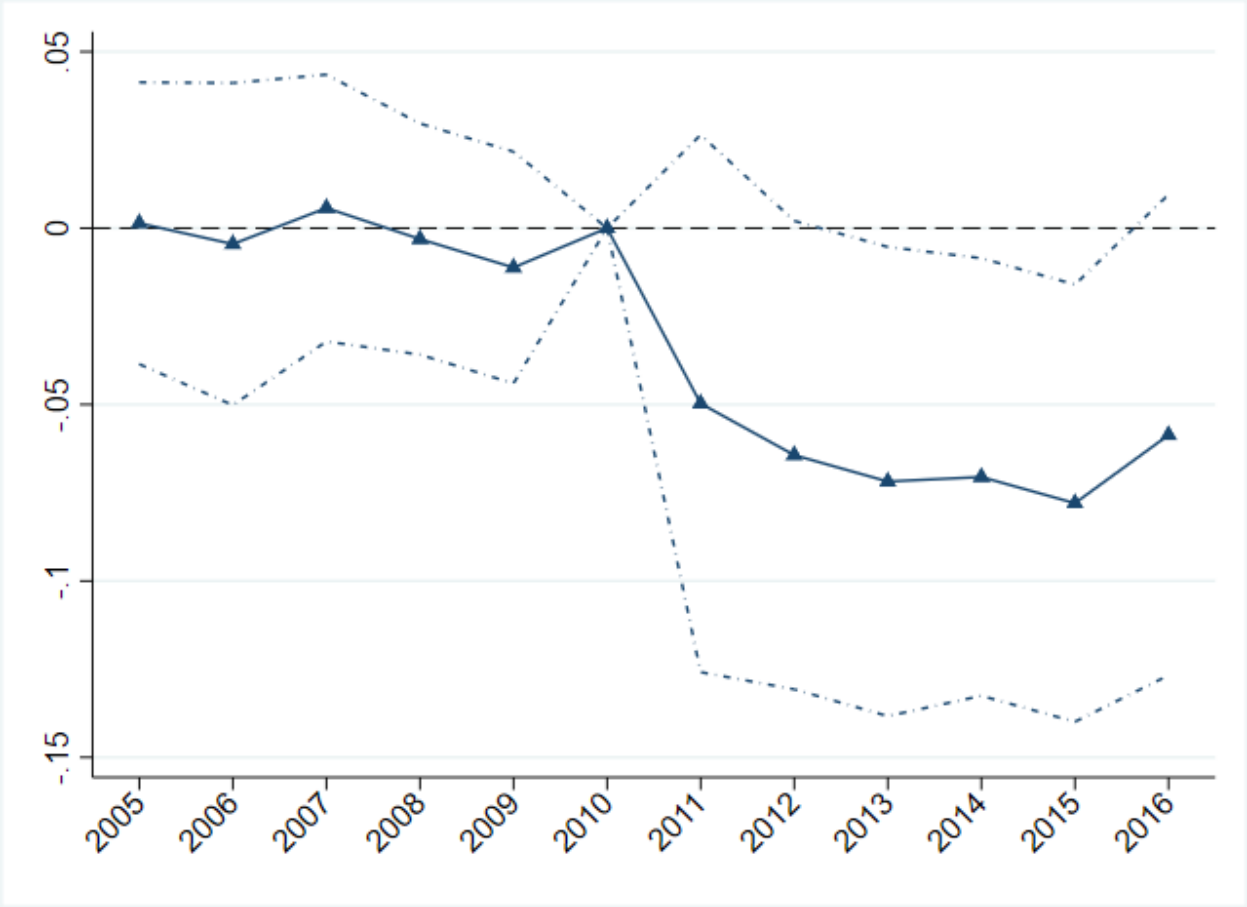


Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for the MCV vaccine. Coefficients are relative to the excluded year (2010), and the specification includes the interaction between the MCV indicator variable and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 2:
Triple-Difference Event Study Estimates of the Effect of the 2011 ACIP Recommendation On MCV4 Vaccination Rates

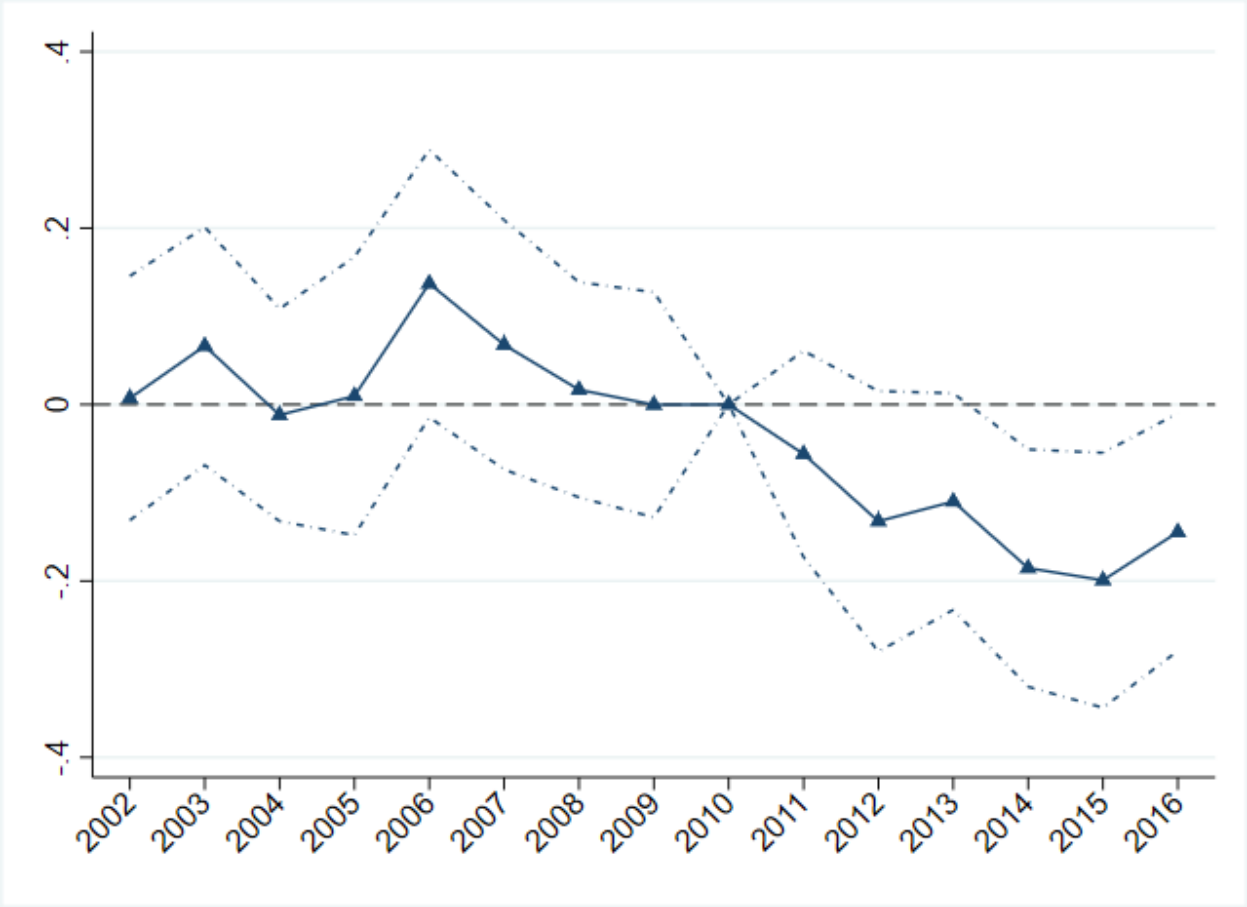
Notes: Reported coefficients are from the interaction between the stated calendar year, the indicator variable for the MCV vaccine, and the indicator variable for being age 17 at the time of survey. Coefficients are relative to the excluded year (2010), and the specification includes the interactions between the treatment group indicators and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 3:
Event Study Estimates of the Effect of the ACIP recommendation on Meningococcal Incidence Rates, Meningococcal serogroups ACWY vs. Meningococcal serogroup B



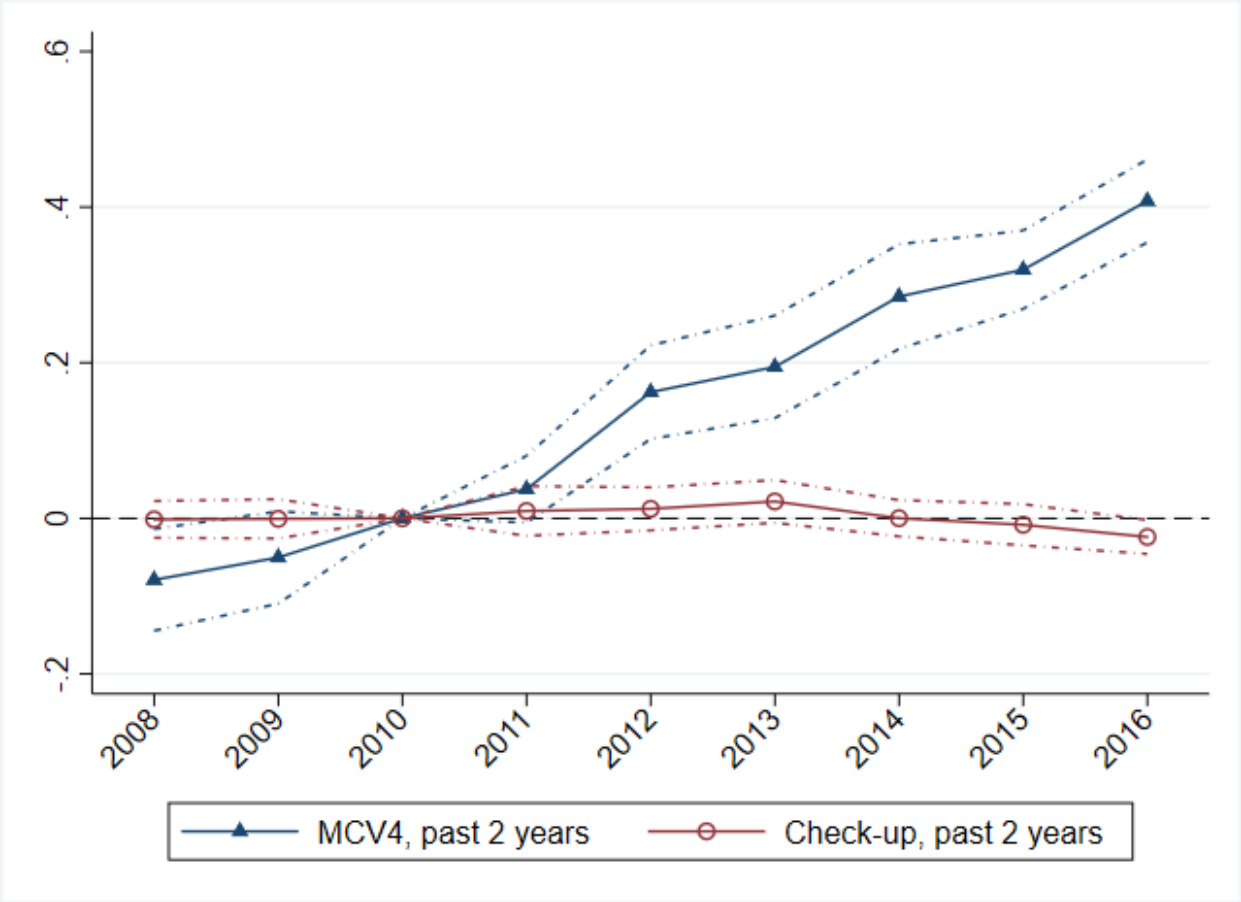
Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for meningococcal serogroups A, C, W, and Y. Coefficients are relative to the excluded year (2010), and the specification includes the interaction between the treatment group indicator variable and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 4:
Event Study Estimates of the Effect of the ACIP recommendation on Meningococcal Incidence Rates, Incidence among 15- to 24-year-olds vs 5- to 14-year-olds



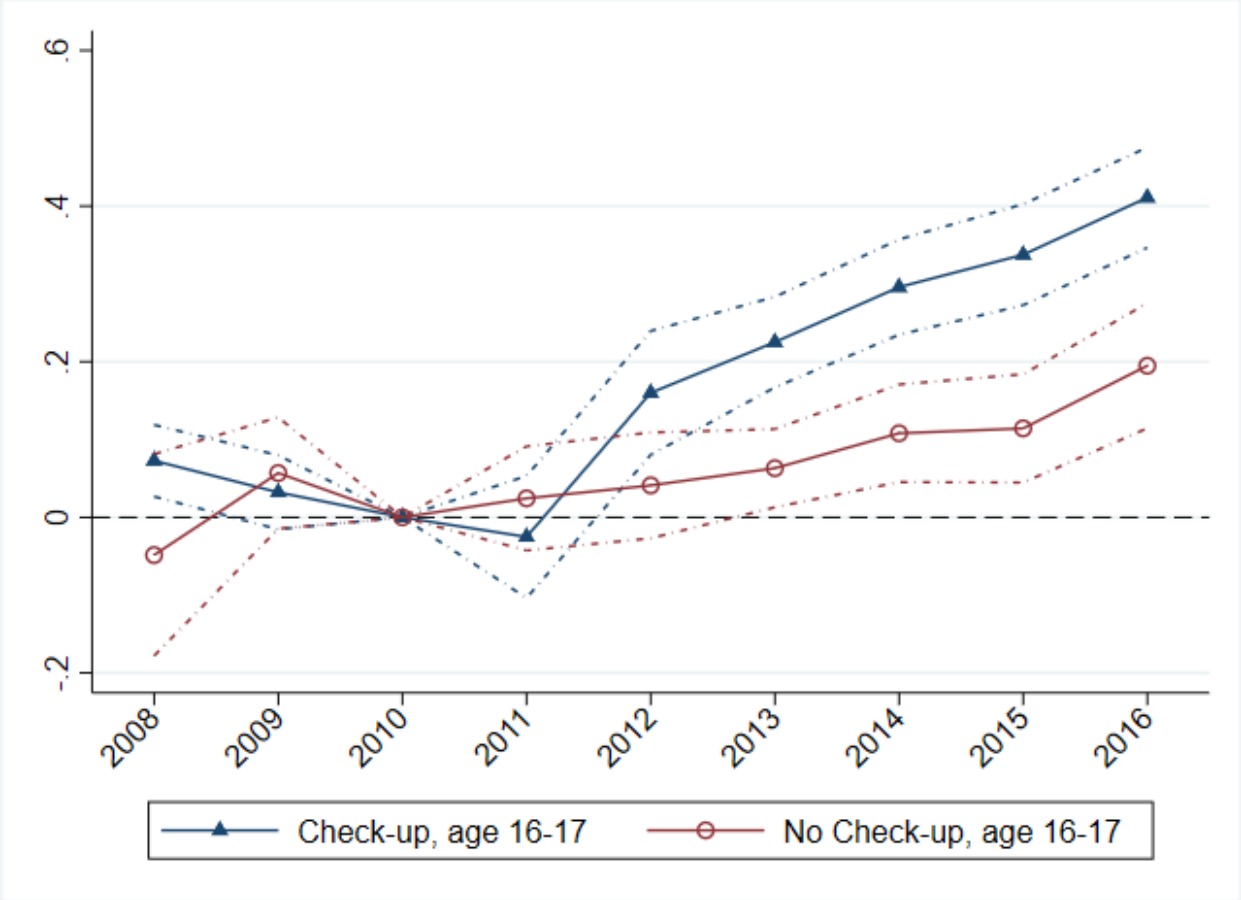
Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for the 15- to 24-year-olds age group. Coefficients are relative to the excluded year (2010), and the specification includes the interaction between the treatment group indicator variable and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 5:
Event Study Estimates of the Effect of ACIP Recommendation on Vaccination and Check-ups, 17- vs. 15-year-olds



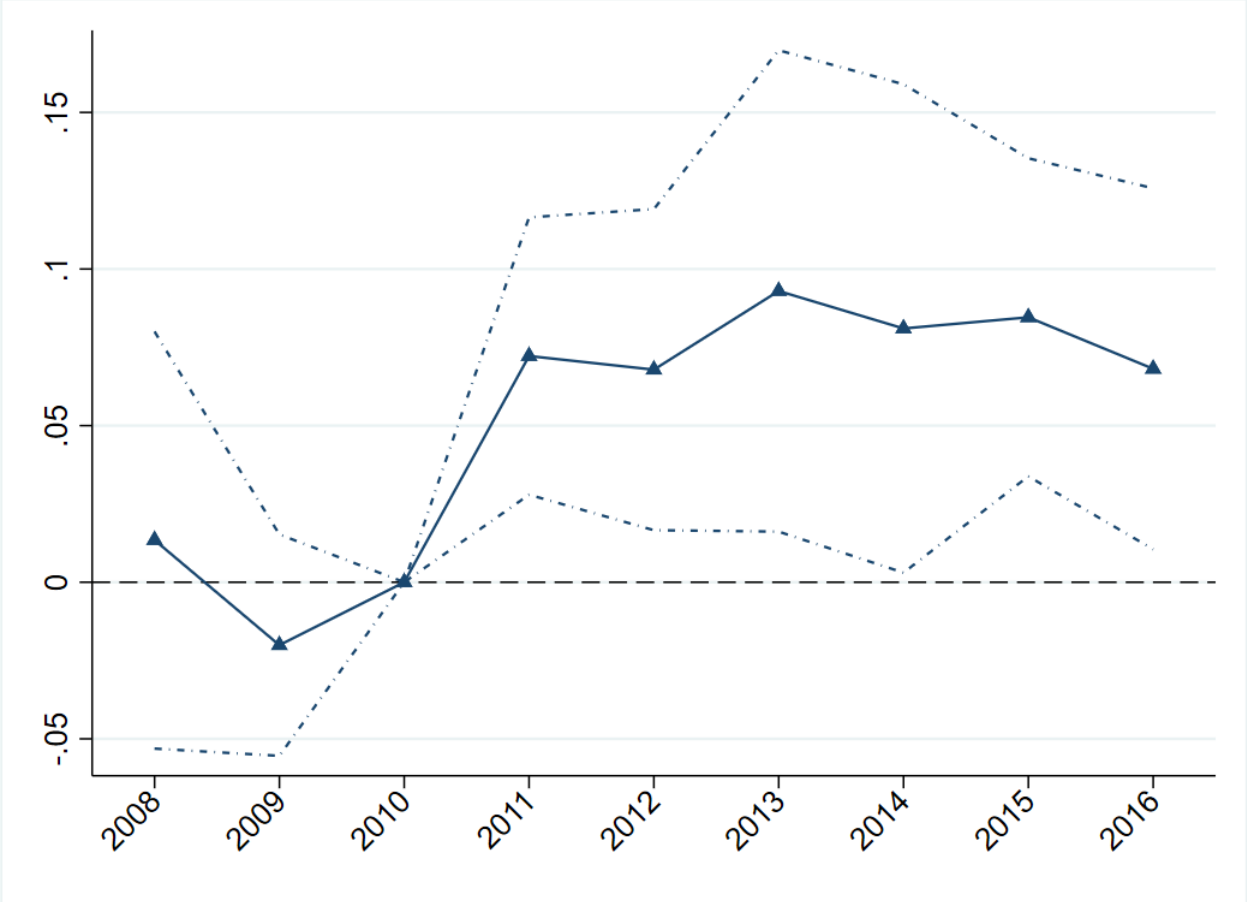
Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for being 17 at the time of interview. Coefficients are relative to the excluded year (2010), and the specification includes the interaction between the age 17 indicator variable and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 6:
Event Study Estimates of the Effects of ACIP Recommendation on Vaccination Rates by Adolescent Check-up Status, Receipt of MCV4 vs. Tdap Vaccine



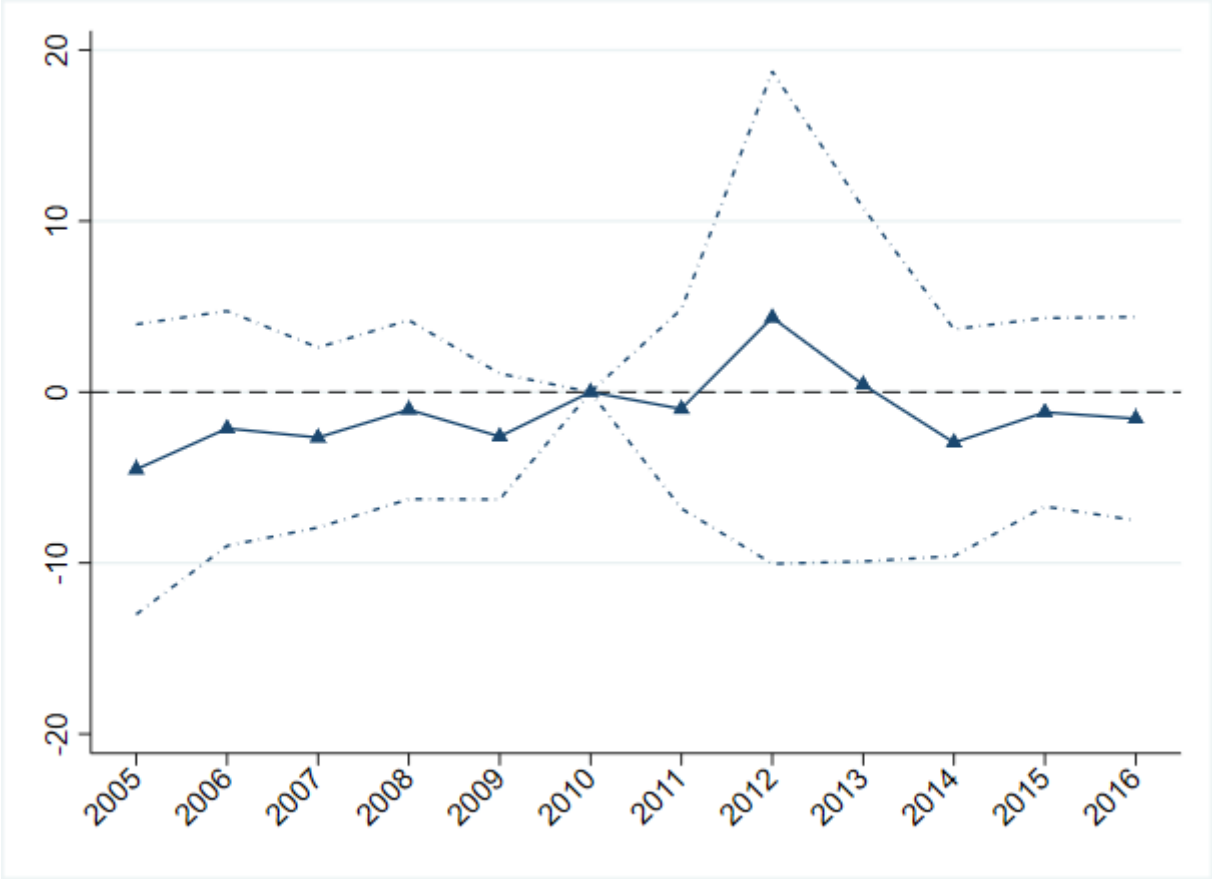
Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for the MCV4 vaccine. Coefficients are relative to the excluded year (2010), and the specification includes the interaction between the MCV4 indicator variable and the baseline vector of state vaccination and insurance policies. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 7:
Effects of ACIP Recommendation on MCV4 Vaccination Rates, Difference-in-Differences Model Using Variation in Provider Participation in Immunization Information Systems



Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for if a state had an above-median provider participation rate in the Immunization Information Systems in 2010. Coefficients are relative to the excluded year (2010), and the specification includes state and year fixed effects and the expanded vector of state policy controls, as described in the text. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Figure 8:
Effects of ACIP Recommendation on Google Searches for Meningococcal Related Terms, Difference-in-Differences Model Using Variation in Provider Participation in Immunization Information Systems



Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for if a state had above-median provider participation rates in the Immunization Information System in 2010. Coefficients are relative to the excluded year (2010), and the specification includes state and year fixed effects and the expanded vector of state policy controls, as described in the text. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Table 1:
Effects of ACIP Recommendations on Vaccination Rates, Comparing MCV4 to Tdap Vaccine Uptake
NIS-Teen (2008-2016)

	DD Estimates, *17-year-olds*: Pr (Receive Vaccine Dose, Past 2 years)		DD Estimates, *15-year-olds*: Pr(Receive Vaccine Dose, Past 2 years)		DDD Estimates: Pr(Receive Vaccine Dose, Past 2 years)	
	(1)	(2)	(3)	(4)	(5)	(6)
Post- 2010 ACIP X MCV	0.226***	0.156***	0.00636	0.00146		
	(0.0153)	(0.0275)	(0.0140)	(0.0212)		
	[0.002]	[0.002]	[0.636]	[0.979]		
Post-2010 ACIP X MCV X 17-year-old					0.220***	0.214***
					(0.0212)	(0.0243)
					[0.008]	[0.004]
Comparison?	MCV vs. Tdap vaccine	MCV vs. Tdap vaccine	MCV vs. Tdap vaccine	MCV vs. Tdap vaccine	MCV vs. Tdap vaccine, 15- vs. 17-year-olds	MCV vs. Tdap vaccine, 15- vs. 17-year-olds
State policy controls?	N	Y	N	Y	N	Y
Unique Observations	36758	36758	33386	33386	70144	70144
R-squared	0.0672	0.0751	0.0650	0.0677	0.0599	0.0711
Mean MCV4 Vacc. Rate Among Treated, Pre-ACIP	0.161	0.161	0.254	0.254	0.161	0.161
Estimated % Effect	140.4%	96.9%	2.5%	0.6%	136.6%	132.9%

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models estimated using NIS-Teen data; the sample in columns 1 and 2 is restricted to 17-year-olds, the sample in columns 3 and 4 is restricted to 15-year-olds, and the sample in columns 5 and 6 includes both 17- and 15-year-olds. Specifications in columns 1-4 include vaccine and year fixed effects, specification in columns 5 and 6 include vaccine, age, and year fixed effects, as well as all two-way interactions. The models in columns 2,4, and 6 additionally include the baseline set of state controls (state-level MCV4- or Tdap-specific vaccine policies and indicators for if the state has insurance mandates for the coverage of well-child visits and immunizations), interacted with the treatment group indicator variable, as specified in the text. All models use NIS-Teen sampling weights. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

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

	Meningitis Rate, Serogroup-Specific		Meningitis Rate, Age Group-Specific	
	(1)	(2)	(3)	(4)
Post- 2010 ACIP X TREAT	-0.0388***	-0.0631**	-0.185***	-0.182***
	(0.00866)	(0.0268)	(0.0271)	(0.0523)
	[0.002]	[0.002]	[0.002]	[0.008]
Comparison?	MenACWY vs. MenB	MenACWY vs. MenB	15- to 24- vs. 5- to 14-year-olds	15- to 24- vs. 5- to 14-year-olds
State policy controls?	N	Y	N	Y
Unique Observations	916	916	1632	1632
R-squared	0.255	0.292	0.451	0.460
Mean Incidence Rate among treated, pre-ACIP	0.140	0.140	0.658	0.658
Estimated % Effect	27.7%	45.1%	28.1%	27.7%

* significant at 10%; ** significant at 5%; *** significant at 1%. Serogroup information is only available starting in 2005, so the sample in columns (3) and (4) is restricted to 2005-2016. All specifications include treatment group and year fixed effects, and are weighted by state population. Columns 2 and 4 additionally include the vector of baseline state policy controls described in the text interacted with the treatment group indicator variable. Standard errors clustered at the state level are reported in parentheses. Also reported in brackets are p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot*.

Table 3:
Effects of ACIP Recommendations on Vaccination and Check-up Rates, NIS-Teen (2008-2016)

	Pr (Check-up, past 2 years)		Pr(Vaccine Dose, ages 16-17), preventive care visit at ages 16-17		Pr(Vaccine Dose, ages 16-17), no preventive care visit at ages 16-17	
	(1)	(2)	(3)	(4)	(5)	(6)
Post- 2010 ACIP X Treat	0.00833	0.00310	0.250***	0.177***	0.0938***	0.0815**
	(0.00599)	(0.00760)	(0.0158)	(0.0316)	(0.0286)	(0.0312)
	[0.080]	[0.528]	[0.000]	[0.006]	[0.194]	[0.238]
Comparison?	17- vs. 15-year-olds	17- vs. 15-year-olds	MCV4 vs. Tdap Vaccine	MCV4 vs. Tdap Vaccine	MCV4 vs. Tdap Vaccine	MCV4 vs. Tdap Vaccine
State policy controls?	N	Y	N	Y	N	Y
Unique Observations	125664	125664	27675	27675	5070	5070
R-squared	0.00444	0.0105	0.0752	0.0861	0.0167	0.0347

* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models, the sample in columns 1 and 2 are restricted to 17- and 15-year-olds, the sample in columns 3 and 4 is restricted to 17-year-olds whose parent reported that the adolescent had a check-up at age 16 or 17, and the sample in columns 5 and 6 is restricted to 17-year-olds whose parents did not report them having had a check-up at ages 16 or 17. All specifications include treatment group and year fixed effects, and use NIS-Teen sampling weights. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Table 4:
Differential Effect of the ACIP Recommendation based on Provider Participation Rates in Immunization Information Systems in 2010

	(1)	(2)	(3)	(4)
	1 dose MCV4, age 16-17	1 dose MCV4, age 16-17	Google Search popularity: Menin.-related terms	Google Search popularity: Menin.-related terms
Post- ACIP X above median IIS participation rate in 2010	0.0749***	0.0798***	2.156	2.009
	(0.0180)	(0.0181)	(2.024)	(1.987)
	[0.000]	[0.000]	[0.999]	[0.999]
Baseline State controls?	Y	Y	Y	Y
Additional State controls?	N	Y	N	Y
Observations	33386	33386	7332	7332
R-squared	0.0899	0.0911	0.313	0.324
Mean	0.259	0.259	19.60	19.60

* significant at 10%; ** significant at 5%; *** significant at 1%. Regressions in columns 1 and 2 are estimated using the sample of 17-year-olds in the NIS-Teen data set, and the outcome variable is an indicator for if the individual received a dose of MCV4 at age 16 or 17. Regressions in columns 3 and 4 are estimated using Google Trends data, and the outcome variable is the relative search popularity at the state-month level of searches that have the word "meningococcal" or searches that include both the words "meningitis" and "vaccine," where the month with the highest search volume in a given state is normalized to 100. All specifications include time and state fixed effects and the baseline set of state time-varying controls, as described in the notes to Table 1. Specifications in columns 2 and 4 additionally include controls for the state's non-medical exemption policy for school vaccine mandates (NCSL 2017), an indicator variable for if the state has expanded Medicaid, and variables that capture the state's race/ethnicity composition (percent black, percent Hispanic, and percent other), percent population female, state age distribution (percent under 21 years and percent 21-64), percent of population with high school degrees and percent with 4 year college degrees, state poverty rate, and state unemployment rate. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Table 5:
Heterogeneous Effects of the ACIP Recommendation on Receipt of MCV4, Triple-Difference Specification

	(1) Pre-2011 mean MCV4 vacc. rate	(2) Pr(Vaccine Dose, past 2 years)
Sub-group		
Females	0.165	0.222 (0.0294)*** [0.004]
Males	0.152	0.207 (0.0243)*** [0.002]
Mom education: Some college or less	0.149	0.190 (0.0269)*** [0.006]
Mom education: Completed College	0.185	0.259 (0.0281)*** [0.000]
Household Income: <$75k	0.148	0.184 (0.0266)*** [0.006]
Household Income: +$75k	0.169	0.257 (0.0267)*** [0.004]
Non-private Insurance	0.156	0.188 (0.0230)*** [0.030]
Private Insurance	0.164	0.231 (0.0278)*** [0.010]

* significant at 10%; ** significant at 5%; *** significant at 1%. Each estimate is from a separate regression. The reported estimate is the coefficient on the interaction term Post-2010 ACIP X MCV X 17-year-old; specifications include vaccine, age, and year fixed effects, and their two-way interactions, as well as the interaction between the baseline set of state policies and the treatment group indicators. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

APPENDIX

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Cost-Benefit Calculation

For my estimates of the social benefits of the ACIP recommendation, I take into account costs of averted medical care, both for treatment during illness and for resulting permanent disabilities, work time lost due to acute illness, and the value of lives saved due to the reduction in cases of meningococcal disease. The probability of sequelae estimates and associated costs are from Ortega-Sanchez et al. (2008) and are presented in Appendix Table 7. When available, I report estimated cost savings using both the base-case cost estimates and the sensitivity analysis range of costs. To estimate total averted cases of meningococcal disease, I use the coefficient estimate from column (2) of Table 2, which implies that per year the ACIP recommendation reduced the incidence of meningococcal ACWY by 0.0631 cases per 100,000 population, or equivalently, reduced total incidence by approximately 203 cases per year ((0.0631 cases/ 100,000) × 322.2 million total population, as of 2016). Using the estimates from the cross-age group comparison (column 4 of Table 2) suggests that 79 of those averted cases would have occurred among 15- to 24-year-olds ((0.182 cases/100,000) × 43.5 million 15- to 24-year-olds, as of 2016).

These estimates conservatively suggest that the ACIP recommendations result in 19 lives saved per year (203 averted cases × 9.3% mortality rate), and approximately 44 fewer individuals per year that are permanently disabled (estimated using disability specific probabilities, as reported in Appendix Table 7). Additionally, the age-group specific morbidity analyses suggest that approximately 17 of the averted disability cases likely would have been individuals in the 15- to 24-year-old age range, and thus the averted illness improved productivity for nearly their

entire working life.

Overall, this averted morbidity and mortality results in substantial social savings. Using the average cost of hospitalization and medical care associated with a case of meningococcal disease provided in Ortega-Sanchez et al. (2008), I estimate that the averted meningococcal cases result in a total savings per year in medical costs of nearly $5.9 million for acute cases (203 cases× $29,000 per case, range: $2.9-$8.7 million), with reductions in life-long medical costs due to averted permanent disability (using disability specific cost estimates) saving approximately $14.0 million (range: $5.6-$18.3 million). Taking into account work time lost for acute illness suggests an additional savings of approximately $351,600 per year. The social benefit from lives saved is even larger: using a value of statistical life of $7.4 million implies $139.7 million in social savings due to averted mortality each year (EPA 2018). In total, these estimates suggest that the ACIP recommendation resulted in approximately $159.9 million in social savings (range: $148.5 - $167.0 million). Notably, this estimate likely substantially underestimates the total social benefit, as it does not include productivity or quality of life gains from the averted permanent disabilities.

To estimate the associated costs of the policy I focus on the price of the additionally administered vaccine doses, their associated administration cost, and the cost of potential adverse events resulting from vaccination. Given the evidence that the recommendation did not change the probability of having a preventive care visit, I do not include in the cost estimate measures of the cost for time off of work and transit associated with the adolescent preventive care visit. My results imply that the recommendation resulted in approximately 898,800 more doses of MCV4 being administered to 16-year-olds each year (.214× approximately 4.2 million 16-year-olds), and, following Ortega-Sanchez et al. (2008), I use $83 as the per dose cost of the vaccine

(including administration costs, sensitivity range: $20-$110). In total this implies the additional vaccine doses and their administration cost approximately $74.6 million per year (range: $18-$98.9 million).

To estimate the costs of adverse events, I use estimates from Ortega-Sanchez et al. (2008) on the probability and average costs of moderate adverse events (e.g., fever or rash) and severe adverse events (e.g., anaphylactic reaction) following administration of the meningococcal vaccine. I find that the administration of the additional 898,800 doses of MCV4 administrated per year results in approximately 270 additional moderate adverse events (898,800 doses × 0.0003 probability of moderate adverse event) and approximately 1.8 additional serious adverse events per year (898,800 doses × 0.000002 probability of serious adverse event). These additional adverse events result in additional costs of approximately $61,196 per year ($117 per moderate adverse event × 270 additional moderate adverse events + $16,448 per serious adverse event × 1.8 additional serious adverse events).

In total, the social cost of the increased MCV4 vaccination, including adverse events and their associated costs, is approximately $74.66 million per year (range: $18.06-$98.96 million), while the estimated social savings estimate is approximately $159.9 million (range: $148.5 - $167.0 million). These cost-benefit analyses suggest that, on average, the social benefits of the increased MCV4 vaccination far outweigh the social costs. Specifically, these estimates suggest that each dollar in costs is associated with an average of 2.14 dollars in social savings.

Appendix Table 1:
Descriptive Statistics

	(1) Full sample	(2) Pre-ACIP Recommendation (pre-2011)	(3) Post-ACIP Recommendation (2011-2016)
NIS-Teen Data, 2008-2016			
Dose of MCV4, age 16-17	0.244	0.161	0.288
Dose of Tdap vaccine, age 16-17	0.105	0.169	0.071
Dose of HPV vaccine, age 16-17	0.186	0.157	0.201
Influenza vaccine (past 3 years)	0.337	0.196	0.411
Individual observations (17-year-olds)	31,585	10,069	21,516
CDC Morbidity Data, 2000-2016			
Meningococcal rate, ages 15-24	0.485	0.658	0.206
Meningococcal rate, ages 5-14	0.234	0.337	0.063
Meningococcal rate, Serogroups ACWY	.107	0.140	0.072
Meningococcal rate, Serogroup B	0.060	0.076	0.046
State-year observations	816	816	816

Notes: All values are weighted means calculated by the author from NIS-Teen 2008-2016 data, using provided sample weights or using CDC NNDSS data, 2000-2016, using age-group specific population measures from SEER. Morbidity rates are all per 100,000 population.

Appendix Table 2:
Effects on Tdap Vaccination Rates, Difference-in-differences model using variation in provider adoption of Immunization Information Systems

	(1) 1 dose TD-containing vaccine, age 16-17	(2) 1 dose TD-containing vaccine, age 16-17
Post- ACIP X above median IIS participation rate in 2010	0.00359 (0.0176) [0.834]	0.00554 (0.0198) [0.770]
Baseline State controls?	Y	Y
Full set of state Xs?	N	Y
Observations	33386	33386
R-squared	0.0511	0.0532
Mean	0.105	0.105

* significant at 10%; ** significant at 5%; *** significant at 1%. Regressions are estimated using NIS-Teen data, restricted to the set of individuals who were 17 years old at the time of the survey. All specifications include year and state fixed effects and the baseline set of state time-varying controls. The specification in column 2 additionally includes controls for the state's non-medical exemption policy for school vaccine mandates (NCSL 2017), an indicator variable for if the state has expanded Medicaid, and variables that capture the state's race/ethnicity composition (percent black, percent Hispanic, and percent other), percent population female, state age distribution (percent under 21 years and percent 21-64), percent of population with high school degrees and percent with 4 year college degrees, state poverty rate, and state unemployment rate. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Appendix Table 3:
Google Trends Searches for Meningococcal-related Terms

	(1) Google Search popularity: Meningococcal	(2) Google Search popularity: Meningococcal	(3) Google Search popularity: Meningitis	(4) Google Search popularity: Meningitis	(5) Google Search popularity: Meningitis AND Vaccine	(6) Google Search popularity: Meningitis AND Vaccine
Post- ACIP X above median IIS participation rate in 2010	0.570 (1.264) [0.999]	0.299 (1.036) [0.999]	0.486 (1.101) [0.999]	0.533 (1.038) [0.999]	1.623 (2.611) [0.999]	2.200 (2.424) [0.999]
Baseline State controls?	Y	Y	Y	Y	Y	Y
Full set of state Xs?	N	Y	N	Y	N	Y
Observations	7800	7800	7956	7956	6864	6864
R-squared	0.305	0.310	0.563	0.568	0.305	0.315
Mean	16.88	16.88	21.75	21.75	16.93	16.93

* significant at 10%; ** significant at 5%; *** significant at 1%. All specifications include month-year and state fixed effects and the baseline set of state time-varying controls. Specifications in columns 2, 4, and 6 additionally include controls for the state's non-medical exemption policy for school vaccine mandates (NCSL 2017), an indicator variable for if the state has expanded Medicaid, and variables that capture the state's race/ethnicity composition (percent black, percent Hispanic, and percent other), percent population female, state age distribution (percent under 21 years and percent 21-64), percent of population with high school degrees and percent with 4 year college degrees, state poverty rate, and state unemployment rate. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Appendix Table 4:
Differential Effect of the ACIP Recommendation based on MCV4 Vaccination Rate in 2010

	(1)	(2)	(3)	(4)
	1 dose MCV4, age 16-17	1 dose MCV4, age 16-17	Google Search popularity: Menin.-related terms	Google Search popularity: Menin.-related terms
Post- ACIP X below median MCV4 rate in 2010	0.0600**	0.0662***	1.584	2.304
	(0.0238)	(0.0219)	(2.000)	(1.995)
	[0.000]	[0.000]	[0.999]	[0.999]
Baseline State controls?	Y	Y	Y	Y
Additional State controls?	N	Y	N	Y
Observations	33386	33386	7332	7332
R-squared	0.0893	0.0905	0.313	0.324
Mean	0.259	0.259	19.60	19.60

* significant at 10%; ** significant at 5%; *** significant at 1%. Regressions in columns 1 and 2 are estimated using the sample of 17-year-olds in the NIS-Teen data set, and the outcome variable is an indicator for if the individual received a dose of MCV4 at age 16 or 17. Regressions in columns 3 and 4 are estimated using Google Trends data, and the outcome variable is the relative search popularity at the state-month level of searches that have the word "meningococcal" or searches that include both the words "meningitis" and "vaccine," where the month with the highest search volume in a given state is normalized to 100. All specifications include time and state fixed effects and the baseline set of state time-varying controls, as described in the notes to Table 1. Specifications in columns 2 and 4 additionally include controls for the state's non-medical exemption policy for school vaccine mandates (NCSL 2017), an indicator variable for if the state has expanded Medicaid, and variables that capture the state's race/ethnicity composition (percent black, percent Hispanic, and percent other), percent population female, state age distribution (percent under 21 years and percent 21-64), percent of population with high school degrees and percent with 4 year college degrees, state poverty rate, and state unemployment rate. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Appendix Table 5:
Heterogeneous Effects of Vaccination Policies on Receipt of MCV4 and Check-ups, Comparing 17- and 15-year-olds

	(1) Pre-2011 mean Check-up rate, 17-year-olds	(2) Check-up, last 2 years
Sub-group		
Females	0.835	-0.00278 (0.0184) [0.504]
Males	0.799	-0.00526 (0.0100) [0.764]
Mom education: Some college or less	0.797	-0.00644 (0.0103) [0.578]
Mom education: Completed College	0.855	-0.00229 (0.0130) [0.558]
Household Income: <$75k	0.788	-0.00328 (0.0112) [0.334]
Household Income: +$75k	0.864	-0.0119 (0.00990) [0.645]
Non-private Insurance	0.799	-0.00187 (0.0146) [0.572]
Private Insurance	0.828	0.000625 (0.0106) [0.840]

* significant at 10%; ** significant at 5%; *** significant at 1%. Each estimate is from a separate regression. The reported estimate is the coefficient on the interaction term POST-2010XAge17; specifications include age and year fixed effects, and the interaction between the baseline set of state policies and the indicator for being age 17 at the time of survey. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Appendix Table 6:
Effects of ACIP Recommendations on Vaccination, Conditional on Check-up at Age 16-17
NIS-Teen (2008-2016)

	Mom ed: ≤some college	Mom ed: completed college	HH income<$75k	HH income≥$75k	Non-private Insurance	Private Insurance
	(1)	(2)	(3)	(4)	(5)	(6)
Dep. variable: Pr(Vaccine Dose, ages 16-17)						
Post- 2010 ACIP X MCV4	0.184***	0.165***	0.150***	0.206***	0.165***	0.201***
	(0.0262)	(0.0517)	(0.0406)	(0.0269)	(0.0391)	(0.0320)
	[0.000]	[0.216]	[0.028]	[0.042]	[0.079]	[0.014]
Comparison?	MCV4 vs. Tdap	MCV4 vs. Tdap	MCV4 vs. Tdap	MCV4 vs. Tdap	MCV4 vs. Tdap	MCV4 vs. Tdap
State policy controls?	Y	Y	Y	Y	Y	Y
Unique Observations	15288	12387	13163	12870	9597	17843
R-squared	0.0780	0.106	0.0740	0.106	0.0770	0.0977

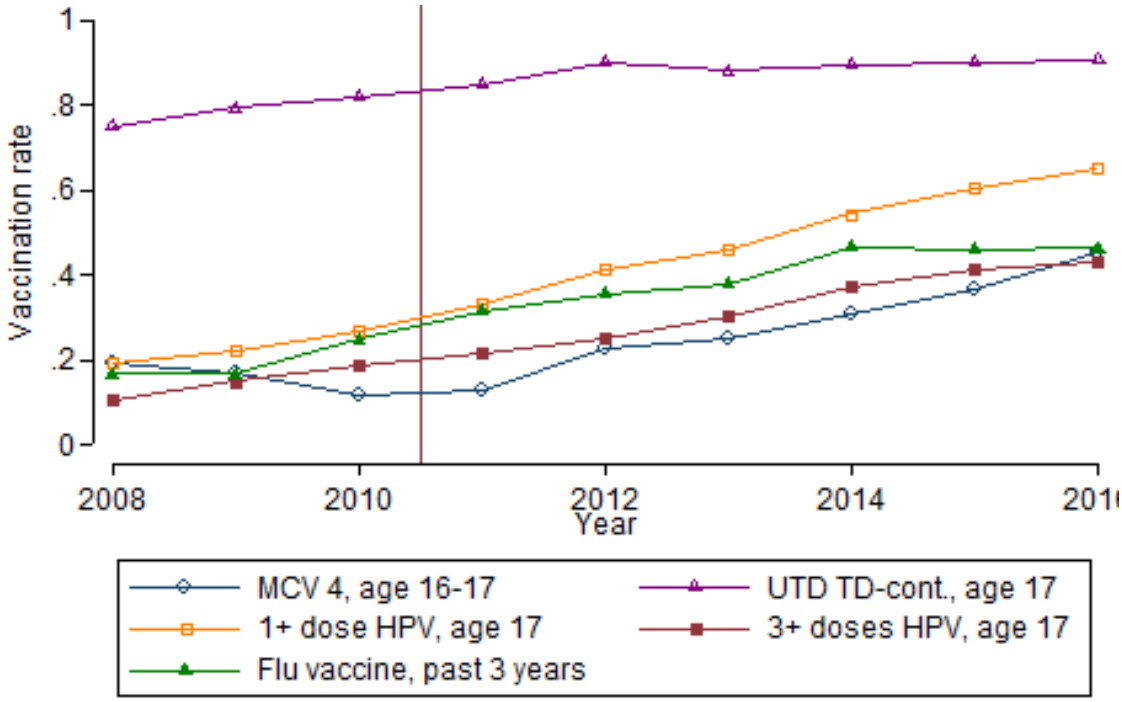
* significant at 10%; ** significant at 5%; *** significant at 1%. Results are from linear probability models, the sample is restricted to 17-year-olds whose parent reported that the adolescent had a check-up at age 16 or 17. All specifications include treatment group and year fixed effects, and use NIS-Teen sampling weights. Standard errors clustered at the state level are reported in parentheses, and p-values from models in which standard errors are clustered at the treatment group-year level, estimated using the wild bootstrap procedure proposed by Cameron, Gelbach, and Miller (2008) and implemented using the Stata command *cgmwildboot* are reported in brackets.

Appendix Table 7:
Probabilities of Sequelae and Costs of Meningococcal Disease

Event	Probability, conditional on acute illness	Average Cost Estimate (sensitivity range)
Medical cost, acute illness		$28,920 (14,244-42,733)
Work time lost, acute illness		$1,732
Permanent Disability		
Skin scarring	0.076	$5,770 (2,849-8,547)
Single amputation	0.019	$168,396 (91,990-275,972)
Multiple amputation	0.012	$20,2075 (110,338-331,165)
Hearing loss	0.088	$69,498 (26,190-68,640)
Neurologic disability	0.021	$2,707,394 (1,046,363-3,533,382)
Mortality	0.093	$7,400,000
Cost to vaccinate		$83 (20-110)

Notes: Estimates are from Ortega-Sanchez et al. (2008), with the exception of the mortality cost estimate, which is a measure of the value of statistical life and is from EPA (2018). The mortality rate estimates correspond to the estimates for 18-22 year olds.

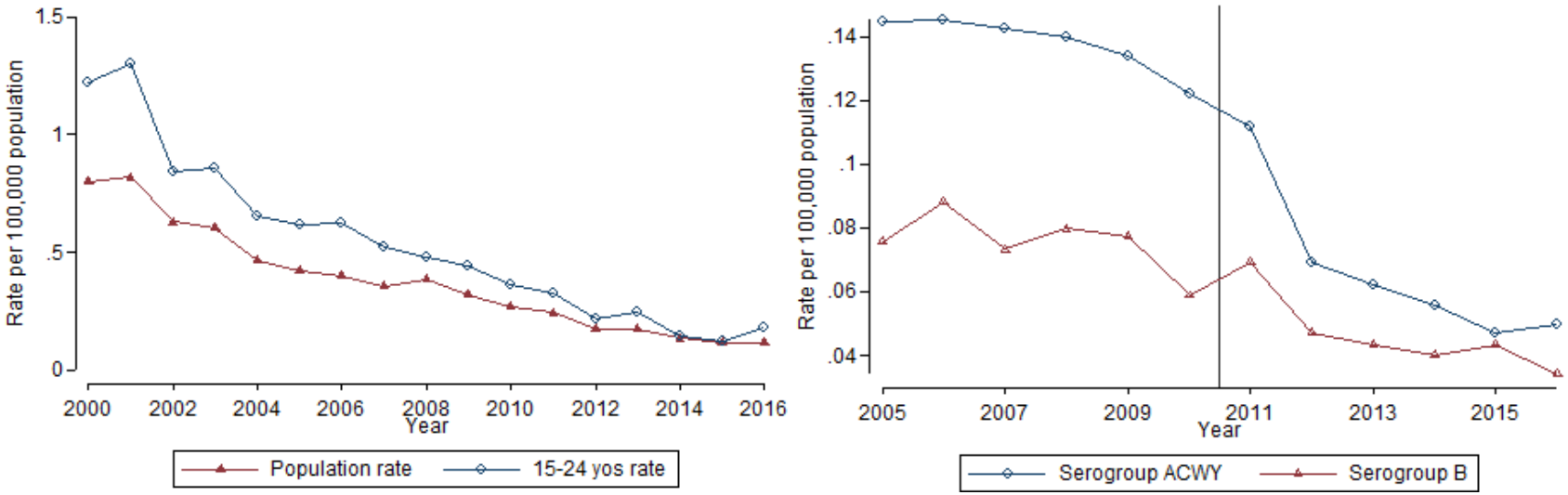
Appendix Figure 1: National Trends in Receipt of Adolescent Vaccines



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

Appendix Figure 2: National Trends in Meningococcal Disease Incidence

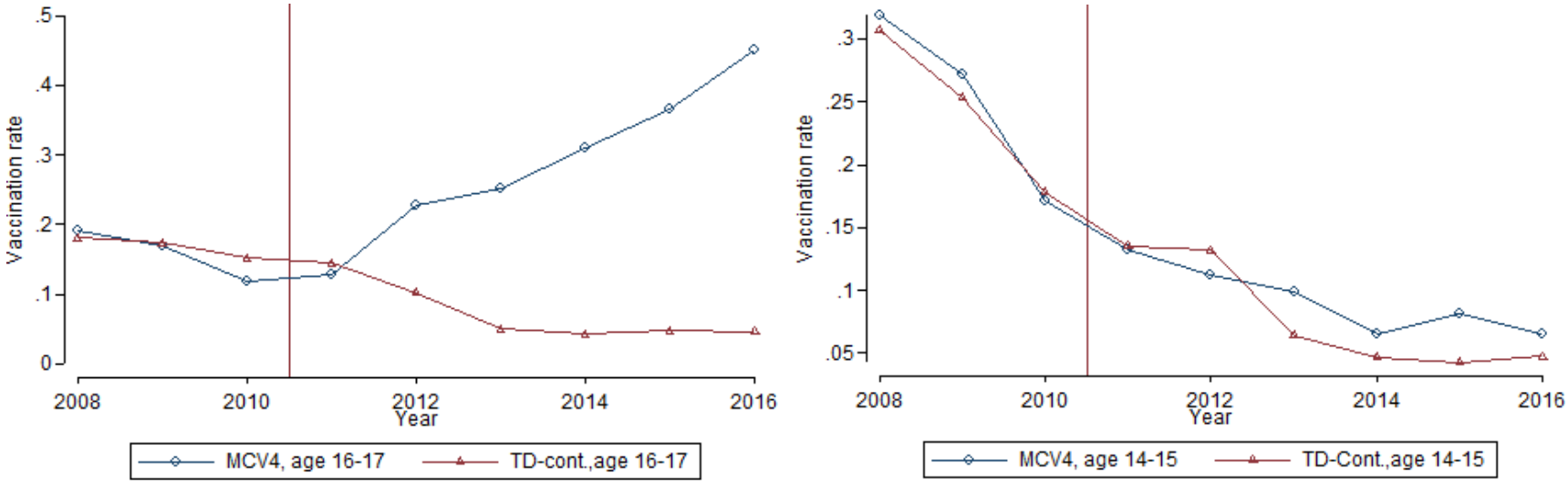
(A) **All serogroups, by age group** (B) **All age groups, by serogroup**



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

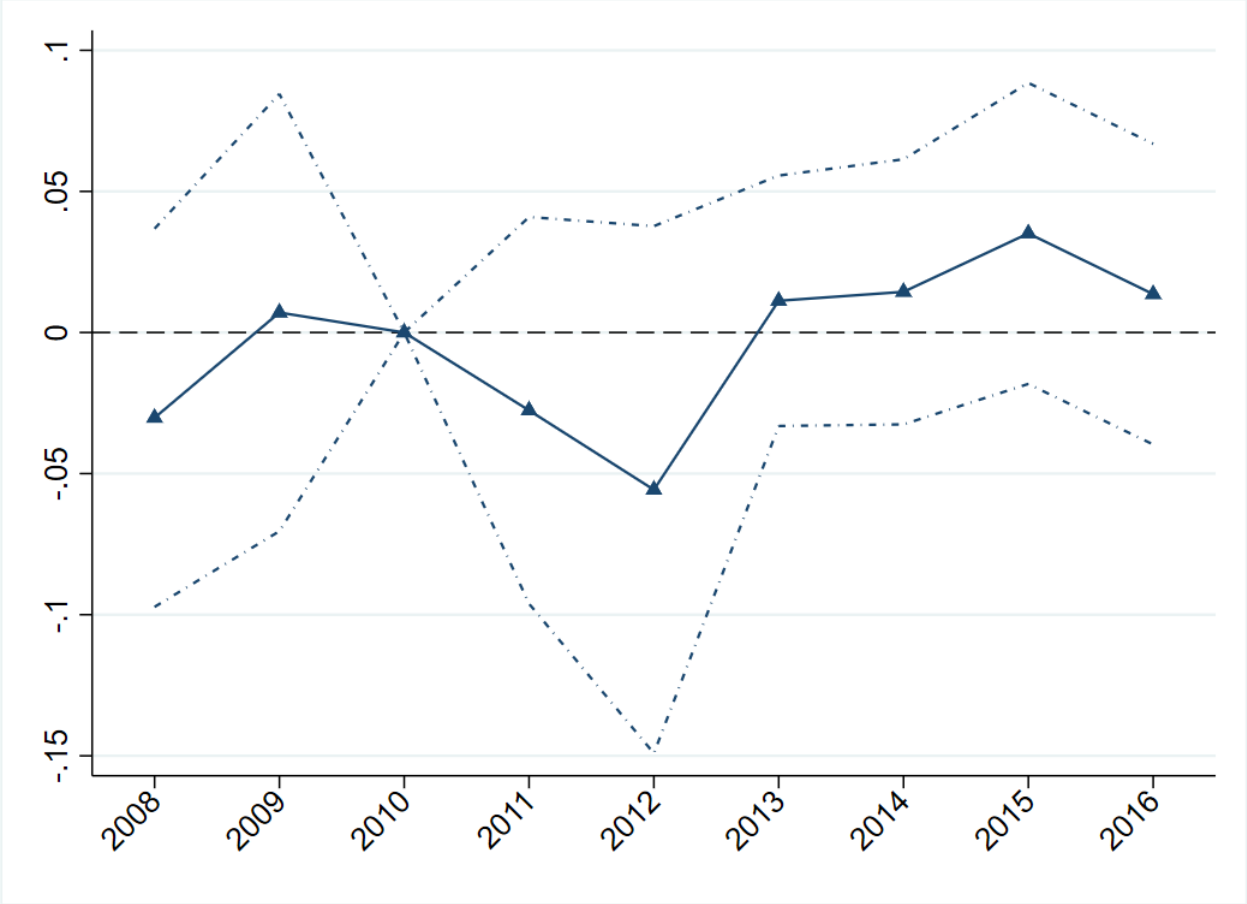
Appendix Figure 3: National Trends in Receipt of MCV4 and Tdap Vaccine, by age

(A) **Receipt at Age 16 or 17** (B) **Receipt at Age 14 or 15**



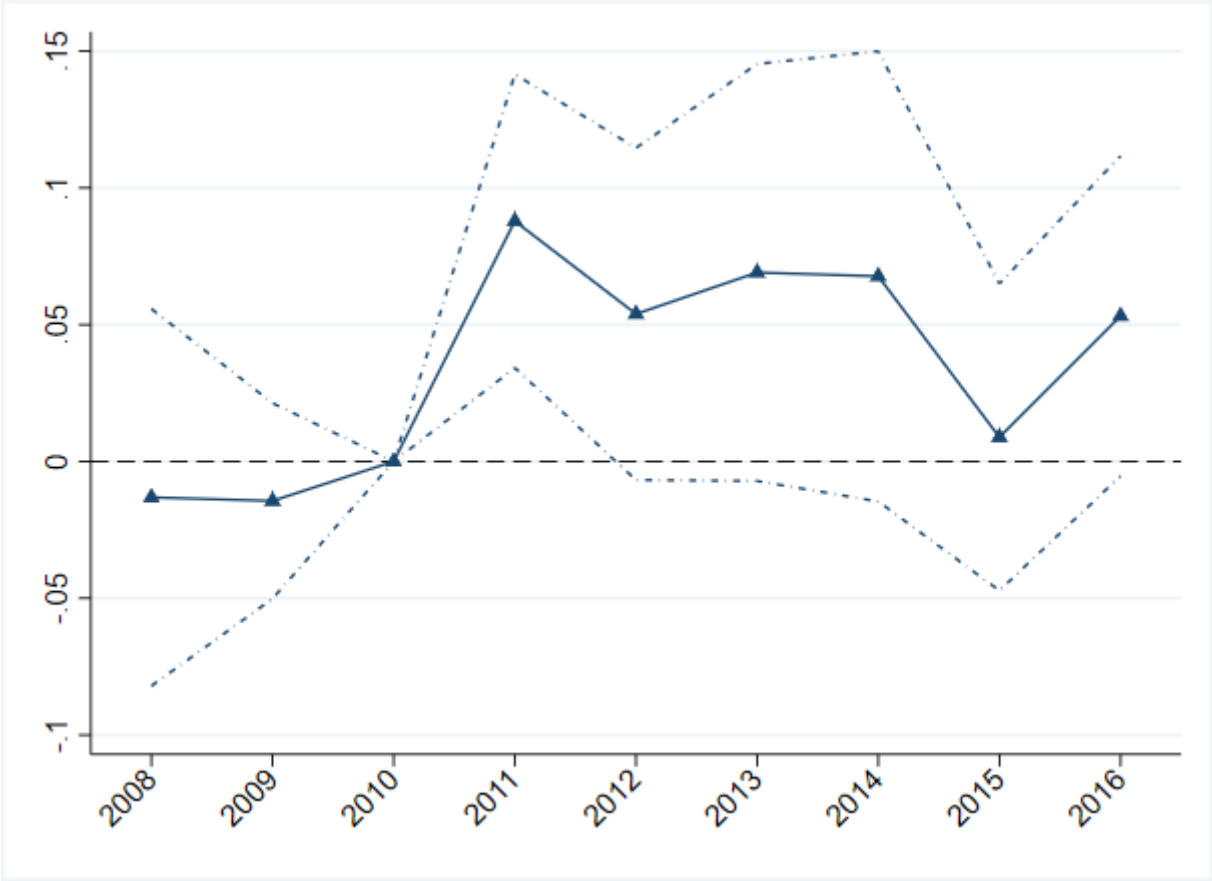
Notes: Data are from NIS-Teen, means are calculated using NIS-Teen provider weights. Sample in (A) is restricted to individuals who were 17 years old at the time of the survey, and the sample in (B) is restricted to individuals who were 15 years old at the time of the survey.

Appendix Figure 4:
Effects of ACIP Recommendation on Tdap Vaccination Rates, Dose Response Model Using Variation in Provider Participation in Immunization Information Systems



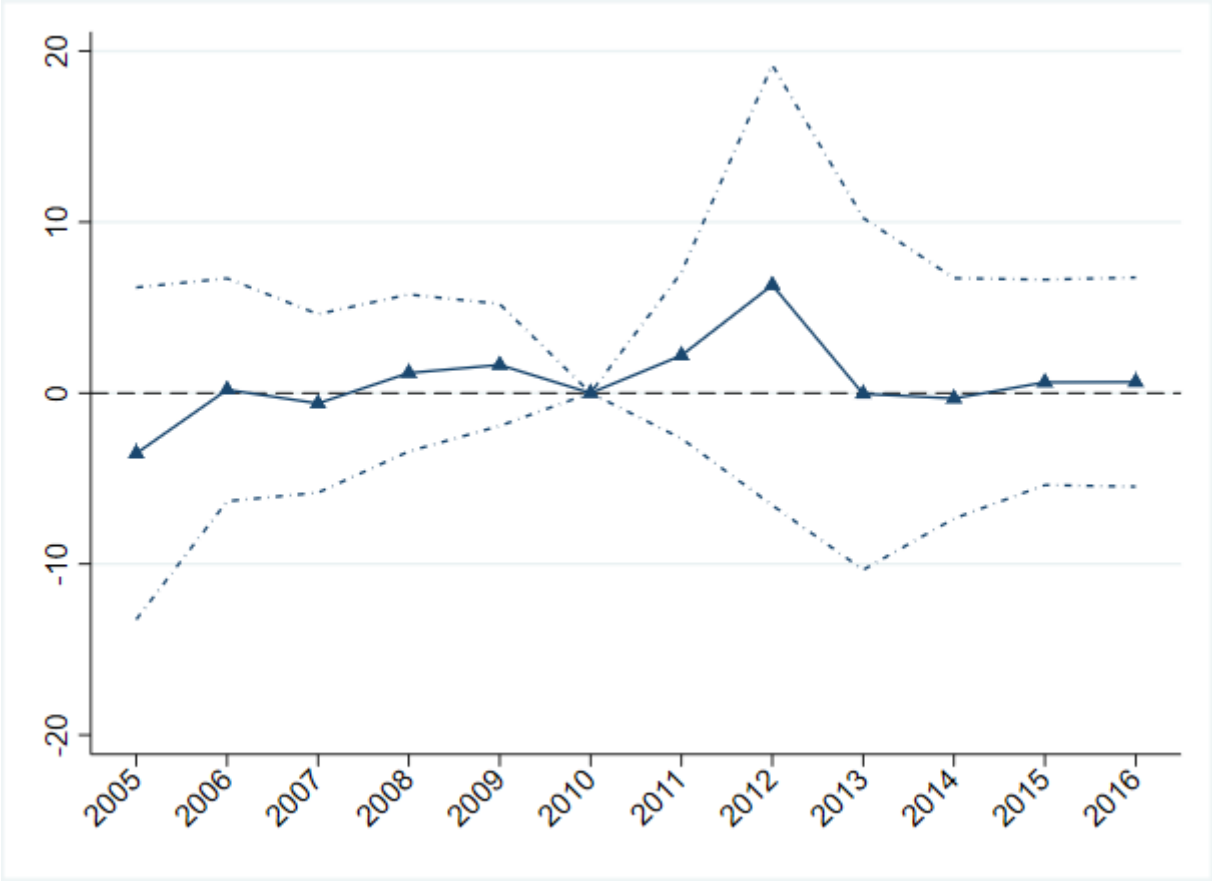
Notes: Estimates are from a regression using NIS-Teen data, in which the sample is restricted to individuals who were 17 years old at the time of the survey and the outcome variable is receipt of a TD-containing vaccine at ages 16 or 17. Reported coefficients are from the interaction between the stated calendar year and the indicator variable for if a state had an above-median provider participation rate in the Immunization Information Systems in 2010. Coefficients are relative to the excluded year (2010), and the specification includes state and year fixed effects and the expanded vector of state policy controls, as described in the text. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval

Appendix Figure 5:
Event Study Estimates of the Effects of ACIP Recommendation on MCV4 Vaccination, Using Variation in Baseline MCV4 Vaccination Rates



Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for if a state had below-median MCV4 vaccination rates in 2010. Coefficients are relative to the excluded year (2010), and the specification includes state and year fixed effects and the expanded vector of state policy controls, as described in the text. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.

Appendix Figure 6:
Event Study Estimates of the Effects of ACIP Recommendation on Google Searches for Meningococcal-Related Terms, Using Variation in Baseline MCV4 Vaccination Rates



Notes: Reported coefficients are from the interaction between the stated calendar year and the indicator variable for if a state had below-median MCV4 vaccination rates in 2010. Coefficients are relative to the excluded year (2010), and the specification includes state and year fixed effects and the expanded vector of state policy controls, as described in the text. Standard errors are clustered at the state level and dashed lines represent the 95% confidence interval.