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ABSTRACT

Reminder Design and Childhood Vaccination Coverage*

A major policy concern across public vaccination programs is non-compliance. Exploiting Danish population data and three national reforms in regression discontinuity designs, we document the effects of reminders for childhood vaccination coverage. Retrospective reminders are primarily effective for families with small children and when sent out close to the recommended vaccination age. Digital and postal reminders are equally effective. Prospective reminders increase timely vaccinations in later childhood and help reaching high coverage for new vaccines in increasingly complex vaccination programs. While reminders prompt additional preventive care for focal children, we find no spillovers to other health behaviors or relatives.

JEL Classification: I1, I12, I18

Keywords: vaccination, child health, public policy, reminder, Denmark

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1 Introduction

High and timely coverage rates in publicly-provided and funded vaccination programs are central public policy goals. Given coverage rates below the recommended target rates for central childhood vaccinations and recurrent outbreaks of preventable diseases in high-income countries with large-scale public vaccination programs (Shetty, 2010; Galles et al., 2021; Plans-Rubió, 2021), an active debate centers around the design of polices to increase (timely) adherence to childhood vaccinations in these settings.

In this paper, we zoom in on one widely used policy, namely reminder systems. Reminders raise the attention of individuals towards a specific action, such as getting a vaccination (Gravert, 2021). Simple reminders only shift focus toward the action without changing the receivers' attitudes, while more sophisticated reminders can include messages that potentially alter the receivers' attitudes and beliefs. Both dimensions may be important in the case of childhood vaccination programs, where parents may be inattentive to the recommended vaccination schedule, reluctant to comply with specific vaccinations, or both.[1]

Existing research from behavioral economics has documented that reminder systems are effective tools for raising vaccination coverage (Szilagyi et al., 2000; Bronchetti et al., 2015; Busso et al., 2015; Hirani, 2021; Milkman et al., 2021).[2] The majority of this evidence on the effectiveness of vaccination reminders comes from field experiments that study the extensive margin (receiving a reminder or not) and factor in questions of specific reminder timing and content (e.g., distributing pure reminders or reminders that include different types of messages) (Szilagyi et al., 2000). Given its experimental nature, this research typically focuses on specific samples of patients (often drawn from individual health care providers)

[1]Other popular policy options are pro-vaccination campaigns and vaccine mandates. In general, research indicates that pro-vaccination campaigns have limited impacts on vaccination decisions (Dubé et al., 2015), while vaccine mandates do increase coverage (Abrevaya and Mulligan, 2011; Karaivanov et al., 2022). In the Danish policy debate, mandates have traditionally been judged to be incompatible with the principle of a voluntary childhood vaccination program.

[2]Moreover, an active literature has studied the effect of reminders in other health care setting (Altmann and Traxler, 2014; Busso et al., 2017), charity donations (Damgaard and Gravert, 2018), savings (Karlan et al., 2016) and climate protection (Eisenbarth et al., 2021) among other areas.

and specific vaccination episodes.

This paper complements the empirical literature on reminders based on field experiments by studying a series of consecutive large-scale reminder policy changes in the national Danish childhood vaccination program. This public program covers all resident children between the ages of three months and 12 years, and it offers an encompassing series of 11 vaccinations. To identify the causal impact of different aspects of reminder design across children of different ages and across vaccination episodes, we exploit variation in reminder design introduced by three reminder policy reforms in regression discontinuity designs (RDD). We use administrative data on the full population of families in Denmark, which in combination with the population-wide reforms allow us to zoom in on three empirically relevant dimensions of vaccination reminder design: the timing and format of reminders, differences in reminder effectiveness across different vaccines (e.g., boosters vs. non-boosters and vaccinations in earlier vs. later childhood), and spillovers to other health behaviors.

Specifically, we exploit changes in the Danish vaccination reminder system in 2014, 2017 and 2019, which differentially impacted families around cut-off dates exclusively defined by children's dates of birth. The 2014 introduction of the national reminder system established a retrospective postal reminder for all non-compliant families, i.e., families with children lacking at least one of the vaccinations offered in the public program at three specific follow-up ages (between seven and 24 months after the recommended vaccination round). In 2017, digital retrospective reminders replaced the postal reminders. In 2019, reminders changed to their current form of being prospective, i.e., reminding all parents about each upcoming vaccination round. Additionally, non-vaccinated children in the 2019 system receive a follow-up reminder four weeks after the recommended vaccination age and the new prospective reminder includes more explicit messages on the positive externalities and social desirability of vaccinations.[3]

[3]See Appendices A.1 and A.2 for translations of the 2014 and 2019 reminder letters. While the 2014 retrospective letter only has limited messaging on the health benefits of vaccinations, the 2019 prospective letter includes more information on health effects, externalities and desirability of vaccinations.

Exploiting the variation in reminder design locally in a set of RDD analyses, we generate five main findings on the importance of timing and formate of reminders, their impact across well-established and new vaccinations, and finally spillover effects to other health behaviors: First, the 2014 introduction of retrospective vaccination reminder letters primarily impacted the coverage for the infant and toddler vaccinations recommended in the first two years of life. For the vaccination coverage among older children (age 6.5 and 14 at reminder receipt), we document that the 2014 retrospective reminder was only moderately effective or ineffective.

Second, switching from a retrospective postal reminder to a retrospective digital reminder letter did not impact the coverage rate of childhood vaccinations in Denmark. This change, however, dramatically decreased the yearly costs of the system. Third, the 2019 reform illustrates that prospective reminders have the potential to boost timely vaccinations: While we find no impact of changing the retrospective reminder to a prospective reminder on the timing of adherence for the youngest children (infant vaccinations), we find that the introduction of prospective reminders increased the timely uptake of later childhood vaccinations. Specifically, prospective reminders increased the uptake of the age four measles, mumps, rubella (MMR) booster by 5.2 percentage points and the age 12 human papilloma virus (HPV) vaccination coverage rate for girls by 18.8 percentage points within one year after the recommended age of vaccination. Thus, reminding all parents in advance of these childhood vaccinations increases timely coverage. This finding indicates that later childhood vaccinations are less salient than the early infant and toddler vaccinations, potentially due to less frequent interactions with the primary health care sector for children in these age groups. While we cannot yet conclude that the prospective reminder increases long-run coverage for treated children, even a pure timing effect for the treatment group is policy relevant. In the case of childhood vaccinations, population and individual health critically depend not only on aggregate coverage but also on timely vaccination uptake (Grant et al., 2003).

Fourth, we study the impact of the prospective reminder policy for a new vaccination: the HPV vaccine for boys. This analysis is an important case study of the scope of reminder

effects for new, and thus less salient, vaccines in increasingly complex vaccination systems. In Denmark, the HPV vaccine was well established for girls by 2019 (though at times subject to public controversies) but only introduced in the publicly provided program for boys in that year. We find strong gender heterogeneity in the impact of the 2019 reminder reform on HPV vaccination coverage. With the prospective reminder letter, the large gender gap (25 percentage points) in HPV vaccination uptake among all eligible girls and all eligible boys was virtually closed. This finding suggests that prospective reminders (providing timely information to families) are especially effective for vaccines that are not yet well-established in public vaccination programs.[4]

Fifth, we ask whether vaccination reminders promote other family health behaviors. Focusing on the introduction of prospective reminders in 2019, we find an eight percentage point increase in the share of children receiving the recommended routine preventive health check at the general practitioner (GP) at age four (scheduled at the same age as the MMR booster vaccine). Our findings suggest that vaccination reminders make this type of GP care more salient to parents (most likely through interactions with the GP office when scheduling vaccinations). In terms of other spillovers, we study older siblings' HPV vaccination uptake and mothers' uptake of cervical cancer screening (a behavior that may be directly impacted by reminders for children's HPV vaccination, as HPV infections are directly linked to this type of cancer). We do not find any spillovers of prospective vaccination reminders.

Our paper contributes to three streams of the literature: First, a large literature studies reminders and recall systems in a wide range of settings, such as health care, charity donations or financial decision making. Recent examples within the area of health behaviors include studies on the impact of reminders related to COVID-19 to foster vaccination uptake and social distancing (Dai et al., 2021; Li et al., 2021; Falco and Zaccagni, 2021; Cappelen et al., 2021; Chang et al., 2021). In line with the findings in this existing literature, we find

[4]As we discuss in detail, interpreting the gender difference in HPV uptake as an impact of the reminder on coverage with a new rather than established vaccine is supported by our analysis of gender gaps in responses to reminders for other (all well-established) vaccines (MMR). For those reminders, we do not find gender differences in reminder impacts.

that reminders can stimulate desired health behaviors at modest costs. Even at high baseline coverage rates for childhood vaccinations in the publicly funded Danish program, our study indicates that there is scope for relatively light interventions to foster positive health investments.

Second, we contribute to a literature that focuses on the determinants of vaccine uptake: Here several important channels have been identified, such as infection risks (Philipson, 1996; Bauch and Earn, 2004; Quadri-Sheriff et al., 2012; Böhm et al., 2016; Oster, 2018; Schaller et al., 2019), peer effects (Karing, 2018; Sato and Takasaki, 2019), religious beliefs (Lahav et al., 2021), societal recommendations and sanctions (i.e. mandatory vaccinations for day-care entry) (Carpenter and Lawler, 2019; Lawler, 2020), the perceived risk and severity of side-effects (Hansen and Schmidtblaicher, 2019; Carrieri et al., 2019; Gørtz et al., 2020), timely interaction and advice from health professionals (Hirani and Wüst, 2022), financial incentives (Banerjee et al., 2010; Campos-Mercade et al., 2021) and reminder systems (Szilagyi et al., 2000). Studying national reminder reforms in population data from Denmark, we complement earlier work that has focused on the impact of reminders in samples drawn from specific providers. At the same time, our estimates based on local RD designs are arguably specific to the respective reform setting. Interestingly, our main point estimates are well in line with findings from experimental work on childhood vaccination reminders: Szilagyi et al. (2000) review reminder policies in the context of childhood vaccinations across five randomized controlled trials. They report a median effect of 12.3 percent on vaccination coverage rates. This estimate is comparable to our effects of introducing prospective reminder letters on MMR coverage (7.2 percent) and female HPV coverage (12.9 percent) one year after the recommended vaccination age.

A third and final contribution of our work is an examination of potential spillover effects of vaccination reminders. Reminders raise attention towards vaccinations and may also impact other health behaviors or family members. Evidence about reminder letter spillovers is instrumental for policy design in the light of a recent literature on the importance of spillovers

in health behaviors within families exposed to other interventions or shocks (Al-Janabi et al., 2016; Daysal et al., 2019; Fadlon and Nielsen, 2019; Einav et al., 2020; Hodor, 2021). We find limited positive spillovers of reminders, and these are concentrated on preventive care at the GP for focal children that can typically be scheduled together with vaccines.

2 Background and Data

2.1 The Danish Childhood Vaccination Program and Reminder Letter Policy Reforms

All resident children in Denmark are offered vaccinations in the Danish Childhood Vaccination Program and preventive care in the GP preventive care program. Table 1 illustrates the schedule for the Danish Childhood Vaccination Program. It consists of eight vaccination rounds providing a total of 11 vaccinations that protect individuals against a host of preventable infectious childhood diseases. All vaccines in the program are voluntary and provided free of charge by the GP or a t rained nurse at the family GP clinics. Vaccinations are independent of each other. A child can, for example, receive the measles, mumps, rubella (MMR) vaccine without receiving the pneumococcal, diphtheria, tetanus, pertussis, polio (DiTeKiPol) vaccines. While the DiTeKiPol, pneumococcal and MMR vaccines have been a well-established part of the vaccination program since at least 1987, the human papilloma virus (HPV) vaccine is the most recent addition to the program and was introduced for girls aged 12 in 2009 and for boys aged 12 in 2019. Parallel to the vaccination program, the public GP preventive care program suggests eight child health checks recommended at five weeks, five months, and yearly for children aged one through six years.[5] Thus, GP preventive care is more frequent in the earliest childhood years, there is timely overlap with the vaccination program, and there are no recommended preventive GP contacts after age six. For all pre-

[5]These GP contacts involve a dialogue on age-related issues and screening for health problems. Moreover, all Danish families with newborns have access to a universal nurse home visiting program offering up to five universal first year home visits.

ventive care sessions parents have to take initiative and there is no national reminder system in place.

Tab. 1 Schedule of the Danish Childhood Vaccination Program

		- - - Vaccination Round and Age - - -							
		1st 3 mo.	2nd 5 mo.	3rd 12 mo.	4th 15 mo.	5th 4yr.	6th 5yr.	7th 12yr.	8th 12yr. 5 mo.
(1)	DiTeKiPol	✓	✓	✓					
(2)	Pneumococcal	✓	✓	✓					
(3)	MMR				✓				
(4)	Booster MMR					✓			
(5)	Booster DiTeKiPol						✓		
(6)	HPV							✓	✓

Notes: The table illustrates the current schedule of the Danish Childhood Vaccination Program. DiTeKiPol: Diphtheria-tetanus-pertussis-polio; MMR: Measles, mumps, rubella; HPV: Human papilloma virus
Source: The Danish National Board of Health (2022).

While not in place for general preventive care, a reminder system exists for the childhood vaccinations: The National Health Agency introduced it in 2014 based on the assessment that forgetfulness rather than reluctance was the main cause of non-adherence to the public childhood vaccination program in Denmark (Suppli et al., 2017; Hirani, 2021). The 2014 system introduced a (postal) reminder for parents of children who lacked at least one scheduled vaccination at specific follow-up ages. Implementation began on May 15, 2014 and children who turned 2, 6.5 and 14 years after this date received reminders (treatment group), while children with birthdays before that date did not receive any reminders (control groups). In earlier work and zooming in on the impact of reminders at age two, Hirani (2021) shows that the 2014 policy increased vaccination coverage for children in this youngest age group by 2.6 percentage points from a baseline of 75 percent. At the same time, 72 percent of parents who received a reminder regarding the vaccination status of their child aged two did not respond to it in the year after receipt of the reminder. Hirani (2021) only considers the impact of the 2014 reform on early childhood vaccinations (those recommended below age two) but do not deal with later vaccinations (MMR booster and HPV) as we do in this study.

The reminder system has been reformed twice since its introduction: First, since February 6, 2017, the reminder letter has been a digital rather than a postal reminder. After the reform, all parents with children who lacked a vaccination at ages 2, 6.5 and 14 years, received this reminder in their "eboks", a digital mailbox used by all Danish public agencies to communicate with residents on a variety of topics, such as health care, taxes or childcare. The 2017 reform created three discontinuities (defined by children's date of birth and thus age at introduction of the reform) with the control group receiving a postal reminder, and the treatment group receiving an identical digital reminder.

A second reform to the reminder system was introduced in 2019: This reform changed the target group, timing, number and specific content of the digital reminders. In the new system, reminders are sent to parents two weeks prior to the recommended vaccination age of their child. Thus, for each of the eight recommended vaccination rounds, all parents are reminded in advance (i.e., not only unvaccinated children's parents receive reminders). Additionally, one month after the recommended vaccination age, non-compliant parents receive an additional reminder.

Parallel to the change in timing and relevant recipient sample, the wording of the reminder letter was changed in the 2019 reform. While previously the reminder included a brief statement on vaccinations protecting the child, the new reminder includes additional statements on positive externalities and the social desirability of vaccinations: First, it informs parents that their vaccination decision is beneficial for other children as well as their own, specifically for children who cannot be vaccinated themselves due to poor health. Second, the letter includes statistics on the share of parents who participate at least once in the vaccination program. In our empirical analyses, we cannot disentangle the importance of the change in timing and the change in content of the reminder letter as both changes were implemented simultaneously and at scale.[6]

[6]Appendix A.1 shows the 2014 reminder letter. This letter was used until the 2019 reform. Appendix A.2 shows the two 2019 reminder letters (the prospective and follow-up reminder). The first letter reminds parents of the upcoming vaccination, informs parents how to get the vaccination (call family GP), briefly explains the benefits of vaccinations (protects other unvaccinated children as well as the child herself) and

Equivalent to the reminder introduction and the 2017 reform, the 2019 reform generates age group-specific cut-offs that assign different birth cohorts to different reminder regimes: First, children born after August 1, 2019 were subjected to the new reminder policy while children born prior to that date were not (thus receiving the retrospective reminder governed by 2017 rules). Second, children turning four years at November 1, 2019 or later enrolled in the new reminder letter policy for all future vaccinations while older children remained on the old policy (and would, if non-adherent, receive a reminder letter at age 6.5). Third, children turning 12 years on November 1, 2019 or later were enrolled in the new reminder letter policy for all future vaccinations, while children turning 12 earlier would, if non-adherent, receive a retrospective reminder letter at age 14. Thus, in the case of the 2019 reform, our comparisons will be across treatment groups that receive a prospective reminder and control groups that have not yet received their reminder (one year after the recommended vaccination date) but will receive a reminder if non-compliant two years after the recommended vaccination date (i.e., in the year 2021). Given that we have not yet enough data for follow up after the 2019 reform, our analysis will primarily focus on the impact of prospective reminders on the timing of vaccination adherence and on vaccination episodes with a full year of follow-up for treated children.[7] In the future, we will be able to see if a later (retrospective) reminder for the control group can help close vaccination coverage gaps that may result from responses of treated families to the prospective reminder.

illustrates the coverage rate (The reminder depicts a drawing of 10 children. Nine of the children wear green clothes and one child wears white clothes. The reminder letter states that "nine out of 10 children get vaccinated").

[7]For example, we cannot study the impact of the prospective reminder on DiTeKiPol booster at age 5. Children turning four years after the cut-off (the treated children) only receive their prospective reminder in the end of the year 2020 and thus we lack follow-up data.

2.2 Trends in Aggregate Vaccination Coverage across Danish Birth Cohorts

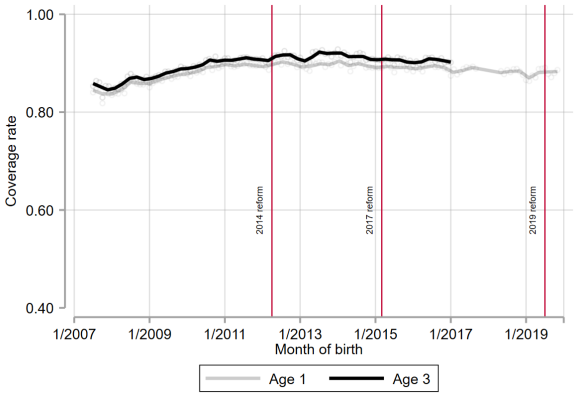
The introduction of the national reminder system in Denmark was not uncontroversial, because it implies that government authorities access personal health data and actively contact either non-adherent parents (in the 2014 and 2017 program) or all families with eligible children (in the 2019 program). Why did the National Health Agency deem this step necessary despite privacy concerns? The main arguments for the reminder system and its reforms are related to the considerable non-adherence in the Danish public vaccination program and its implied potential negative consequences for population health.

While we note that childhood vaccination coverage in Denmark is well above global averages,[8] we observe substantial non-adherence with (timely) vaccinations in Denmark. Across universally offered vaccines recommended at defined ages of the child, a considerable share of children receives vaccinations either with significant delays or not at all. Figure 1 presents short- and long-term coverage rates after the recommended vaccination age for a set of Danish birth cohorts observed in our data.[9] Panel (a) shows the coverage rate for the two infant vaccinations, panel (b) shows the coverage rate for all four vaccination rounds recommended prior to age two. Panels (c) and (d) illustrate the coverage rates for the MMR booster (recommended at age four) and the 12 year initial HPV vaccination (for girls only), respectively.

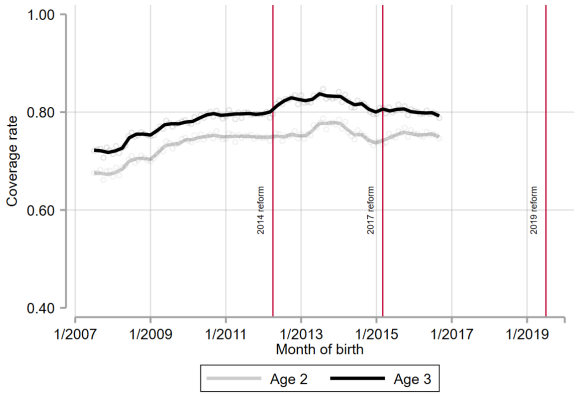
Some general observations emerge from Figure 1: First, across childhood vaccinations and boosters (DiTeKiPol and MMR), coverage rates recommended by the WHO that imply herd immunity (around 95 percent of all children) are not consistently reached. Only the first-year vaccinations reach coverage rates close to 90 percent (for cohorts born after 2010, slightly lower for older cohorts). Second, delays in coverage are important, i.e., longer-run coverage at two years after recommended vaccination age is higher than short-run coverage. This observation holds for all (childhood vaccination) coverage rates except first-year infant

[8] Globally, only 50-60 percent of children receive a DiTeKiPol and measles vaccine (Galles et al., 2021)

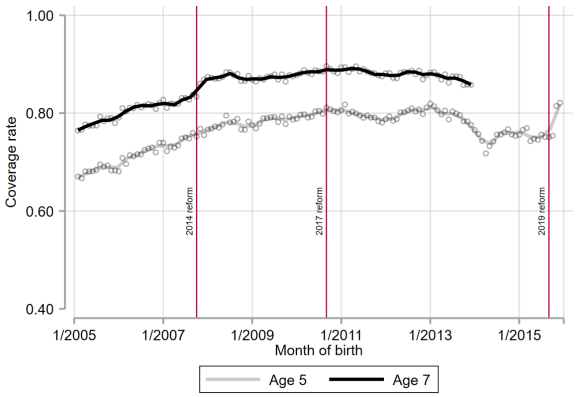
[9] As we detail in the data section, we construct these average coverage rates from individual level administrative records at Statistics Denmark.



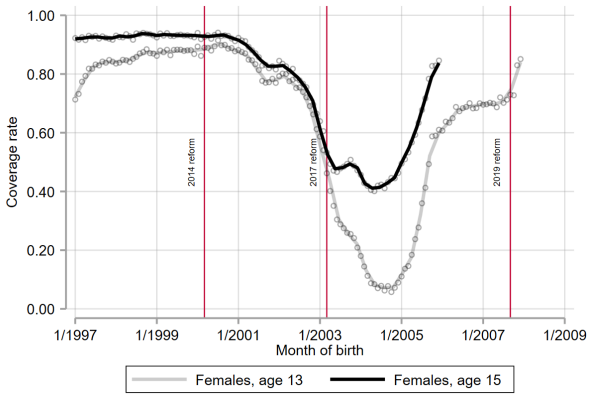
(a) Infant vaccinations at age 1 and 3



(b) Early childhood vaccinations at age 2 and 3



(c) MMR booster at age 5 and 7



(d) Female initial HPV vaccination at age 13 and 15

Fig. 1 Vaccination Coverage by Cohort and Age

Notes: The figure shows the share of children in each month of birth who received the first-year infant vaccinations (DiTeKiPol and Pneumococcal 1 and 2), all four early childhood vaccination rounds in the first two years of life, the MMR booster and the first HPV vaccination at specific ages. Dots mark the coverage rate for children born at a monthly level. Lines are estimated using local linear regression with a bin width of 2 months and triangular kernel. The figure is based on individual level administrative records on vaccination coverage from Statistics Denmark. For information on the vaccination schedule, consult Table 1. In the 2014 introduction of reminder letters, reminders were sent at age 2, 6.5 and 14 to parents of non-adherent children. The 2019 reform changed to timing of reminder dispatch such that reminders were sent two weeks in advance for all vaccination rounds and again one month after the recommended vaccination age if the child was non-adherent.

vaccinations. For early-childhood vaccinations recommended in the first two years, the difference between coverage at age two and three is around five percentage points, implying delays and less timely uptake than for first-year vaccinations. MMR booster coverage at age five is markedly lower than coverage at age seven (10-15 percentage points).[10] These figures indicate that a relatively large share of children receives vaccinations with a considerable delay.

Third, coverage rates are relatively smooth for all vaccinations except HPV. Panel (d) shows very large fluctuations in the coverage rate for this most recently added vaccine in the Danish program for girls.[11] Female children born prior to 2001 have coverage rates close to 90 percent at one and three years after the recommended vaccination date. However, for children born in the 2001-2005 period, the coverage rate drops sharply and reaches a minimum of 10 percent at age 13 for children born in 2004 (with a recommended vaccination date in 2016).[12] As other studies have documented, the drop in HPV coverage was closely linked to extensive media coverage of suspected severe side-effects from the vaccine, including a critical television documentary airing in March 2015 (Gørtz et al., 2020; Humlum et al., 2021). When those claims were refuted by the health authorities, coverage rates increased again and plateaued at around 70 percent prior to the 2019 reminder reform.

These general patterns in vaccination coverage over time set the stage for our study of the effectiveness of reminder letters. To identify the impact of reminders, we will zoom in locally on variation around reminder reforms that credibly distinguish longer run trends and other factors (such as extensive media attention) from reminder effects. The red lines in Figure 1 mark the 2014, 2017 and 2019 reminder reforms and thus highlight the local samples of children who will be studied in our main RD analyses on the impact of reminder design. As illustrated in the figures, we will be able to study short and longer-run impacts of the 2014

[10]MMR booster coverage at age seven has increased from below 80 percent for the 2005 cohort to 90 percent for the 2010 to 2012 cohorts.

[11]We focus on girls here as the HPV vaccine was only introduced for males in July 2019 (boys were eligible if born 12 years prior, i.e., in 2007).

[12]For the 2004 cohort, the difference between coverage at age 13 and age 15 is 30 percentage points, highlighting that most children in that cohort were very delayed in the uptake of the HPV vaccination.

and the 2017 reform on vaccine take-up but only short-run (timely) impacts on uptake in the case of the 2019 reform.

2.3 Data

We use administrative data from Statistics Denmark for the universe of births between 1997 and 2019. We link data across sources and family members using a unique personal identifier. From GP reimbursement data, we obtain information on our main outcome of interest, children's vaccination status at a given point in time for all vaccinations in the public system.[13] While we do not observe diagnoses in the GP data, we observe a set of other services, namely reimbursements for child health checks in the preventive care program, cervical cancer screenings for mothers, and overall GP reimbursement claims per patient and week. Those data allow us to assess spillovers to other health behaviors and family members. Finally, the data include background information on children and their families, including the child's date of birth and parental characteristics, such as age, education, employment and cohabitation status. These data help us assess the validity of our RD design.

Even though we have a long panel of children in our data (as also illustrated in Figure 1), in our analyses we create local reform samples of children of relevant ages around the cut-off dates of the initial introduction and reforms of the reminder system. For the 2014 introduction, we define three separate samples of children turning 2, 6.5 and 14, 100 days around the implementation date on May 15, 2014. Children with birthdays prior to that date did not receive a reminder letter at the specific ages, while children with birthdays after received the retrospective reminders. For the 2017 reform, we create three samples of children turning 2, 6.5 and 14 in the 100 days prior to and past the introduction date for digital reminders on February 6, 2017. Finally, for the 2019 reform, we create three separate samples of children who are born, turn four and 12 years respectively in the 100/60 days prior to and after the relevant cut-off dates for the introduction of prospective reminders for

[13] The reimbursement data contain the week of service rather than the actual day.

Tab. 2 Summary Statistics for the Reminder Reform Samples

	Reform					
	2014		2017		2019	
	Control	Treatment	Control	Treatment	Control	Treatment
	(1)	(2)	(3)	(4)	(5)	(6)
Inc., father	372.65	367.83	378.91	384.08	393.79	384.24
Inc., mother	247.14	228.79	228.04	236.18	260.77	255.48
Health educ., mother	0.15	0.15	0.14	0.14	0.13	0.13
Health educ., father	0.03	0.03	0.03	0.03	0.03	0.03
Prim. educ., mother	0.12	0.12	0.11	0.11	0.10	0.10
Prim. educ., father	0.14	0.14	0.13	0.13	0.11	0.12
Higher educ., mother	0.29	0.29	0.28	0.29	0.26	0.26
Higher educ., father	0.20	0.19	0.19	0.19	0.17	0.16
Uni. degree, mother	0.15	0.16	0.17	0.17	0.19	0.19
Uni. degree, father	0.15	0.15	0.15	0.16	0.17	0.17
Danish, mother	0.84	0.84	0.81	0.82	0.79	0.79
Danish, father	0.83	0.83	0.81	0.81	0.78	0.78
Employed, mother	0.85	0.84	0.81	0.82	0.86	0.86
Employed, father	0.92	0.91	0.91	0.92	0.93	0.92
Married	0.59	0.58	0.57	0.56	0.48	0.46
Cohabiting	0.79	0.79	0.80	0.81	0.82	0.81
Observations	43203	43440	40967	42044	33424	32573

Notes: The table shows means of background characteristics measured one year prior to the reforms for parents of children included in the control and treatments groups for the 2014, 2017 and 2019 reforms. The table combines families in the control and treatment groups across the three reform samples. For summary statistics by reform sample, see Appendix Tables A1, A2 and A3. Health education is an indicator for at least one of the parents of a focal child having completed training as either a medical doctor, midwife, early childhood teacher or nurse. Income of mothers and fathers is in 1,000DKK.

all families: For the first-year vaccination sample (cut-off date is August 1, 2019) we choose a 100-day bandwidth around the cut-off, while for the MMR booster and HPV samples (cut-off date is November 1, 2019) we choose a 60-day bandwidth. This constraint is due to our data covering GP expenses up to and including the year 2020. Thus, we have to restrict our bandwidths for the MMR booster and HPV samples to observe outcomes (vaccination adherence at least one year after receipt of the reminder) for all children in our analysis sample. Finally, as discussed, our main analyses for the HPV reminders are only based on (eligible) female children.

Table 2 presents summary statistics for the parents of control and treatment groups of

children included in our study. For brevity, we collapse the treatment and control groups across all three reforms.[14] Treatment and control families in Table 2 are very similar in central parental background characteristics, indicating no imbalance at the relevant cut-offs. This finding is central for our identification strategy discussed in the following section.

3 Empirical Strategy

To identify the causal effects of reminder design, we rely on exogenous variation in treatment status generated by the cut-off dates in separate regression discontinuity designs (RDD). Parents of children with birth dates around these cut-off dates are very similar in all aspects other than treatment assignment, which is exclusively determined by children's date of birth:

$$T_i = 1\{d_i \geq 0\}, \tag{1}$$

where T_i is an indicator for treatment (i.e., assignment to a specific reminder letter policy) and d_i is child i's date of birth relative to the cut-off date. We identify the causal effect of the reminder letter reforms (α) relative to the relevant counterfactual, no reminder policy or the previous reminder policy, on vaccination behavior (y_i) by estimating the discontinuity in (y_i) at the cut-off $d_i = 0$,

$$\alpha = \lim_{\epsilon \downarrow 0} E[y_i \mid d_i = \epsilon] - \lim_{\epsilon \uparrow 0} E[y_i \mid d_i = \epsilon]. \tag{2}$$

To estimate α we use local linear regressions with a triangular kernel and conventional

[14] Appendix Tables A1 through A3 show descriptive statistics for the separate reform samples. As the Appendix Tables show, for each reform and age group, the control and treatment groups are comparable along parental background characteristics. The HPV samples for the 2014 introduction of reminder letters and the 2017 reform are half the size of the other samples because the samples only include female children. The first-year vaccination sample for the 2019 reform includes more children due to the larger bandwidth compared to the 2019 reform samples for older children.

standard errors. In our main specification, we present estimates using a fixed bandwidth (100 and 60 days) and the optimal bandwidth as developed in Calonico et al. (2020). To assess the robustness of our main results, we perform a host of robustness tests. For conciseness, we present those analyses in Appendix Figures A8 through A10. These figures contain specification curves for our three reform RD analyses with coefficients from alternative specifications sorted from lowest to highest (along with 95 percent confidence intervals). In the analyses summarized in those figures, we vary our main bandwidths using local linear regressions, we estimate alternative OLS regressions with linear, quadratic and separate trends on either side of the cut-off, and we implement a Regression Discontinuity-Difference in Differences (RD-DD) specification (including treatment and control groups of children from a year prior to the relevant reforms as in Bound and Jaeger (1996); Buckles and Hungerman (2013); Currie and Schwandt (2013)). We use seven different bandwidths and five different estimation method resulting in a total of 35 distinct specifications. In general, our main results and conclusions are very robust to the changes in sample and specifications considered. As discussed in the results section, our main specification produces estimates that, for the most part, are located in the middle of the specification curves.

In addition to testing the robustness of our findings to changes in our specification, we have conducted two sets of analyses to informally assess the two central identifying assumptions in our analyses: First, our analyses assume that parents cannot select into treatment. This assumption is undoubtedly true as all children in our analyses are born by the time of the reforms. To assess the assumption with actual data, we test for bunching around the reform cut-offs. We perform both a graphical and a formal test to assess bunching (McCrary, 2008). Appendix Figures A1 through A3 show the distribution of children across the cut-offs in 2-day binned histograms for the 2014, 2017 and the 2019 reforms and for each cut-off separately. The figures show that children are uniformly distributed across the range of the running variable, including close to the cut-off, but that there is a lot of (expectable) variation across two day bins. A formal McCrary test (Appendix Table A4) cannot reject the hypothesis of

no bunching in either the 2014 and 2019 reform samples but finds indication for bunching in two of the 2017 samples (significant at the 10 percent level).

Second, in the RD analyses, we assume that other pre-treatment characteristics develop smoothly around the cut-offs that we use. Appendix Tables A5 through A7 show results for tests for discontinuities at the cut-off in a set of pre-birth parental characteristics. In general, we do not find any systematic discontinuities in family characteristics at the relevant cut-offs. Given the large number of tests, the share of significant estimates (and their small size) leaves us confident that the treatment and control groups in our RD samples represent very similar groups of families, as expected.

4 Results

4.1 Introduction of Reminder Letters (2014 Reform)

Figure 2 presents our results for the impact of the introduction of reminder letters for non-compliant families in 2014. We present analyses for samples of children turning 2, 6.5 and 14 around the relevant cut-off date. The depicted outcome is the vaccination coverage one year after receipt of a reminder.[15]

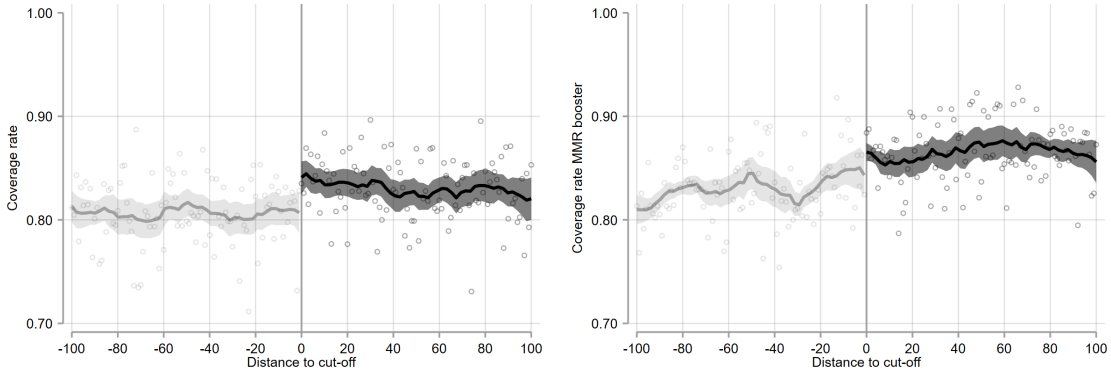
The graphical evidence points to small impacts of the 2014 reminder on early childhood vaccinations but not for later childhood vaccinations. Table 3 presents formal estimates of the effect of introducing reminder letters in 2014 using a 100-day bandwidth on both sides of the cut-off and the optimal bandwidth (Calonico et al., 2020). The estimates mirror the graphical evidence from Figure 2: For the earliest vaccinations, a retrospective postal reminder letter at age two has a positive effect on coverage at age three. The reform increases the share of children receiving all four vaccinations by around three percentage points, corresponding to a 3.7 percent increase evaluated at the below cut-off mean. Our estimates also suggest a 1.7 percentage point and a 2.5 percentage points (significant at the five percent level)

[15]Thus, the outcomes are vaccination coverage of children at age three, 7.5 and 15 years. The HPV sample only includes females, as males were not offered the HPV vaccination in 2014.

increase in MMR booster and DiTeKiPol booster coverage respectively at age 7.5 using the full bandwidth. The booster estimates are not robust to bandwidth choice. Thus, our results for the childhood boosters are at odds with earlier work on the 2014 reform in Suppli et al. (2017), who conclude that the 2014 retrospective reminder was particularly effective for children aged 6.5 at receipt of the reminder. This earlier work, however, compared children in a large window around the reform (one year on both sides of the cutoff) to analyze the impact of reminders.[16]

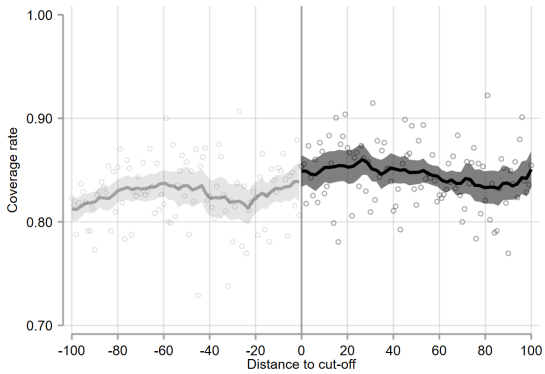
One explanation for the ineffectiveness of retrospective postal reminders for later childhood vaccinations may be the timing of the reminder relative to the recommended vaccination age. Results for the impact of the retrospective reminder on coverage for the separate early childhood vaccination episodes in Appendix Table A8 are in line with this reasoning: The effect on the combined early childhood vaccinations is driven by increases in the coverage of the MMR vaccination recommended at 15 months after birth but there is no effect for the vaccines in the DiTeKiPol series. The MMR vaccination is due only a few months prior to the retrospective reminder dispatch at age two.

[16] As illustrated in Appendix Figure A8, our main conclusions are supported by a host of robustness tests confirming that our results are not driven by a specific choice of functional form or sample.

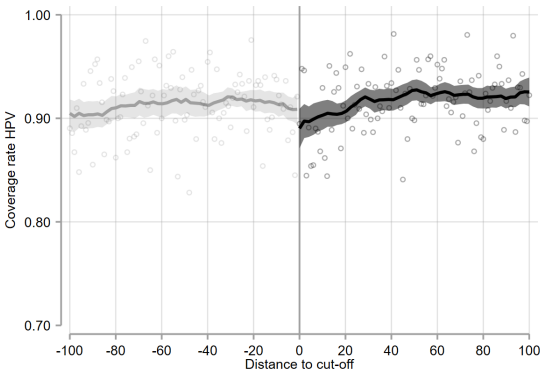


(a) All early childhood vaccinations (DiTeKiPol1-3 and MMR1) at age 3

(b) MMR booster at age 7.5



(c) DiTeKiPol booster at age 7.5



(d) Initial HPV vaccination at age 15, girls

Fig. 2 The Effect on Vaccination Coverage of Introducing Retrospective Reminders, 2014 Reform
Notes: The outcome in the figures is an indicator equal to one if the child has all recommended vaccinations one year after dispatch of the reminder: All four early childhood vaccinations at age 3 in panel (a), the MMR booster at age 7.5 in panel (b), the DiteKiPol booster at age 7.5 in panel (c) and the HPV vaccination at age 15 in panel (d). Reminders were issued to families with a child who lacked at least one relevant vaccine at the given age and was in the treatment group. In panel (a), the sample includes 32,471 children who turned two between 100 days prior to and after 15 May, 2014. In panel (b) and (c), the sample includes 35,809 children who were 6.5-years of age between 100 days prior to and after 15 May, 2014. In panel (d), the sample includes 18,363 female children with 14-year birthdays 100 days prior to and after 15 May, 2014. The vertical lines indicate the cut-off dates. Solid lines are fitted values from a local linear regression with a bin width of 10-days and rectangular kernel. Dots are means for daily bins. Shaded areas are 95% confidence intervals.

Tab. 3 The Effect on Vaccination Coverage of Introducing Retrospective Reminder Letters, 2014 Reform

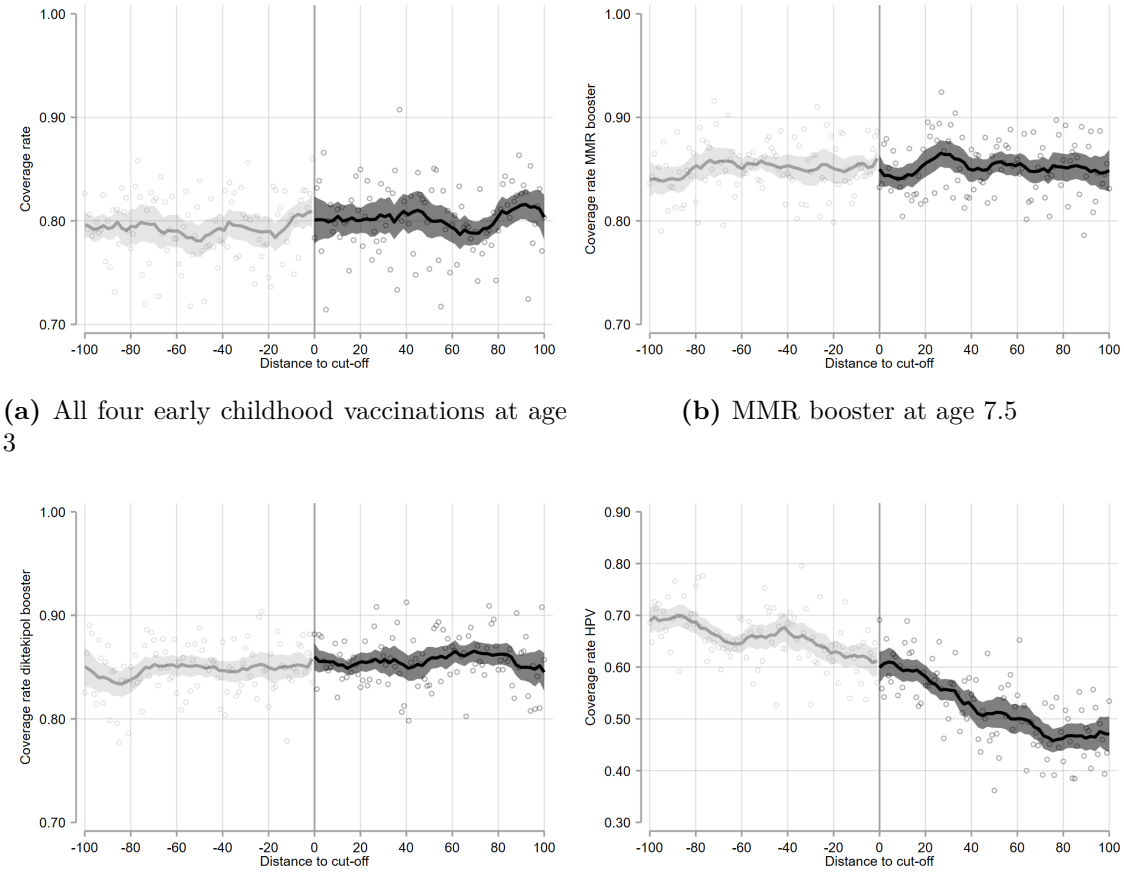
	(1) All early childhood vacs. at age 3	(2) MMR booster at age 7.5	(3) DiTeKiPol booster at age 7.5	(4) HPV at age 15
Full bandwidth	0.030	0.017	0.025	-0.014
	(0.009)	(0.008)	(0.009)	(0.010)
Optimal bandwidth	0.029	0.012	0.007	-0.008
	(0.015)	(0.013)	0.015	(0.017)
Below cut-off mean	0.81	0.83	0.83	0.91
Observations	32471	35809	35809	18363
Obs. opt. b.width	12153	13980	11239	6301

Notes: Each cell shows coefficients from separate regressions. The outcomes are indicators given by the column labels. Coefficients are estimates of the discontinuity at the cut-off. The cut-off is the implementation date of the introduction of reminder letters on 15 May, 2014. We use local linear regressions, a triangular kernel and a 100-day and the optimal bandwidth as developed in Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

4.2 Postal vs Digital Reminder Letters (2017 Reform)

Figure 3 presents a graphical analysis of the impact of the 2017 reform that changed the retrospective postal reminder into a retrospective digital reminder letter. As in the previous analysis, we focus on coverage across samples of children turning 2, 6.5 and 14 in the bandwidth around the cutoffs and the outcomes are indicators for vaccination completion one year after dispatch of the reminder. Across all samples, the graphical evidence does not suggest an impact of mode of delivery on coverage.[17]

[17]Appendix Table A9 shows the corresponding estimates for discontinuities presented in Figure 3.



(a) All four early childhood vaccinations at age 3

(b) MMR booster at age 7.5

(c) DiTeKiPol booster at age 7.5

(d) Initial HPV vaccination at age 15

Fig. 3 The Effect on Vaccination Coverage of Switching from Postal to Digital Reminders, 2017 Reform

Notes: The outcome is an indicator equal to one if the child has all recommended vaccinations one year after dispatch of reminders: All four early childhood vaccinations at age 3 in panel (a), the MMR booster at age 7.5 in panel (b), the DiteKiPol booster at age 7.5 in panel (c) and the HPV vaccination at age 15 in panel (d). Digital (rather than postal) reminders were issued to families with a child who lacked at least one relevant vaccine at the given age and was in the treatment group. In panel (a), the sample includes 30,302 children with who were two years of age in the 100 days prior to and after 6 February, 2017. In panel (b) and (c), the sample includes 36,143 children who were 6.5-years of age between 100 days prior to and after 6 February, 2017. In panel (d), the sample includes 16,566 female children with 14-year birthdays 100 days prior to and after 6 February, 2017. The vertical line indicates the cut-off date. Solid lines indicate fitted values from a local linear regression with a bin width of 10-day and rectangular kernel. Shaded areas are 95% confidence intervals. Dots are means for daily bins.

While panels (a), (b) and (c) of Figure 3 show very stable coverage rates across the cut-off, panel (d) displays the declining trend in HPV coverage for girls in the relevant cohort from 70 percent for children 40 days below the cut-off to below 50 percent for children 100 days above the cut-off. Girls in this sample were born between October 29, 2002 and May 17, 2003 and were recommended to have their HPV vaccination at age 12 between October 29, 2014 and May 17, 2015. Thus, the decline in HPV coverage mirrors well-documented issues with public concerns about potential negative side effects from the HPV vaccine for this cohort. As apparent in the graph, even within a group of children born only a few months apart, vaccination coverage changed tremendously and simultaneously with the public controversy around the vaccine, which puts the estimates for the impact of the 2014 reminders (or other reminder systems) into perspective.[18]

4.3 The Introduction of Prospective Reminder Letters (2019 Reform)

Figure 4 presents our results for the effects of the vaccination reminder letter reform in 2019 that changed the timing and content of the letters. In the new regime (the treated group), all parents – not only non-adhering parents – receive reminder letters shortly prior to the recommended age for a vaccination and potentially a follow-up (if non-adherent, a month after).[19] Recall that we adjust our analyses of this final reform: First, for the 2019 reform we use a bandwidth of 60 rather than 100 days because we only have outcome data until 2020. Thus, to be able to follow children for a full year we have to constrain the RDD sample. Second, we cannot study the DiTeKiPol booster (recommended at age five).[20]

[18] In line with our main findings, Appendix Figure A9 shows that all coefficients for the impact of the digital reminder vs the postal reminder are very close to zero and imprecise, i.e., they support our main conclusion that the vaccination coverage rates are unaffected by the mode of delivery.

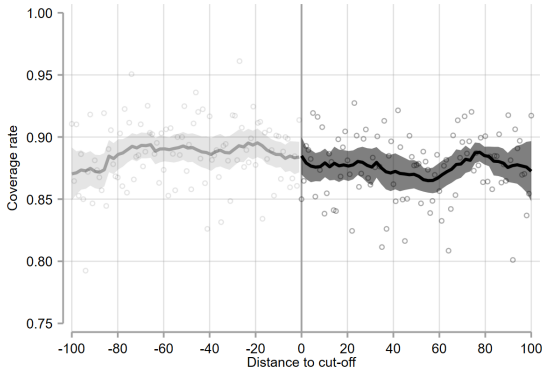
[19] The control groups in our samples do not receive any reminder letters (yet) but continue to be under the old reminder letter regime of reminder letters for non-adhering parents of children at ages 2, 6.5 and 14 years.

[20] As discussed initially, we cannot study the DiTeKiPol booster (recommended at age five) with our data: Our 2019 reform sample consists of children having their fourth birthdays in the 60 days before and after November 1, 2019. Thus the treated children receive their prospective DiTeKiPol booster reminder in the

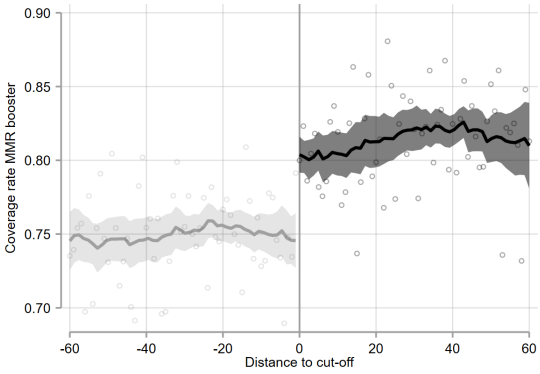
Third, given the data constraint of available vaccination data up to and including the year 2020, we consider shorter-run vaccination outcomes in this last setting. We focus on the coverage of relevant vaccinations at age one for the first year vaccinations and the one-year coverage rates for the MMR and HPV vaccinations (one year after recommended vaccination age rather than one year after reminder dispatch). Thus, our analyses compare a prospective reminder with no reminder at all for control children. As a result, the focus in the 2019 reform analysis is on studying whether the prospective reminder increases timely uptake in particular. In future analyses we will also be able to study whether control children catch up due to the retrospective reminder – to be sent to non-complying parents in the control groups – and longer run vaccination coverage.

Panel (a) of Figure 4 displays no evidence that prospective reminders increase children's coverage of the two first-year vaccinations at age one. Coverage below and above the cut-off is around 88 percent. This evidence suggests that timely coverage for the first-year vaccinations is less susceptible to reminder responses and that non-adherence at this point is not due to inattention but predominantly reluctance or an active choice by parents. For the MMR booster and the HPV vaccine for girls later in childhood, the figure indicates large effects of the new prospective reminder letter policy on timely vaccination coverage one year after the recommended vaccination age.

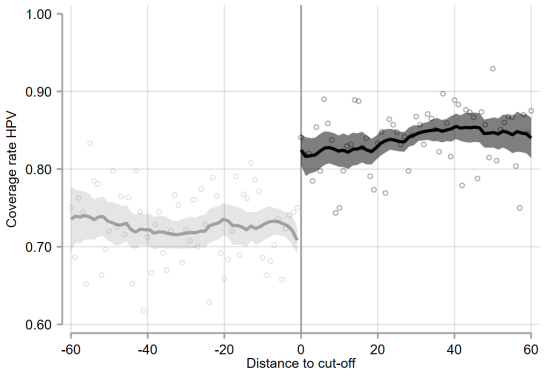
end of the year 2020, leaving us with insufficient outcome data to study this vaccination.



(a) The 3 and 5 months vacs. (DiTeKiPol1 and 2) at age 1



(b) MMR booster at age 5



(c) Female initial HPV vaccination at age 13

Fig. 4 The Effect on Vaccination Coverage of Introducing Prospective Reminders, 2019 Reform
Notes: The outcome is an indicator equal to one if the child has all first-year vaccinations at age 1 in panel (a), the MMR booster at age 5 in panel (b) and the HPV vaccination at age 13 in panel (c). In panel (a), the sample includes 35,583 children with date of births 100 days prior to and after 1 August, 2019. In panel (b), the sample includes 19,942 children who turned four years 60 days prior to and after 1 November, 2019. In panel (c), the sample includes 10,472 female children who turned 12 years 60 days prior to and after 1 November, 2019. The vertical line indicates the cut-off date. Solid lines indicate fitted values from a local linear regression with a bin width of 10-day and rectangular kernel. Shaded areas are 95% confidence intervals. Dots are means for daily bins.

Table 4 shows the corresponding estimated discontinuities for the 2019 reminder letter policy reform. In line with the graphical evidence, the coverage rate for first-year vaccinations is not affected by the reform. We estimate a 5.4 percentage point (7.2 percent) higher coverage of the MMR booster vaccine at age five and a 9.4 percentage point (12.9 percent) increase in HPV vaccination coverage at age 13 caused by the reformed reminder letter policy.

Tab. 4 The Effect on Vaccination Coverage of Introducing Prospective Reminders in 2019

	(1) All first-year vacs. at age 1	(2) MMR booster at age 5	(3) HPV at age 13
Full bandwidth estimate	-0.010	0.054	0.094
	(0.007)	(0.012)	(0.013)
Optimal bandwidth estimate	-0.004	0.061	0.104
	(0.014)	(0.024)	(0.022)
Below cut-off mean	0.89	0.75	0.73
Observations	35583	19942	10472
Obs. with optimal bandwidth	10133	5861	3775

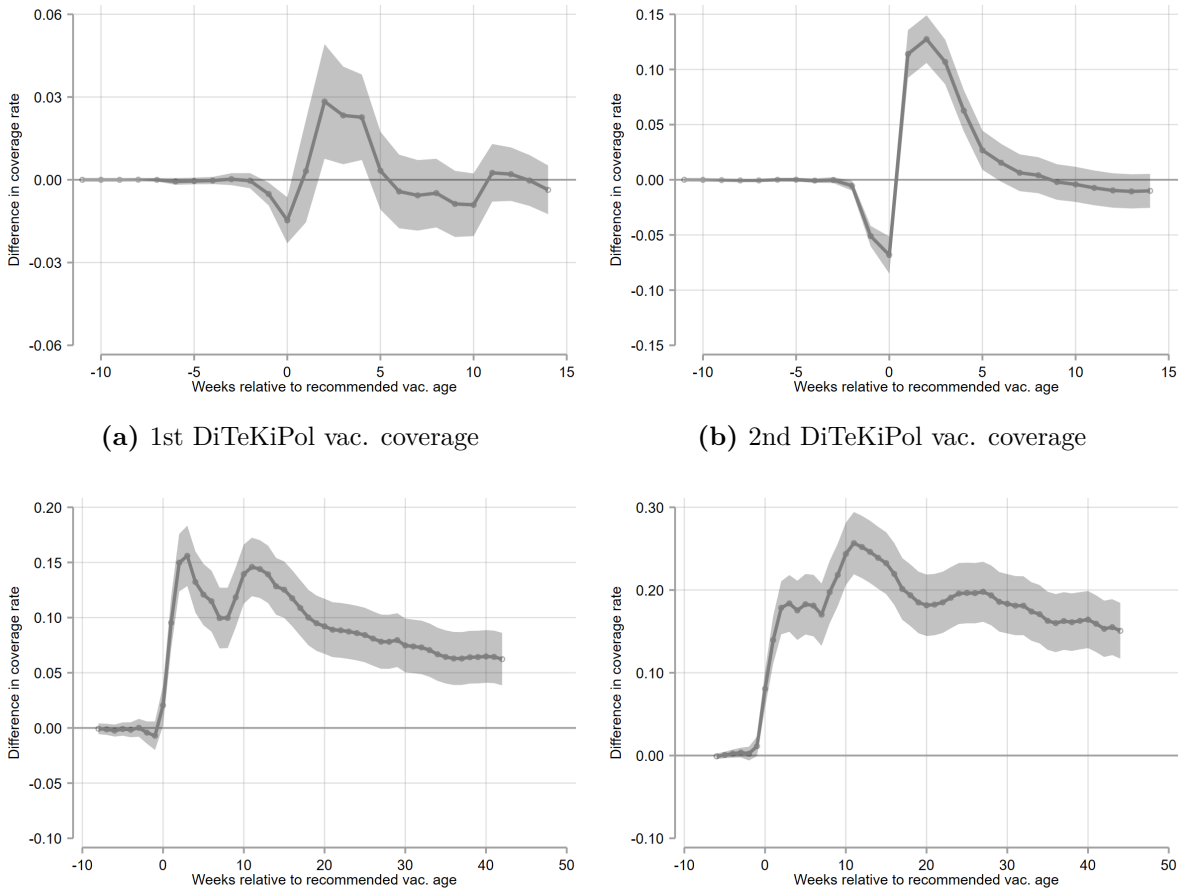
Notes: Each cell shows coefficients from separate regressions. The outcomes are indicators given by the column labels. Coefficients are estimates of the discontinuity at the cut-off. The cut-off is the implementation date of the 2019 reminder letter policy. We use local linear regression, a triangular kernel and a 100-day bandwidth in (1) and a 60-day bandwidth in (2) and (3) and the optimal bandwidth as developed in Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

One interpretation of our results is that parents are well aware and attentive to the infant vaccinations but an increasingly larger share of parents are inattentive in later vaccination rounds (and responsive to reminders). This finding points to the role of reminders in childhood periods with less frequent contacts to the primary health care system: While infants and children below age two in Denmark regularly interact with primary health care professionals, such as home visiting nurses and GPs in the universal childhood preventive care program, older children are less exposed to this type of care, which may serve as additional and indirect reminders.

While the above discussion of the 2019 reminder reform has focused on the main element of the reform, the prospective reminder for all parents, the 2019 reform also introduced a second (follow-up) reminder for non-responsive parents (one month after the recommended vaccination age). To study the relevance of this reform element for the main finding, Figure

5 breaks down the effects of the 2019 reminder into coverage estimates for the specific vaccinations at a weekly level around the relevant age for the reminder dispatch. Thus, the figure shows the estimated difference in vaccination coverage at the cut-off across weeks around the recommended age for each vaccination. The initial reminder is sent to all parents two weeks prior to the recommended vaccination age (week -2 in the graphs) and the follow-up reminder is sent to non-complying parents one month after the recommended vaccination age (between weeks four and five in the graphs). While we do not find any effect on first-year vaccination coverage in our main analysis, panels (a) and (b) show that the new reminder policy has an impact on the timing of first-year vaccination uptake even in the sample of very young children. Specifically, the prospective reminder leads to more timely vaccination (and fewer vaccinations prior to the recommended age) resulting in higher coverage of both first-year vaccinations for up to five weeks after the recommended vaccination age with convergence in the following weeks. This finding is policy relevant as the timing of, especially, the second infant vaccination (displayed in panel (b)) coincides with the typical daycare starting age in Denmark; thus, high timely vaccination coverage around this age of increased exposure to childhood diseases is crucial.

Figure 5 also shows which reminder (the prospective or the follow-up) parents respond to. In terms of first-year vaccinations, only the prospective reminder changes behavior. For the MMR booster, coverage is five percentage points higher close to a year after the recommended vaccination age. Moreover, parents are responsive to both reminders as indicated by the increase in the difference in coverage around the dispatch of both reminders. Likewise, for the female HPV vaccination coverage we see a large difference in coverage close to a year after and responses to both the prospective and the follow-up reminders.



(a) 1st DiTeKiPol vac. coverage

(b) 2nd DiTeKiPol vac. coverage

(c) MMR booster coverage

(d) HPV vaccination coverage, females

Fig. 5 Timing of Response to the 2019 Prospective Reminder Letter across specific Vaccinations
Notes: Each dot represent the coefficient from separate regressions. The outcomes are indicators of whether the child has received the specific vaccinations in the weeks around the recommended age for each vaccination. Coefficients are estimates of the discontinuity at the cut-off. The cut-off is the implementation date of the 2019 reminder letter policy. We use local linear regression, a triangular kernel and a 100-day bandwidth in (a) and (b) and 60-day bandwidth in (c) and (d) on each side of the cut-off. Reminders are sent two weeks prior to the recommended age (week -2) and a follow-up reminder one month after (weeks 4-5). Shaded areas are 95% confidence intervals associated with the weekly estimates.

Assessing the robustness of these findings, panel (a) in Appendix Figure A10 shows very small, and mostly insignificant, impacts of the 2019 reform on first-year vaccinations across bandwidth and specifications. In panel (b) in Appendix Figure A10 we see that all specifications in the curve produce positive and significant effects for the MMR booster close to the results from our main specification. Similarly for the impact on HPV coverage, all presented

estimates are close to 10 percentage points (main estimate: 0.094) and highly significant.[21]

At first glance, our results across the 2014 reform and the 2019 reform may appear conflicting: the 2014 reform primarily impacted the early childhood vaccinations (below age two), more specifically the MMR vaccination recommended at age 15 months. The 2019 reform only impacted booster and the HPV vaccinations. We believe a main lesson from these results is that reminders need to be in relatively close proximity to the target age for the vaccination in order to have an impact. In the 2014 policy, there is a large lag between recommended vaccination age and reminder dispatch (at least a year) for every vaccination except the MMR vaccination. In the 2019 policy, the distance between reminder dispatch and recommended vaccination age is constant across all vaccination rounds. Thus, we conclude that the 2019 policy (a prospective reminder and a follow-up reminder) is strictly more effective than the 2014 policy and that the difference in effectiveness arises for the booster and HPV vaccinations, where inattention is likely to be more widespread.

4.4 Reminders for New Vaccination Recommendations: HPV Vaccination for Boys

Reminders raise awareness of a particular health behavior and may thus be of particular importance for reaching high coverage rates in newly-established vaccinations quickly. We illustrate this potential by exploiting the introduction of the HPV vaccination for boys in the Danish public vaccination program, which overlaps with the 2019 reminder reform (implemented November 1, 2019). Thus, we can compare the response to reminders across female and male children (who are all eligible for the HPV vaccine): In July 2019, HPV vaccination for males was included in the Danish Childhood Vaccination Program. Prior to July 2019, only females were offered the HPV vaccination as part of the public program. Thus, the 2019

[21] Across all specifications presented in the specifications curves (Appendix Figures A8 to A10) the estimates display the greatest sensitivity to the RD-DD specifications. Thus we use the control samples from the RD-DD specifications in placebo analyses using the respective cut-off dates but for the year before. Results show that there are no significant jumps in the outcomes. This finding confirms that there are no discontinuities in the outcomes in relevant placebo years. Results are available on request.

reminder letter reform came only shortly after the inclusion of the HPV for males. While all males in our HPV vaccination sample are covered by the public HPV vaccine, only boys in the treated group are reminded about it.

As shown in Figure 6, in the absence of the new reminder letter policy, the gender gap in HPV coverage among eligible children is above 25 percentage points (below the cut-off). After the reminder letter reform, this gap is reduced to below five percentage points. This finding strongly implies that inattention among parents of male children explains the largest share of the gender gap in HPV coverage prior to the reform. Are there other differences than informational across boys and girls that may explain this finding? Looking at gender differences in the MMR booster response (Appendix Figure A4) and differences in the HPV coverage along other dimensions of potential heterogeneity, such as parental cohabitation, university education, health education and the child's birth order (Appendix Figure A5), we do not find similar patterns. These findings strongly support our explanation that that the gendered response to reminders in the HPV case reflects the recent introduction of the HPV for males and a lack of salience for parents in this situation.

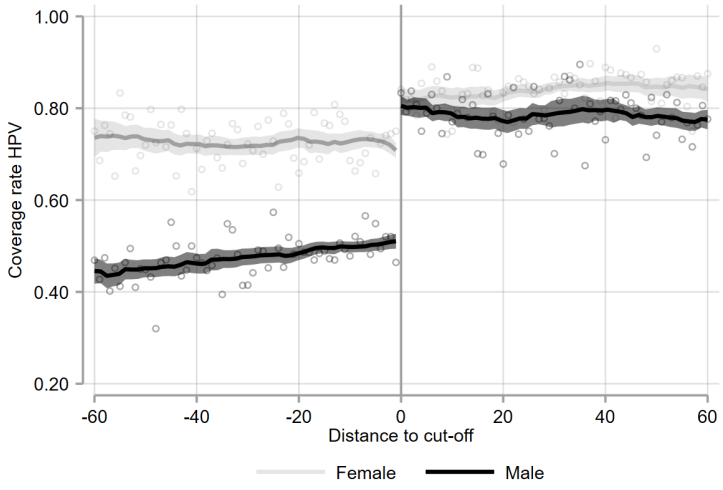


Fig. 6 The Effect on HPV Vaccination Coverage of Introducing Prospective Reminders in 2019; by Child Gender

Notes: The outcome is an indicator equal to one if the child has taken up the HPV vaccination at age 13. We divide the sample by child gender. For details see notes to Figure 4.

4.5 Reminders and Spillovers: Child Preventive Care and Family Health Behavior

The increase in timely MMR booster and HPV vaccination coverage as a result of the 2019 reform implies that responding families make an appointment at the family GP clinic that they would not have made in the absence of the reform. Thus, we test whether this induced contact prompts additional health care in the primary health care sector (beyond the vaccination in question) for the focal child and other family members.

We focus on the 2019 reminder reform in these analyses, as this reform actually promoted timely responses and is the system in place today. In our spillover analyses we focus on the MMR booster sample and the HPV vaccination sample both because we do not observe main effects in the first-year vaccination sample on focal children and because for older children (as opposed to the youngest ones) there are fewer or no recommended default GP preventive care visits. For spillovers to health behaviors related to the focal child, our outcomes are therefore additional GP preventive care visits and GP costs around the MMR vaccine. Children in our MMR booster sample are eligible for a free preventive health check at age four (while children at age 12 are no longer eligible for preventive GP checks).[22] Parents have to schedule the age-four preventive health check and may be induced to do so given the timely vaccination reminder. Concerning spillovers to other family members, we study preventive health decisions that are directly related to the child vaccination, namely HPV vaccination uptake of non-vaccinated older (female) siblings and the triennial screening for cervical cancer offered to every woman between 23 and 59 years. Cervical cancer is the exact type of cancer that the HPV vaccine immunizes against and reminding parents of the HPV vaccine may bring salience to parents' own cervical cancer screening.

Figure 7 shows that children who are exposed to the 2019 reminder policy and receive the MMR booster reminder are more likely to take up preventive GP care. The estimated

[22]GP preventive health checks are yearly around that age and thus less salient as the closely spaced early childhood offers, as detailed in section 2.

effect is an 8.1 percentage point increase in participation in the preventive health check (a 10 percent increase evaluated at the below cut-off mean). A likely explanation for this impact is that when scheduling the vaccination with the GP office (often via phone), parents receive a (vocal) reminder about the possibility of combining the vaccination appointment with a GP health check. As the preventive health check is scheduled in combination with the MMR booster, this spillover is somewhat mechanical and very specific to the structure and the alignment of vaccinations and health checks at the GP.[23] This finding suggests that the reminder policy may have additional benefits for children in this age group under the assumption that additional preventive care is beneficial for children's health. It may lead to further detection of health issues and referrals to specialists.

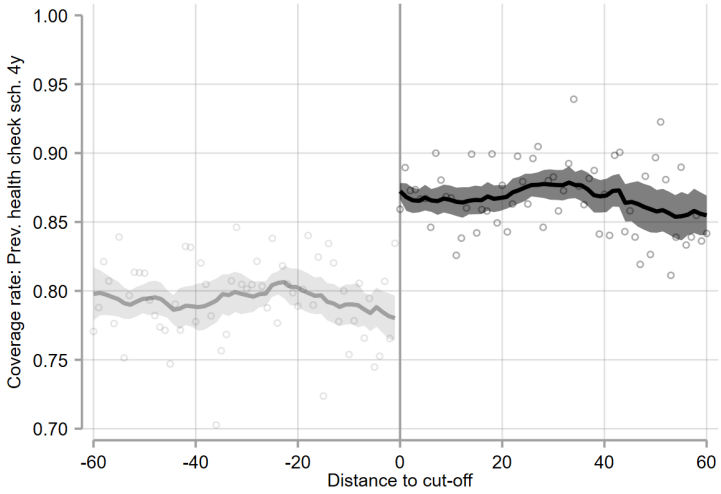
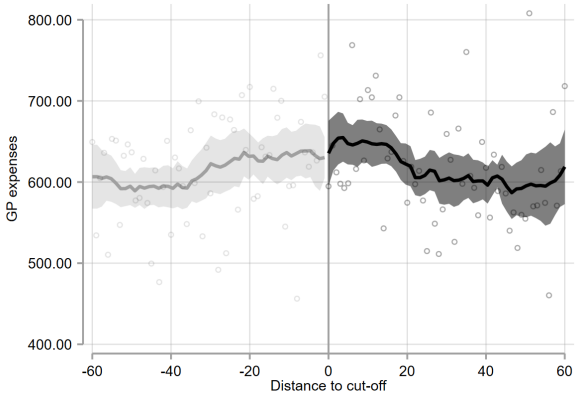


Fig. 7 The Spillover Effect on Preventive Health Check Participation of Introducing Prospective Reminders in 2019

Notes: The outcome is an indicator equal to one if the child has a preventive health check at the GP during the 4th year of life (between ages 4 and 5). For further details see notes to Figure 4.

[23]To dig deeper into the finding that prospective reminders increase health check participation more than actual participation in the MMR booster vaccination, Appendix Figure A6 breaks down the response into i) children who receive both the MMR booster and the health check, ii) children who receive only the MMR booster and iii) children who receive only the preventive health check. As the figure shows, we see a 7 percentage point effect on children who receive both the booster and the health check and also a 2.5 percentage point increase in the share of children who only receive the health check and not the booster. The share of children who only receive the booster is unaffected. Thus, the findings suggest that some parents are reminded of the booster, which coincides with the health check and take up the health check while still being reluctant toward the booster.

To examine this latter question, Figure 8 examines the effect of the 2019 prospective reminder letter on child GP expenses (a measure of intensity of treatment at the GP) a year following treatment. We exclude vaccinations and preventive health checks from the GP expenses to measure additional GP care beyond the care that is directly induced by the reminder. We do not find any differences in GP expenses at the cut-off.[24] Thus we do not find spillovers to GP care other than the preventive health check. This finding is also supported by Appendix Figure A7, where we consider other types of health care, namely consultations at ear and/or eye specialists that require referral from the family GP. An increase in the preventive health check at the GP may prompt referrals due to hearing or vision problems that would otherwise go untreated. We do not find any spillovers to this type of specialist care.



(a) GP expenses for the MMR booster sample

Fig. 8 The Spillover Effect on GP Care of Introducing Prospective Reminders in 2019
Notes: The outcome is GP expenses for the child during the year following treatment. For further details see notes to Figure 4.

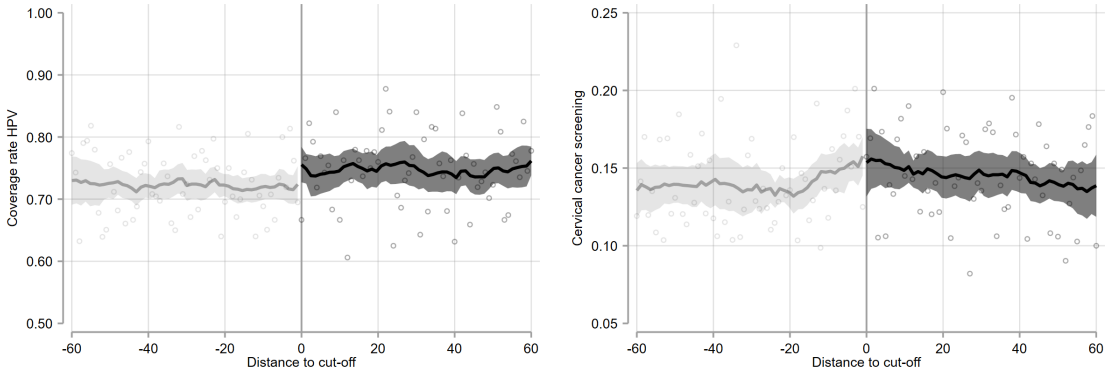
Turning to other family members, Figure 9 presents results for sibling HPV vaccination uptake and maternal cancer screenings for the HPV sample around the 2019 reminder reform. Panel (a) shows sibling spillover results for the HPV vaccine. The 21,453 children (both genders) in the HPV sample have 7,102 older female siblings (all eligible for the publicly-funded

[24]Similarly, for the HPV sample (who are not eligible for preventive GP care at this age) we do not detect any differences in GP expenses following the reminder letter reform.

HPV vaccine). We study the coverage rate among these siblings within a year after their younger siblings received the reminder. As the figure shows, we see no difference in the coverage rate at the cut-off. Having a younger sibling in the family who is in the treatment group (receives a reminder for the HPV vaccination) does not increase older siblings' vaccination coverage. In related work, Humlum et al. (2022) demonstrate that the initial introduction of the HPV vaccine in the publicly-funded Danish vaccination program in 2008 (for girls only) had positive spillover effects to older (ineligible) siblings (i.e., siblings who would not receive the vaccine for free). They conclude that a dominant channel for this spillover effect was the information campaign that accompanied the introduction of the public HPV program. In our setting – in the well-established HPV program – the results seem to indicate that the remaining non-compliance among older siblings is not impacted by information through reminders, potentially due to a large share of reluctance among non-compliers for this specific vaccine. Panel (b) shows results for the probability of mothers of focal children receiving a cervical cancer screening within a year following the age of dispatch of the HPV reminder. About 15 percent of mothers have a screening in that period and we find no evidence of a discontinuity at the cut-off.[25]

In sum, our analysis shows limited spillovers to other health behaviors of reminding parents about vaccinations of their children. In our setting, these spillovers are limited to the focal child and heavily dependent on availability of other coupled primary care services, such as preventive health checks. While we have explored potential longer-run impacts of these primary care spillovers – that could arise through the timely identification of more severe health problems in the extra primary care consultations – our (local) RDD analyses are underpowered to study this margin further.

[25]We also have explored the uptake of vaccines by other family members. In the public system, grandparents of focal children typically can take up seasonal influenza vaccines. We do not find any indication that these vaccine decisions are impacted by the 2019 reminder reform and its impact on focal children's vaccine take-up. We do not consider influenza vaccinations for focal children as only the elderly part of the population was offered free influenza vaccines during the study period.



(a) HPV vaccination for siblings of children in the HPV sample

(b) Cervical cancer screening for mothers of children in the HPV sample

Fig. 9 The Spillover Effect on Sibling HPV Vaccination Uptake and Cervical Cancer Screening for Mothers of Introducing Prospective Reminders, 2019 Reform.
Notes: The outcomes are HPV vaccination for unvaccinated siblings and cervical cancer screening for mothers one year after dispatch of the reminder letter. For technical details, see notes to Figure 4.

5 Conclusion

As reminders are a widely used and a low-cost policy tool, understanding their impacts in the context of families' vaccination behavior is instrumental for policy. Analyzing several national reminder reforms in the publicly-funded Danish childhood vaccination program, we contribute several insights into the role of large-scale reminder programs. First, our analyses across reforms and vaccinations underscore the importance of timing. We find that retrospective reminders have limited impacts and those are concentrated among families with the youngest children and generally the highest vaccination compliance rates. Retrospective reminders are most effective when the timely distance between the reminder and the recommended vaccination age is relatively short.

Second, prospective reminders are effective in increasing (timely) coverage for later childhood vaccinations (booster and HPV) and they can be a powerful tool to help increase coverage of new vaccination programs (as shown in the case of HPV for boys in Denmark). This finding is important as coverage rates for boosters, follow-up and new vaccinations are usually lower than for infancy and toddler vaccinations. The finding that prospective re-

minders are effective at increasing timely vaccinations will likely also map into longer-run coverage rates, a factor that we have to study in future work when cohorts have aged and data become available.

While reminders typically are narrow in scope, they may have much broader impacts on health behaviors and policy makers should factor in the issue of spillovers across health behaviors and family members. We find that vaccination reminders have limited spillovers in our setting but can help with salience issues around preventive health checks for children. In our setting, we find that reminders can increase take-up of a (coupled) GP health check for focal children – a policy goal in itself that may contribute to the timely detection of more severe health issues. We lack power to consider this potential impact of increased preventive care uptake for future child health in our study.

Importantly, our research and the mere existence of a national reminder system in Denmark critically rely on the excellent data infrastructure in the Nordic countries with nationwide administrative registers covering all residents and their contacts with the public health care system. These data, alongside a well-established digital infrastructure for government-citizen communications, make vaccination reminders at scale feasible and allow us to study them.

In the Danish context with a well-developed digital infrastructure, we show that digital reminders work just as well as postal reminders, implying significantly lower yearly costs for prospective reminders (when compared to prospective postal reminders for full birth cohorts of children). One important and final question that we cannot study in our design is the impact of reminder content on reminder effectiveness in the setting of childhood vaccinations. Changes in reminder content to include messages about positive externalities have been introduced for all children in parallel to changes in reminder timing. However, it would be feasible to randomly vary messages to either include or exclude those messages in the population-wide current digital reminder letter. We hope to pursue this research in the future.

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A Appendix - For Online Publication

A.1 Translation of 2014 Reminder Letter

Dear parent

The Danish Childhood Vaccination Program is a free offer for all children in Denmark. The vaccinations are to ensure that children do not become ill of preventable diseases. According to The Danish Vaccination Register NAME (social security number) lacks those vaccinations marked in red:

Anbefalet alder (Age)	Børnevaccinationer (Childhood vaccinations)	Børneundersøgelser (Child health examinations)
3 mdr.	Difteri – tetanus – kighoste – polio – Hib 1	
5 mdr.	Difteri – tetanus – kighoste – polio – Hib 2	Børneundersøgelse
12 mdr.	Difteri – tetanus – kighoste – polio – Hib 3	Børneundersøgelse
15 mdr.	Mæslinger – fåresyge – røde hunde (MFR 1)	
2 og 3 år		Børneundersøgelse
4 år	Mæslinger – fåresyge – røde hunde (MFR 2)	Børneundersøgelse
5 år	Difteri – tetanus – kighoste – polio revaccination	Børneundersøgelse

We ask you to check whether the child has received the marked vaccinations – either by checking the yellow vaccination card or by contacting your doctor.

Note, that the child might have received all the recommended vaccinations without proper registration in The Danish Vaccination Register, if e.g. your doctor has not billed the vaccination or if the vaccination has been given abroad or at a hospital. Also, vaccination registrations can be delayed up to 3 months. You can disregard the letter if the child has

recently received the vaccinations.

You can log any unregistered vaccinations in your medical records at www.sundhed.dk using NEMID.

If you want exemption from future vaccination reminder letters, go to www.ssi.dk/fravalg and follow the instructions.

A.2 Translation of 2019 Reminder Letter

Prior Reminder Letter

Dear parent

It is time for NAME's childhood vaccination. Remember to book a GP appointment if you have not already done so.
You can see your child's vaccinations at www.sundhed.dk/info/vaccinationer. It is important that your child receives the vaccination at the recommended age.
Vaccination not only protects your own child but also children who do not tolerate or are still too young for vaccinations.
Read more about vaccination reminders at *www.ssi.dk/paamindelser* and the Childhood Vaccination Program at *www.sst.dk/vaccinationsprogram.*

The letter also contains two diagrams: 1) the schedule of the Danish Childhood Vaccination Program and 2) an illustration of 10 children. Nine of the children wear green clothes and one child wears white and a text stating "9 out 10 children get vaccinated".

After Reminder Letter

Dear Parent

According to the Danish Vaccination Register your child lacks one or more of the vaccinations in the Danish Childhood Vaccination Program. Your GP knows which vaccinations are missing.

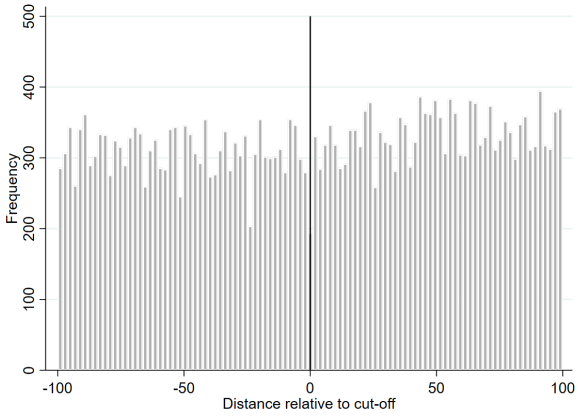
Remember to book a GP appointment if you have not already done so. It is important that your child receives the vaccination at the recommended age.

Vaccination not only protects your own child but also children who do not tolerate or are still too young for vaccinations.

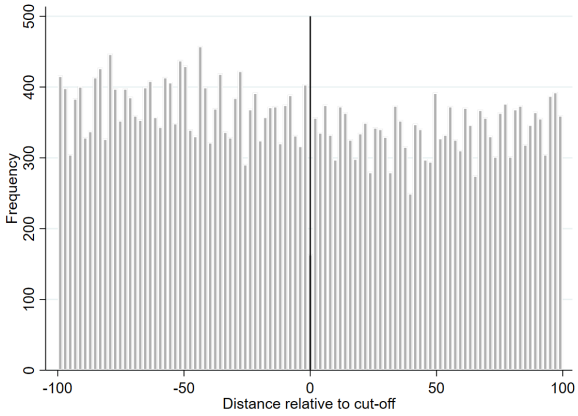
Read more about vaccination reminders at *www.ssi.dk/paamindelser* and the Childhood Vaccination Program at *www.sst.dk/vaccinationsprogram*.

The letter also contains two diagrams: 1) the schedule of the Danish Childhood Vaccination Program and 2) an illustration of 10 children. Nine of the children wear green clothes and one child wears white and a text stating "9 out 10 children get vaccinated".

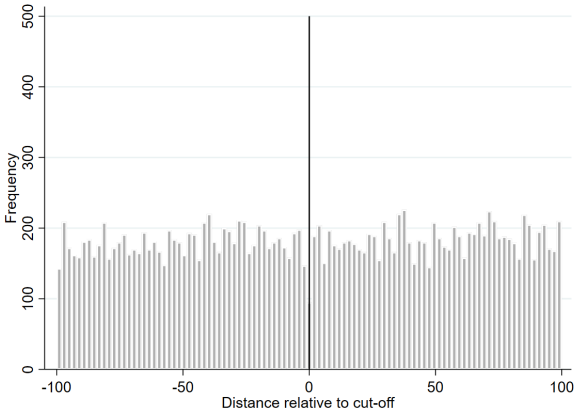
A.3 Appendix Figures and Tables



(a) Early vac. sample

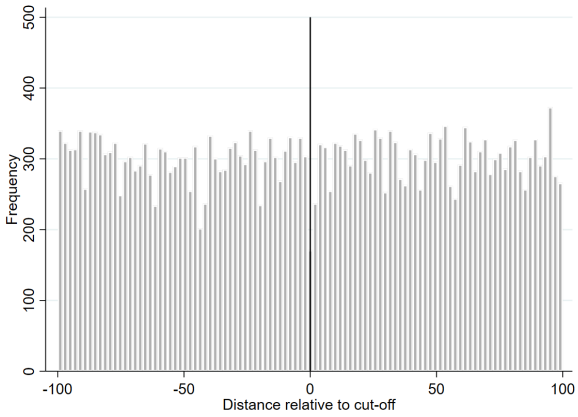


(b) MMR/DiteKiPol booster sample

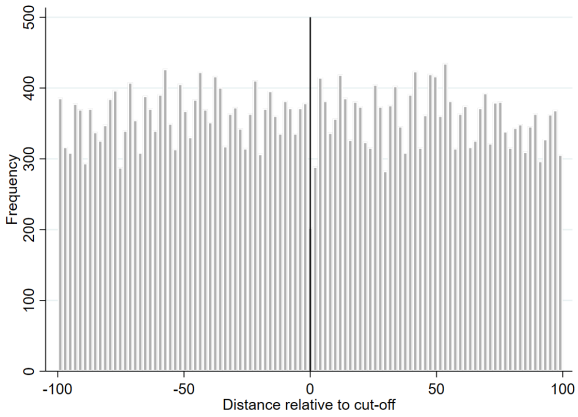


(c) HPV sample

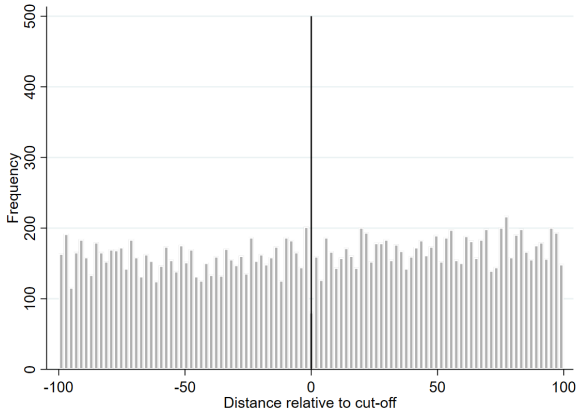
Fig. A1 Density of Births around the Introduction of Prospective Reminder Letters in 2014
Notes: The figure shows the number of children around the cut-off for each sample. Children to the left of the cut-off (black vertical line) received no reminder letters, while children to the right received prospective postal reminder letters. The figure includes the number of children in 2-day bins.



(a) Early vac. sample

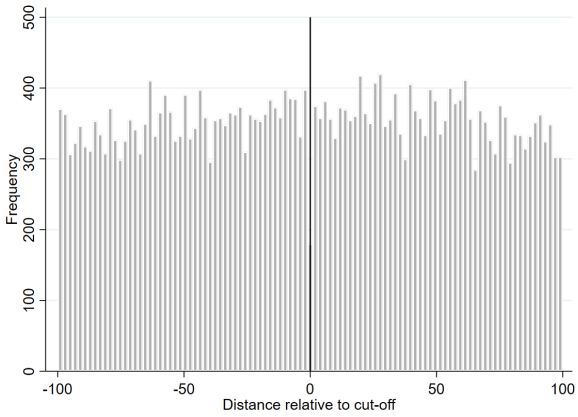


(b) MMR/DiteKiPol booster sample

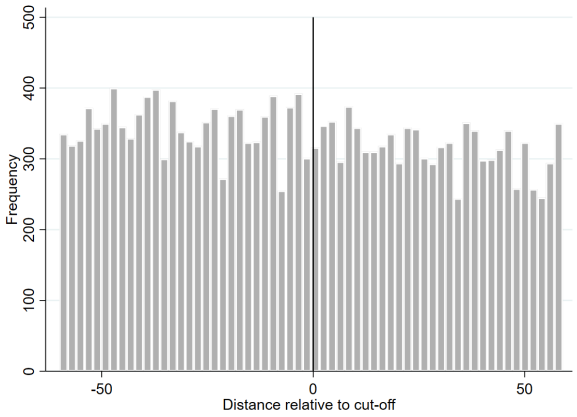


(c) HPV sample

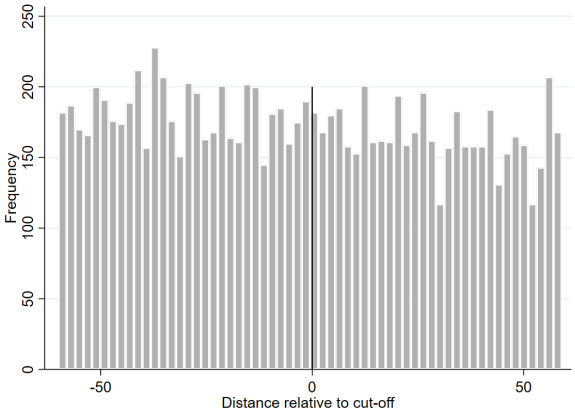
Fig. A2 Density of Births around the Switch from Postal to Digital Reminder Letters in 2017
Notes: The figure shows the number of children around each cut-off. Children to the left of the cut-off (black vertical line) received postal reminder letters, while children to the right received digital reminder letters. The figure includes the number of children in 2-day bins.



(a) 1st-year vac. sample



(b) MMR booster sample



(c) HPV sample

Fig. A3 Density of Births around the Introduction of Prospective Reminders in 2019

Notes: The figure shows the number of children around each cut-off. Children to the left of the cut-off (black vertical line) are on the 2017 reminder letter policy, while children to the right are on the 2019 reminder letter policy. The figure includes the number of children in 2-day bins.

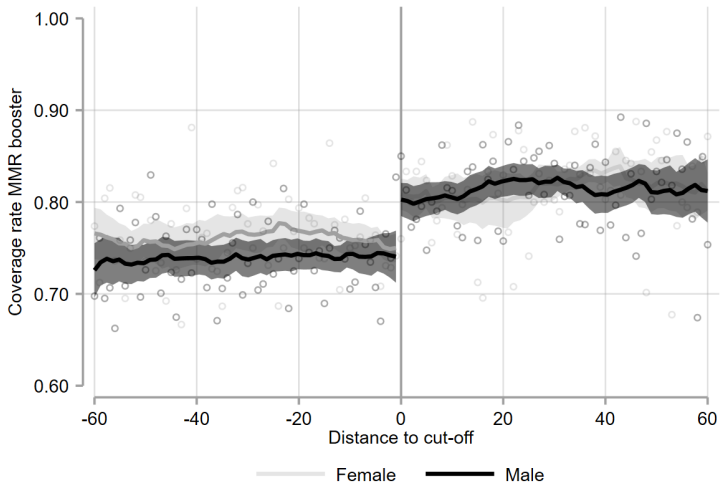
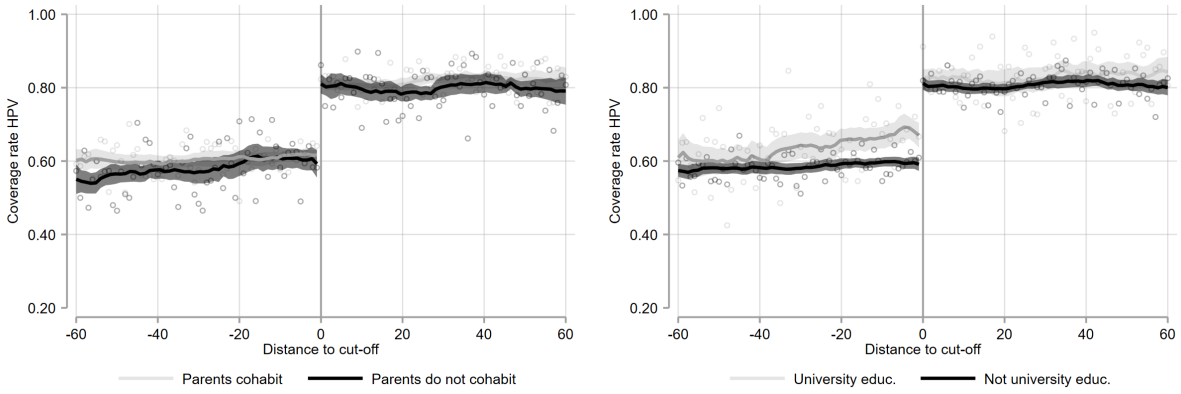


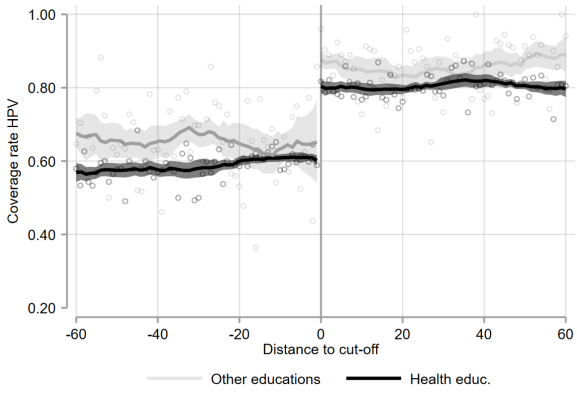
Fig. A4 The Effect on the MMR Booster Coverage Rate of Introducing Prospective Reminders in 2019 by Gender

Notes: The outcome is an indicator equal to one if the child has the MMR booster at age 5. We divide the sample by child gender. For technical details see notes to Figure 4.

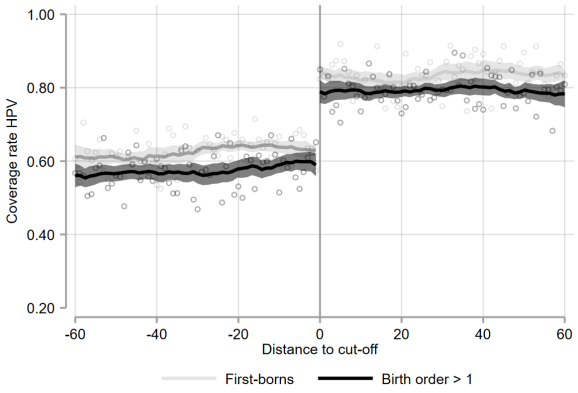


(a) Cohabitation

(b) University educ.



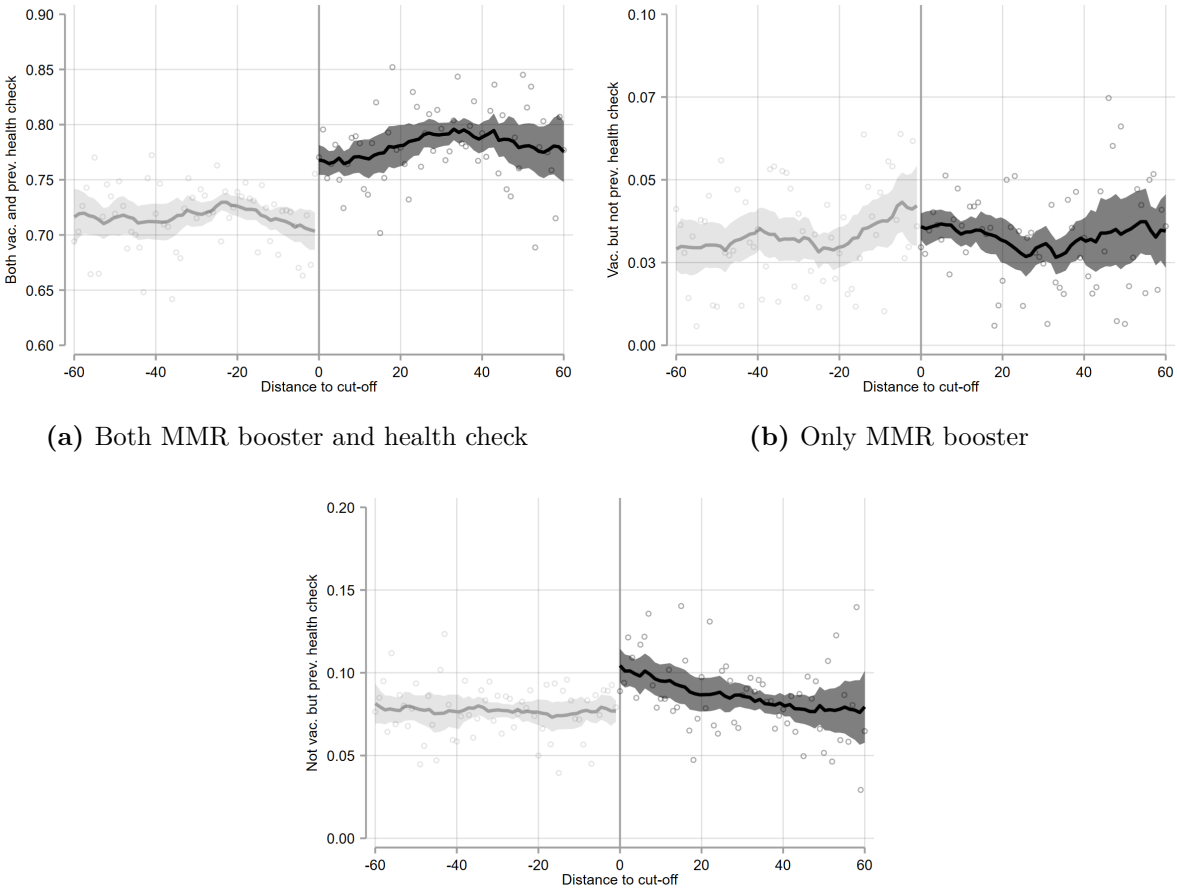
(c) Health educ.



(d) Birth order

Fig. A5 Heterogeneity: The Effect on the HPV Coverage Rate of Introducing Prospective Reminders in 2019

Notes: The outcome is an indicator equal to one if the child has the HPV vaccination at age 13. We divide the sample by the predetermined characteristics indicated by the panel titles. For technical details see notes to Figure 4.



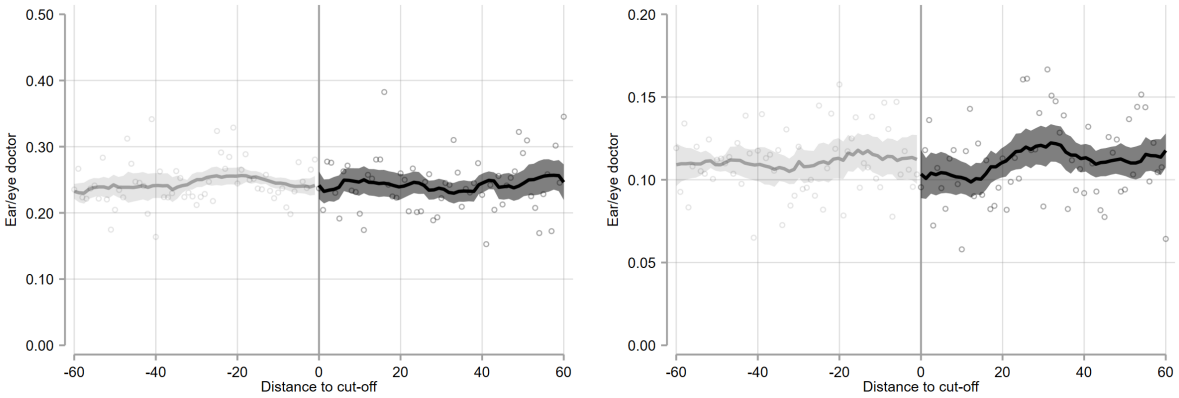
(a) Both MMR booster and health check

(b) Only MMR booster

(c) Only health check

Fig. A6 The Spillover Effect on Combined MMR Booster and Health Check Participation of Introducing Prospective Reminders in 2019

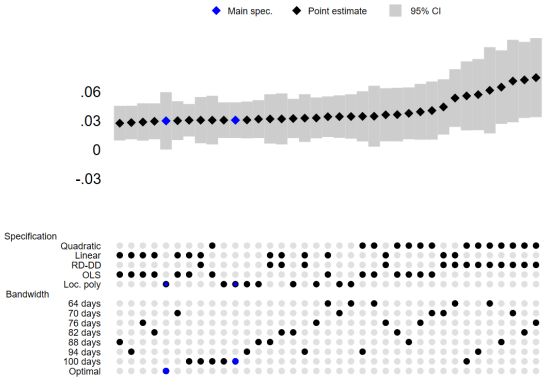
Notes: The outcomes are combinations of MMR booster at age 5 and preventive health check at the GP during the 4th year of life (between ages 4 and 5). For technical details see notes to Figure 4.



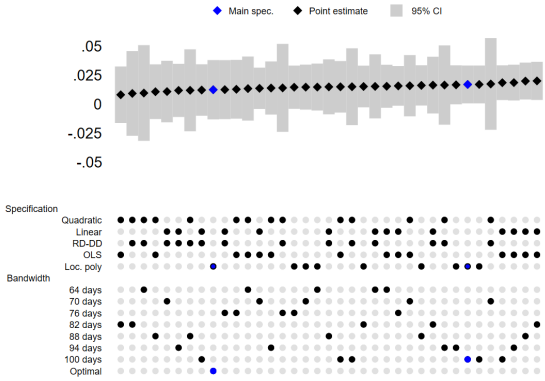
(a) Ear/eye doctor MMR booster sample **(b)** Ear/eye doctor HPV sample

Fig. A7 The Spillover Effect on Eye/ear Specialist Consultations of Introducing Prospective Reminders in 2019

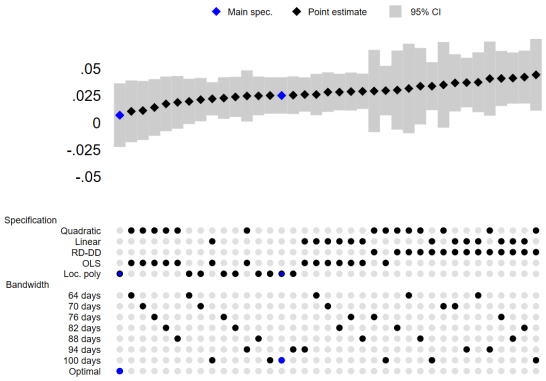
Notes: The outcome is an indicator for the child having been to an ear or eye specialist during the year following treatment. For technical details see notes to Figure 4.



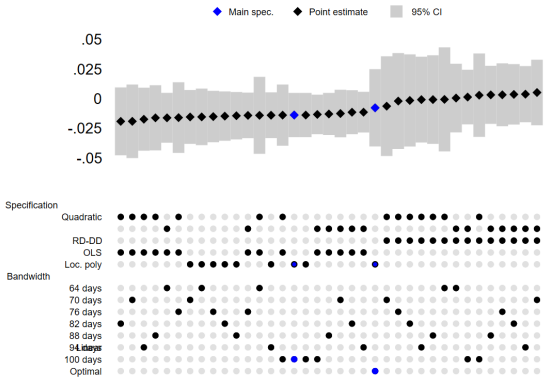
(a) All early vacs. at age 3



(b) MMR booster at age 7.5

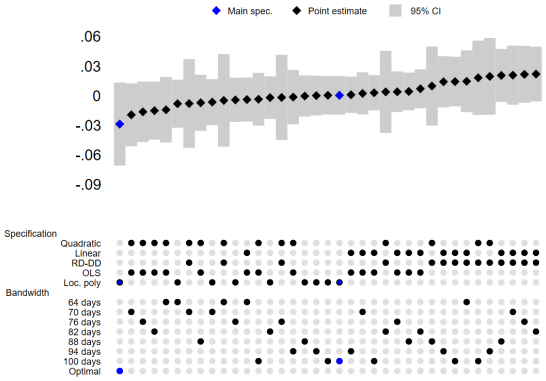


(c) DiTeKiPol booster at age 7.5

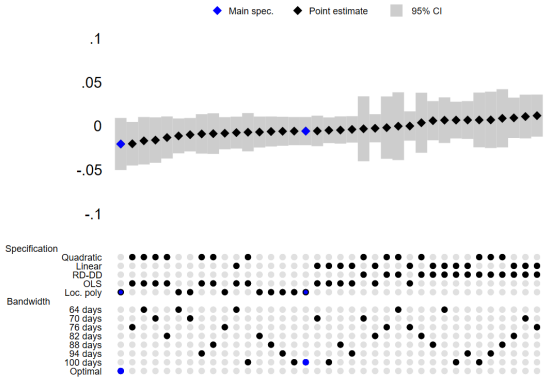


(d) HPV vaccination at age 15

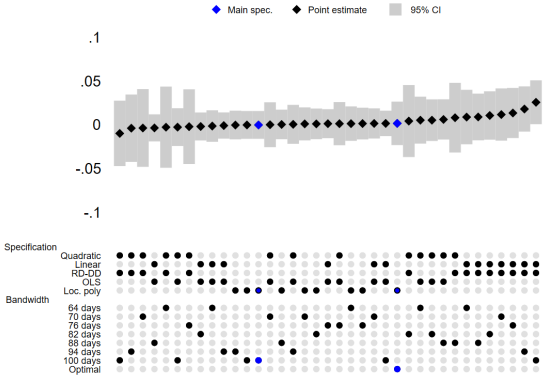
Fig. A8 Specification Curves for the Effect of Introducing Retrospective Reminder Letters in 2014
Notes: Each dot represents coefficients from separate regressions with a specific specification given by a combination of bandwidth and estimation method. The specific specification used to estimate a coefficient can be read from the bottom panel below each specification curve. The grey bars indicate 95% confidence intervals. Standard errors are robust in the parametric estimations (OLS and RD-DD).



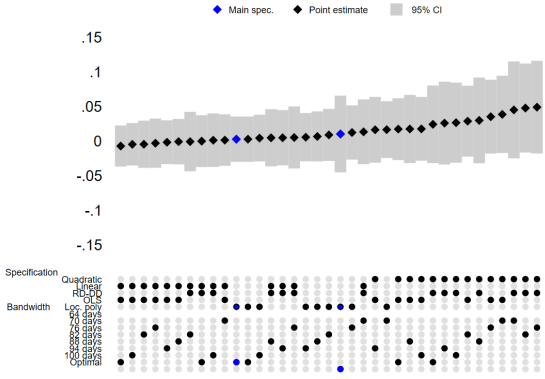
(a) All early vacs. at age 3



(b) MMR booster at age 7.5

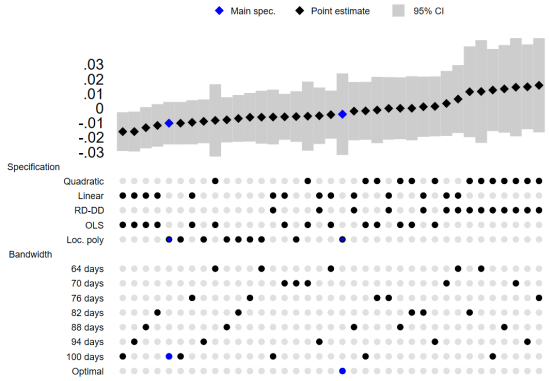


(c) DiTeKiPol booster at age 7.5

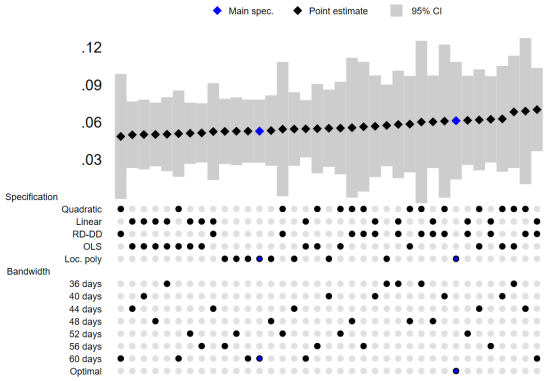


(d) HPV vaccination at age 15

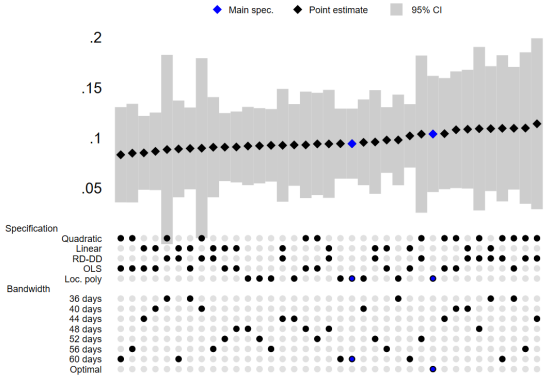
Fig. A9 Specification Curves for the Effect of Switching from Postal to Digital Reminders in 2017
Notes: See notes to Figure A8.



(a) All first-year vacs. at age 1



(b) MMR booster at age 5



(c) HPV vaccination at age 13

Fig. A10 Specification Curves for the Effect of Introducing Prospective Reminders in 2019
Notes: See notes to Figure A8.

Tab. A1 Summary Statistics for Samples used to Evaluate the Introduction of Retrospective Reminder Letters in 2014

	Samples					
	Early vacs.		MMR/DiteKiPol booster		HPV	
	Control	Treatment	Control	Treatment	Control	Treatment
	(1)	(2)	(3)	(4)	(5)	(6)
Inc., father 000' DKK	348.09	344.30	381.41	373.16	396.71	400.75
Inc., mother 000' DKK	213.84	176.01	261.56	253.60	274.51	279.17
Health educ., mother	0.14	0.14	0.15	0.15	0.14	0.15
Health educ., father	0.03	0.03	0.03	0.03	0.02	0.03
Prim. educ., mother	0.13	0.13	0.11	0.12	0.12	0.12
Prim. educ., father	0.14	0.13	0.13	0.14	0.15	0.14
Higher educ., mother	0.28	0.29	0.31	0.31	0.27	0.28
Higher educ., father	0.19	0.19	0.21	0.19	0.19	0.20
Uni. degree, mother	0.18	0.18	0.15	0.15	0.11	0.11
Uni. degree, father	0.17	0.17	0.15	0.15	0.11	0.12
Danish, mother	0.82	0.82	0.85	0.84	0.85	0.85
Danish, father	0.82	0.82	0.85	0.84	0.83	0.83
Employed, mother	0.82	0.81	0.87	0.86	0.86	0.87
Employed, father	0.92	0.92	0.92	0.92	0.91	0.90
Married	0.56	0.55	0.63	0.62	0.57	0.57
Cohabiting	0.88	0.88	0.78	0.77	0.65	0.65
Observations	15493	16978	18717	17092	8993	9370

Notes: The table shows means of background characteristics of parents of children included in the control and treatments groups for each sample given by the three cut-offs for the 2014 introduction of retrospective reminder letters.

Tab. A2 Summary Statistics for Samples used to Evaluate the Switch from Postal to Digital in 2017

	Samples					
	Early vacs.		MMR/DiteKiPol booster		HPV	
	Control	Treatment	Control	Treatment	Control	Treatment
	(1)	(2)	(3)	(4)	(5)	(6)
Inc. father 000' DKK	313	327	307	302	249	256
Inc. mother 000' DKK	216	227	223	220	160	169
Health educ., mother	0.12	0.13	0.13	0.13	0.10	0.11
Health educ., father	0.03	0.03	0.03	0.03	0.02	0.02
Prim. educ., mother	0.13	0.12	0.14	0.14	0.17	0.15
Prim. educ., father	0.15	0.14	0.15	0.15	0.18	0.16
Higher educ., mother	0.25	0.26	0.27	0.27	0.22	0.23
Higher educ., father	0.16	0.17	0.18	0.18	0.16	0.18
Uni. educ., mother	0.18	0.19	0.16	0.16	0.10	0.11
Uni. educ., father	0.16	0.17	0.15	0.16	0.11	0.11
Danish, mother	0.78	0.79	0.84	0.84	0.84	0.85
Danish, father	0.77	0.79	0.84	0.83	0.83	0.84
Employment, mother	0.85	0.85	0.89	0.89	0.84	0.85
Employment, father	0.90	0.92	0.93	0.93	0.91	0.92
Married	0.39	0.42	0.46	0.42	0.47	0.51
Cohabitation	0.82	0.86	0.85	0.82	0.85	0.89
Observations	15012	15290	18053	18090	7902	8664

Notes: The table shows means of background characteristics of parents of children included in the control and treatments groups for each sample given by the three cut-offs for the 2017 switch from postal to digital reminders.

Tab. A3 Summary Statistics for Samples used to Evaluate the Introduction of Prospective Reminders in 2019

	Samples					
	First-year vac.		MMR booster		HPV	
	Control	Treatment	Control	Treatment	Control	Treatment
	(1)	(2)	(3)	(4)	(5)	(6)
Inc., father	363.98	362.33	409.99	390.66	459.01	450.62
Inc., mother	247.82	244.39	254.17	248.39	315.06	308.82
Health educ., mother	0.12	0.12	0.14	0.14	0.15	0.15
Health educ., father	0.03	0.03	0.03	0.03	0.03	0.03
Prim. educ., mother	0.10	0.10	0.10	0.10	0.09	0.10
Prim. educ., father	0.11	0.11	0.12	0.12	0.13	0.13
Higher educ., mother	0.24	0.24	0.27	0.26	0.32	0.31
Higher educ., father	0.16	0.15	0.18	0.17	0.22	0.19
Uni. degree, mother	0.20	0.19	0.20	0.19	0.16	0.16
Uni. degree, father	0.17	0.17	0.17	0.17	0.15	0.16
Danish, mother	0.77	0.78	0.78	0.77	0.84	0.84
Danish, father	0.76	0.77	0.78	0.77	0.84	0.83
Employed, mother	0.87	0.87	0.85	0.83	0.89	0.89
Employed, father	0.92	0.91	0.95	0.94	0.92	0.92
Married	0.41	0.38	0.56	0.56	0.58	0.57
Cohabiting	0.85	0.82	0.85	0.85	0.69	0.68
Observations	17590	17993	10374	9568	5460	5012

Notes: The table shows means of background characteristics of parents to children included in the control and treatments groups for each sample given by the three cut-offs for the 2019 introduction of prospective reminders.

Tab. A4 McCrary tests: All Reform Samples

	(1) T-statistics	(2) p-value
	2014 introduction of reminder letters	
Early childhood vac. sample	-0.095	0.344
MMR/DiTeKiPol booster sample	0.268	0.789
HPV vac. sample	0.087	0.931
	2017 reform to digital reminders	
Early childhood vac. sample	-1.832	0.067
MMR/DiTeKiPol booster sample	-0.138	0.890
HPV vac. sample	-1.920	0.055
	2019 reform of timing of reminders	
First-year vac. sample	-1.400	0.162
MMR booster sample	0.015	0.988
HPV vac. sample	0.211	0.833

Notes: The table shows t-statistics and p-values from McCrary tests proposed by Cattaneo et al. (2018) for each reform and sample.

Tab. A5 Covariate Balance at the Cut-off for the Introduction of Prospective Reminder Letters in 2014

	Early vac. sample	Booster sample	HPV sample
Income, father	29.927	8132.747	31.060
	(11034.161)	(13456.193)	(24016.245)
Income, mother	-12527.247	4879.418	13389.098
	(7841.845)	(8247.935)	(12701.185)
Health educ., mother	-0.029	-0.002	0.011
	(0.015)	(0.014)	(0.019)
Health educ., father	-0.009	-0.002	0.012
	(0.007)	(0.007)	(0.009)
Prim. educ., mother	0.020	0.004	0.001
	(0.013)	(0.015)	(0.019)
Prim. educ., father	-0.009	-0.010	-0.003
	(0.015)	(0.014)	(0.023)
Higher educ., mother	-0.040	0.031	0.041
	(0.021)	(0.022)	(0.025)
Higher educ., father	0.004	0.008	0.018
	(0.017)	(0.016)	(0.021)
Uni. degree, mother	0.013	0.002	0.013
	(0.018)	(0.016)	(0.021)
Uni. degree, father	-0.007	-0.004	-0.009
	(0.016)	(0.014)	(0.017)
Danish, mother	-0.001	0.012	-0.001
	(0.015)	(0.014)	(0.023)
Danish, father	-0.023	-0.000	0.012
	(0.015)	(0.016)	(0.023)
Employed, mother	-0.025	0.015	0.029
	(0.017)	(0.015)	(0.021)
Employed, father	-0.012	0.018	0.005
	(0.011)	(0.011)	(0.021)
Married	-0.032	0.013	-0.022
	(0.023)	(0.021)	(0.027)
Cohabiting	-0.041	0.017	-0.061
	(0.013)	(0.020)	(0.033)

Notes: Each cell shows coefficients from separate regressions. The right-hand side variables are parental background characteristics realized prior to the reform (2013). Coefficients are estimates of the discontinuity at the cut-off and thus test for balance across the cut-off. We use local linear regression, a triangular kernel and the optimal bandwidth as developed by Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

Tab. A6 Covariate Balance at the Cut-off for the Switch from Postal to Digital Reminder Letters in 2017

	Early vac. sample	Booster sample	HPV sample
Income, father	9542.517	32557.207	4623.025
	(13613.968)	(16493.184)	(24216.689)
Income, mother	1587.304	4501.867	-27858.226
	(6870.597)	(7608.716)	(13449.027)
Health educ., mother	-0.021	-0.012	0.002
	(0.014)	(0.014)	(0.021)
Health educ., father	-0.018	-0.007	-0.009
	(0.008)	(0.008)	(0.009)
Primary educ., mother	0.010	-0.008	0.030
	(0.015)	(0.013)	(0.022)
Primary educ., father	0.028	-0.025	0.011
	(0.016)	(0.016)	(0.021)
Higher educ., mother	-0.015	0.000	-0.043
	(0.021)	(0.017)	(0.030)
Higher educ., father	0.022	-0.005	-0.014
	(0.021)	(0.015)	(0.022)
Uni. degree, mother	-0.002	0.004	-0.018
	(0.019)	(0.014)	(0.021)
Uni. degree, father	-0.004	-0.019	-0.036
	(0.020)	(0.016)	(0.022)
Danish, mother	0.018	0.004	0.005
	(0.020)	(0.014)	(0.023)
Danish, father	0.004	-0.005	-0.000
	(0.021)	(0.015)	(0.025)
Employed, mother	0.006	0.022	-0.005
	(0.022)	(0.015)	(0.018)
Employed, father	0.039	0.013	-0.002
	(0.014)	(0.013)	(0.016)
Married	-0.013	0.011	-0.003
	(0.023)	(0.018)	(0.030)
Cohabiting	0.016	0.034	0.017
	(0.014)	(0.021)	(0.027)

Notes: Each cell shows coefficients from separate regressions. The right-hand side variables are parental background characteristics realized prior to the reform (2015). Coefficients are estimates of the discontinuity at the cut-off and thus test for balance across the cut-off. We use local linear regression, a triangular kernel and the optimal bandwidth as developed by Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

Tab. A7 Covariate Balance at the Cut-off for the Introduction of Prospective Reminders in 2019

	1st-year vac. sample	MMR booster sample	HPV sample
Income, father	14339.779	26567.902	-204430.099
	(9858.684)	(19990.553)	(123008.843)
Income, mother	2091.170	12194.100	-9536.537
	(6910.485)	(10849.079)	(17426.748)
Health educ., mother	-0.014	-0.033	0.009
	(0.012)	(0.024)	(0.026)
Health educ., father	0.004	0.003	-0.006
	(0.007)	(0.010)	(0.013)
Prim. educ., mother	-0.018	0.035	0.021
	(0.011)	(0.020)	(0.023)
Prim. educ., father	0.001	0.008	0.034
	(0.012)	(0.019)	(0.027)
Higher educ., mother	-0.039	-0.042	0.089
	(0.020)	(0.031)	(0.038)
Higher educ., father	0.007	0.007	0.004
	(0.015)	(0.021)	(0.029)
Uni. degree, mother	0.035	0.046	-0.060
	(0.018)	(0.027)	(0.031)
Uni. degree, father	0.021	0.052	0.008
	(0.014)	(0.025)	(0.025)
Danish, mother	-0.013	0.035	0.015
	(0.018)	(0.022)	(0.028)
Danish, father	-0.005	0.071	0.042
	(0.018)	(0.024)	(0.028)
Employed, mother	-0.004	0.027	-0.002
	(0.014)	(0.020)	(0.023)
Employed, father	-0.004	0.004	0.008
	(0.010)	(0.016)	(0.019)
Married	0.015	0.016	-0.065
	(0.023)	(0.030)	(0.046)
Cohabiting	0.002	0.041	-0.058
	(0.014)	(0.023)	(0.042)

Notes: Each cell shows coefficients from separate regressions. The right-hand side variables are parental background characteristics realized the year prior to the reform (2018). Coefficients are estimates of the discontinuity at the cut-off and thus test for balance across the cut-off. We use local linear regression, a triangular kernel and the optimal bandwidth as developed by Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

Tab. A8 Estimates of the Effect on Overall Coverage Rates of Switching from Postal to Digital Reminders in 2017

	(1) DiTeKiPol1 at age 3	(2) DiTeKiPol2 at age 3	(3) DiTeKiPol3 at age 3	MMR1 at age 3
Full bandwidth estimate	-0.000	0.004	0.007	0.022
	(0.003)	(0.004)	(0.008)	(0.007)
Optimal bandwidth estimate	0.003	0.004	0.001	0.042
	(0.006)	(0.007)	(0.015)	(0.015)
Below cut-off mean	0.98	0.97	0.87	0.89
Observations	32471	32471	32471	32471
Obs. with optimal bandwidth	8991	10522	8677	8066

Notes: Each cell shows coefficients from separate regressions. The outcomes are indicators given by the column labels. Coefficients are estimates of the discontinuity at the cut-off. The cut-off is the implementation date of the introduction of reminder letters on 15 May, 2014. We use local linear regressions, a triangular kernel and a 100-day and the optimal bandwidth as developed in Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.

Tab. A9 Estimates of the Effect on Overall Coverage Rates of Switching from Postal to Digital Reminders in 2017

	(1) All early vacs. at age 3	(2) MMR booster at age 7.5	(3) DiTeKiPol booster at age 7.5	(4) HPV at age 15
Full bandwidth	-0.000	-0.006	-0.001	0.002
	(0.010)	(0.008)	(0.008)	(0.017)
Optimal bandwidth	-0.029	-0.021	0.001	0.010
	(0.022)	(0.015)	(0.013)	(0.028)
Below cut-off mean	0.79	0.85	0.85	0.66
Observations	30302	36143	36143	16566
Obs. opt. b.width	6217	10678	14341	5690

Notes: Each cell shows coefficients from separate regressions. The outcomes are indicators given by the column labels. Coefficients are estimates of the discontinuity at the cut-off. The cut-off is the implementation date of the switch to digital reminder letters on February 6, 2017. We use local linear regression, a triangular kernel and a 100-day and the optimal bandwidth as developed in Calonico et al. (2020) on each side of the cut-off. Standard errors in parentheses.