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3G Internet and Information Frictions in Childhood Vaccination: Evidence from India

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3G Internet and Information Frictions in Childhood Vaccination: Evidence from India*

Abstract

Childhood vaccination rates often fall over the course of the immunization schedule. We study whether local mobile internet coverage reduces this decline, using data on about 113,000 children from India's National Family Health Survey (2019–21) matched to georeferenced maps of 3G network coverage. To address the non-random placement of 3G networks, we instrument coverage with terrain ruggedness, which raises the cost of deploying and maintaining network infrastructure. Comparing clusters within the same district, we find that 3G coverage has no detectable effect on the doses due in the first year of life but increases receipt of the doses due at 16–24 months. The effect emerges when children reach the age at which these doses become due. In a within-child design comparing earlier and later vaccinations of the same child, which removes all factors that affect both vaccinations equally, 3G coverage raises completion of the 16–24-month stage of the schedule but not of earlier stages. Taken together, the results point to information and coordination frictions as one barrier to completing vaccination in the second year of life.

JEL classification

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Keywords

mobile internet, 3G coverage, vaccination, health information, digital connectivity, India, child health

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1 Introduction

Childhood vaccination is one of the most cost-effective public health interventions, yet coverage remains incomplete and declines as immunization schedules progress. One possible reason is that completing the schedule requires more than willingness to seek care: families must know when each dose is due and organize each visit, while health services must keep track of which children are due and follow up in time.

India’s National Family Health Survey (NFHS-5, 2019–21) illustrates this pattern. Among children aged 16–35 months, 95 percent have received the BCG (Bacillus Calmette–Guérin) vaccine, given at birth, and 88 percent the third dose of the vaccine against diphtheria, pertussis and tetanus (DPT), due at 14 weeks. Among the same children, only 61 percent have received the DPT booster and 54 percent the second dose of measles-containing vaccine (MCV-2), the two doses due at 16–24 months.¹ India is a useful setting for studying completion of the doses due at 16–24 months because their receipt remains far from universal even under a common national schedule, while households and health services differ in the resources available for keeping track of the schedule and coordinating follow-up. All doses are provided free of charge under the Universal Immunization Programme, so the lower coverage of the later doses cannot be attributed to differences in the cost of the vaccines themselves. This paper studies whether the lower receipt of these doses partly reflects information and coordination frictions in following the immunization schedule, and whether local mobile internet coverage reduces them.

A common asymmetry in childhood immunization schedules is that early doses are clustered within a relatively dense sequence of vaccination contacts, while later doses can follow much longer intervals. In India, the first-year doses are scheduled at birth, at 6, 10 and 14 weeks, and at 9–12 months, whereas the doses due at 16–24 months follow a longer interval without any scheduled vaccination contact. The 16–24-month stage therefore places greater information and coordination demands on both families and health services. When these frictions are costly, coverage can remain high for first-year doses while falling at the 16–24-month stage.

This asymmetry suggests a specific role for digital connectivity. Mobile internet may lower the cost of meeting these information and coordination demands by making it easier to obtain information about the schedule, keep track of when children become due and coordinate follow-up, for families and health services alike.

A simple conceptual framework, presented in Section 2, helps organize the empirical patterns implied by this role of digital connectivity. First, the effect of local 3G coverage should be larger for the doses due at 16–24 months than for those due in the first year of life. Second, the effect on these later doses should emerge when children reach the age at which

¹Weighted shares among the children aged 16–35 months in our analytical sample, all of whom have reached the minimum recommended age of these doses. Table 1 reports descriptive statistics for every dose.

they become due, and not before. Third, if connectivity and households' own information resources are substitutes in reducing information and coordination frictions, the effect may be larger among households with fewer such resources, such as those of less educated mothers.

We study these questions using individual-level data on about 113,000 children under three years of age from NFHS-5, living in about 24,500 survey clusters, which correspond to rural villages or urban census enumeration blocks, in 608 districts. We match these locations to high-resolution raster data on local 3G mobile internet coverage in 2018. Because 3G coverage is not randomly assigned, we use terrain ruggedness as an instrument, exploiting the higher cost of deploying and maintaining cellular infrastructure in rugged areas. Our benchmark specification includes district fixed effects, so that the effect of 3G coverage is identified from terrain-induced variation in coverage across clusters within the same district. Each effect is estimated among the children who have reached the age at which the corresponding doses become due, with fixed effects for the child's exact age in months.

The results mirror the asymmetry of the schedule. For the doses due in the first year of life, the estimated effects of 3G coverage are small and statistically insignificant. For the doses due at 16–24 months, by contrast, they are positive. In the benchmark specification with district fixed effects, 3G coverage increases the share of these doses that a child has received by about 22 percentage points and the probability of having received both by about 27 percentage points. Both estimates are statistically significant, as is the effect on MCV-2, while the effect on the DPT booster is positive but not statistically significant. With state fixed effects, the estimates are larger and statistically significant for all these outcomes. The contrast between stages does not arise from less precise estimates for the earlier doses. Several first-year outcomes are far from universal: only 66 percent of children in uncovered clusters have received all the birth doses, and 76 percent all the doses of the primary series. Yet the confidence intervals of the estimated effects on these outcomes rule out effects as large as the effect on having received both doses due at 16–24 months.

A separate analysis by age shows when the effect of 3G coverage appears. Within each age group, the effects on early and later doses are estimated among children living in the same clusters. Among children younger than 16 months, 3G coverage has no detectable effect on the doses due at 16–24 months. Among children aged 16–24 months, it increases receipt of MCV-2 and the probability of having received both doses due at that age, and both estimates are statistically significant. In the same age group, its estimated effects on the doses due in the first year of life remain small and statistically insignificant. The positive effect of 3G coverage is therefore concentrated on the doses that become due at that age. Among children aged 25–35 months, the estimates remain positive but are smaller and less precise. Receipt of these doses after 24 months is rare and not significantly associated with 3G coverage, so the evidence gives no indication that the effect reflects catch-up after the recommended window.

The main threat to this strategy is that rugged terrain may affect vaccination directly,

independently of 3G coverage, by making health facilities harder to reach and outreach harder to deliver. If this disadvantage affected all vaccinations alike, the instrument would attribute it to 3G coverage at every stage of the schedule, and we would also find positive effects on the doses due in the first year of life. This is not what we find. Ruggedness could, however, weigh more on the later doses, which require a return after a longer interval and may therefore be more sensitive to access and outreach conditions. In that case, an effect of terrain specific to the later doses would be attributed to 3G coverage.

We address this remaining threat in two steps. First, we introduce a within-child completion design that compares, for the same child, a later vaccination with an earlier one. Child fixed effects remove everything that affects both vaccinations equally, including any common disadvantage due to terrain, so the design requires only that ruggedness has no direct effect specific to the later vaccination. In this design, 3G coverage increases completion of the 16–24-month stage of the schedule, whereas its effects on completion of the primary series and on the return around 9 months, which also require repeated visits, are small and statistically insignificant. The difference between the effect at the 16–24-month stage and that for the primary series is statistically significant; with district fixed effects, the difference from the 9-month return is positive but not statistically significant.

Second, we examine directly the conditions through which ruggedness could affect later vaccinations differently, bringing in additional data and linking them to each child’s cluster and, where relevant, to the months in which the later dose falls due. Harmonized nighttime lights for 2000–2007 capture local development before the diffusion of mobile broadband. District flood records and monthly rainfall around each cluster measure temporary disruptions of physical access when the later dose is due. Travel time to the nearest health facility and NFHS-5 records of whether the mother met frontline health workers describe access and outreach. Allowing each of these conditions to affect the later vaccination differently from the earlier one does not attenuate the completion estimate.

The effects of 3G coverage on the doses due at 16–24 months are concentrated among children of mothers with fewer than eight years of schooling. With district fixed effects, the effect on the share of these doses received is large and statistically significant in this group and small and statistically insignificant among children of more educated mothers; the difference between the two groups is statistically significant. This pattern is consistent with the third prediction outlined in the conceptual framework, which holds when connectivity and households’ own information resources are substitutes in reducing information and coordination frictions. It is compatible with effects working through families as well as through health workers. Less educated families may benefit directly from easier access to information, or indirectly, because better connected frontline health workers can follow up with them more effectively.

Section 6 examines these channels with additional data on connectivity. NFHS-5 records mothers’ own phone ownership and internet use only in a subsample of about 15 percent of

households, where the estimates are too imprecise to show whether local 3G coverage changes their use. The household questionnaire, which asks every household whether it has internet, provides suggestive evidence that 3G coverage increased household internet access. We also use 2G coverage maps for 2014 and 2018 from the Mobile Coverage Explorer of the GSM Association (GSMA), produced in partnership with Collins Bartholomew, to ask whether our estimates merely capture access to basic mobile services, which suffice for calls and text-message reminders. Controlling for 2G coverage leaves the estimates essentially unchanged, and restricting the sample to clusters already covered by 2G gives less precise estimates that remain close to the benchmark in most specifications.

On the provider side, official documents show that during the survey period the national Reproductive and Child Health portal and, in several states, its tablet application for auxiliary nurse midwives (ANMOL) gave frontline health workers digital tools to track children due for vaccination, prepare due lists and plan vaccination sessions. These workers are central to vaccine delivery: among vaccinated children aged 16–35 months in our sample, 70 percent received most of their vaccinations at community-based sites, such as Anganwadi centres and outreach sessions. These facts make a provider pathway plausible. Taken together, the evidence is consistent with local 3G coverage reducing information and coordination frictions through families, frontline health workers or both, while leaving open which of the two channels drives the effects on vaccination.

The pattern across stages of the schedule also holds under alternative specifications and measures. With state fixed effects, the estimates are larger. The pattern is the same under alternative measures of 3G coverage, such as the share of the area or of the population covered around each cluster, which account for the random displacement of DHS cluster coordinates, and when the analysis is restricted to one child per woman. Our interpretation rests on the combination of these patterns rather than on any single estimate.

The paper contributes to three strands of literature. First, it adds to the economics of vaccination and preventive health behavior. A large literature studies how immunization responds to prices, incentives, beliefs, institutional design, and perceived disease risk (Dupas, 2011; Oster, 2018). Randomized evidence from rural India shows that even modest incentives can increase vaccination uptake (Banerjee et al., 2010), while work in higher-income countries documents the effects of vaccination mandates, including spillovers to other vaccines (Carpenter and Lawler, 2019).

More recently, several studies have examined how digital information environments shape vaccination decisions. Amaral-Garcia et al. (2024), for example, show that broadband expansion reduced MMR uptake in England following the public controversy over an alleged link between vaccination and autism, while Deiana et al. (2022), exploiting the temporary suspension of a COVID-19 vaccine in Italy, show that a rise in perceived vaccine risk depresses immunization, especially where online attention to side effects is greater. This literature has clarified how digital media can amplify hesitancy and attitudinal responses in settings where

basic awareness of vaccination is already widespread.

Our results point to a barrier distinct from vaccine attitudes: the difficulty of following a prolonged schedule once scheduled vaccination contacts become less frequent. Exploiting the stages of the schedule, the age at which each dose becomes due, and the comparison between earlier and later vaccinations of the same child, we show that local connectivity matters at the stage at which completion requires a return after a longer interval without a scheduled vaccination contact. Our findings also differ from the evidence on hesitancy in who responds. In England, the decline in MMR uptake associated with broadband was larger in areas with more high-skilled and less deprived residents, consistent with these parents responding faster to false information (Amaral-Garcia et al., 2024). In our setting, the effects of connectivity are positive and concentrated among children of less educated mothers, who have fewer information resources of their own. This pattern is closer to evidence that broadband changed childbirth choices in England mainly among first-time mothers and mothers in less educated and lower-income areas (Amaral-Garcia et al., 2022). In both cases, connectivity matters most where families can draw least on their own knowledge and experience. These patterns point to information and coordination frictions as a channel through which digital infrastructure can affect vaccination.

Second, the paper contributes to the literature on the economic, political, and behavioral effects of digital infrastructure in low- and middle-income countries. This literature shows that internet expansion can reduce information frictions, improve market outcomes, and reshape political and social behavior (Hjort and Poulsen, 2019; Manacorda and Tesei, 2020; Guriev et al., 2021; Donati, 2023; D’Andrea and Limodio, 2024). Related work in both lower- and higher-income settings documents effects on migration attitudes, social capital, mental health, political participation, and firm performance (Falck et al., 2014; Akerman et al., 2015; Miner, 2015; Campante et al., 2018; McDool et al., 2020; Akerman et al., 2022; Geraci et al., 2022; Arenas-Arroyo et al., 2025; Donati et al., 2025). Relative to this literature, our contribution is not simply to document another outcome affected by connectivity. It is to show that digital infrastructure affects the use of a public health service in a selective way: the effects are concentrated at the stage of the immunization schedule at which completion places greater demands on acquiring, retaining and acting on information about when a dose is due.²

Third, the paper is related to the literature on mobile health interventions. Studies of SMS reminders, alone or combined with small cash incentives, show that targeted messages can improve childhood immunization coverage and timeliness in low- and middle-income countries (Gibson et al., 2017; Eze et al., 2021). These interventions are designed to deliver reminders about vaccination. We study instead general-purpose infrastructure that exists independently of vaccination programmes, and our results suggest that the local availability

²For broader discussions of the effects of internet expansion and the associated identification challenges, see Hjort and Tian (2025) and Sabatini (2025).

of mobile internet can produce related effects even without a dedicated intervention. The two approaches are complementary: one evaluates messages designed for vaccination, the other the broader digital environment in which families and health workers operate.

The remainder of the paper is organized as follows. Section 2 presents a simple conceptual framework that organizes the empirical analysis. Section 3 describes the institutional setting and the data. Section 4 presents the empirical strategy. Section 5 reports the results. Section 6 discusses possible mechanisms. Section 7 concludes.

2 Conceptual framework

This section presents a simple framework that organizes the empirical analysis. The framework is deliberately stylized. We use it to make explicit the information and coordination mechanism that motivates the paper and the assumptions behind the empirical patterns we examine, without attempting to model vaccination behavior in full.

2.1 Setup

Consider child i in location c and a dose v of the immunization schedule. Doses are indexed by the stage at which they become due: at birth, at 6–14 weeks, at 9–12 months and at 16–24 months (Section 3). Let S_{ivc} denote the net surplus associated with completing dose v for child i ; the child receives the dose if $S_{ivc} \geq 0$. The net surplus combines two components,

$$S_{ivc} = B_{ivc} - K_{ivc}.$$

The first, B_{ivc} , collects the determinants of vaccine demand other than the information and coordination friction: perceived disease risk, expected health gains, trust in vaccination, and the cost of reaching vaccination services, which enters with a negative sign. The second, K_{ivc} , is the information and coordination friction associated with completing dose v : knowing that the dose exists, knowing and remembering when it becomes due, and organizing the visit at which it is administered. These requirements are inherent in multi-dose immunization schedules and need not fall on the household alone. In India, frontline health workers identify eligible children, remind families of upcoming sessions and follow up missed doses (Section 3), so the friction is shared between families and the health system.

The friction varies with the position of the dose in the schedule. The doses due at birth and at 6–14 weeks are embedded in a denser sequence of scheduled vaccination contacts, with MCV-1 closing the first-year schedule used to define full immunization under the programme (Section 3). The doses due at 16–24 months follow a longer gap in the vaccination schedule, so completing them requires families, health workers or both to keep track of when the child

becomes due and to organize a return. We therefore write

$$K_{ivc} = K_v(e_i, m_c),$$

where e_i denotes the household's own information resources, such as the mother's schooling, and m_c denotes local mobile internet coverage, and we assume that, for any given (e_i, m_c) , K_v is larger for the doses due at 16–24 months than for the doses of the first year. Local connectivity lowers the friction, $\partial K_v / \partial m_c < 0$, whether because families obtain and retain information about the schedule directly or because health workers reach families and coordinate with health facilities more effectively. We assume, further, that 3G coverage has greater scope to reduce the friction where the friction is larger, so that the reduction in K_v is greatest for the doses due at 16–24 months, where $\partial K_v / \partial m_c$ is most negative. The first of the predictions stated in the next subsection rests on this second assumption.

The effect of 3G coverage on vaccination depends on how much it shifts the net surplus and on how many children are close to the threshold $S_{ivc} = 0$ at each stage. The predictions therefore hold other things equal, and we examine the pattern across stages together with the timing of the effects by child age and the within-child completion design (Section 5). Connectivity may also affect B_{ivc} : for instance, information can change how families perceive disease risk. For this reason, we state the predictions in terms of the net surplus, with $\partial S_{ivc} / \partial m_c > 0$. We assume, however, that any effect of connectivity on B_{ivc} does not vary systematically across stages of the schedule. The demands of the schedule differ across stages through the information and coordination friction K_v , and the stage-specific response to 3G coverage therefore comes from its effect on K_v . The within-child completion design builds on this assumption: comparing a later and an earlier dose of the same child removes any effect of connectivity on B_{ivc} that is common to the two doses, together with any other determinant of vaccination that affects both equally.

2.2 Empirical predictions

We expect three patterns in the data.

First, the effect of local 3G coverage should differ across the stages of the schedule. Because 3G coverage produces a larger positive shift in the net surplus for the doses due at 16–24 months than for the doses of the first year, we expect larger effects on the receipt of the later doses, other things equal. The doses due in the first year of life therefore provide a benchmark. If 3G coverage affected them as much as the later doses, the pattern would be hard to attribute to the greater information and coordination demands of the 16–24-month stage.

Second, the effect on the doses due at 16–24 months should emerge when children reach the age at which these doses become due, and not before. This prediction follows from the framework combined with the schedule: younger children are not yet due for these doses,

which are rarely administered before 16 months (Section 5.3).

Third, the effect may be larger among households with fewer information resources of their own. This prediction requires an additional assumption. Formally, we assume $\partial^2 S_{ivc} / \partial e_i \partial m_c < 0$: the marginal effect of 3G coverage on the net surplus is larger when the household's own information resources are lower. This is the case if connectivity and own information resources are substitutes in reducing the information and coordination friction. Connectivity may, for instance, provide information that more educated households obtain in other ways, or support follow-up by health workers that matters most for families with fewer resources of their own. If instead connectivity and own resources were complements, for instance because using the internet to obtain health information requires skills that come with schooling, the cross-partial derivative would be positive, and the heterogeneity in receipt would run in the opposite direction, other things equal. The sign is an empirical question, and the third prediction is conditional on the substitution assumption. A negative cross-partial derivative could also arise through B_{ivc} , if information obtained through connectivity changes the perceived benefits of vaccination more among households with fewer information resources of their own. Heterogeneity by maternal schooling can therefore indicate the sign of the cross-partial derivative, but not whether it operates through B_{ivc} or through K_{ivc} .

3 Data and institutional setting

To study the effect of 3G coverage on childhood vaccination, we combine individual-level survey data on children and mothers with geospatial data on mobile coverage, terrain and local conditions. We first describe the immunization schedule and how vaccination services are delivered in India.

3.1 Immunization schedule and service delivery in India

India's Universal Immunization Programme (UIP) provides childhood vaccines free of charge under a nationally defined schedule. For the doses studied in this paper, BCG, the birth dose of oral polio vaccine and the birth dose of hepatitis B vaccine are administered at birth; three doses of DPT-containing vaccine and of oral polio vaccine at 6, 10 and 14 weeks; and the first measles-containing dose (MCV-1) at 9–12 months. The second measles-containing dose (MCV-2) and the first DPT booster are scheduled at 16–24 months. The schedule is national in scope, although some vaccines are included only in selected areas; in particular, the Japanese encephalitis vaccine is part of routine immunization only in endemic districts (MoHFW, 2018). Appendix Table A1 summarizes the elements of the vaccination schedule relevant to the construction and selection of the outcomes.

In practice, routine immunization is delivered through a combination of fixed and outreach sessions and relies heavily on frontline health workers. Auxiliary Nurse Midwives (ANMs),

Accredited Social Health Activists (ASHAs), and Anganwadi Workers (AWWs) help identify eligible children, prepare due lists, maintain records, inform caregivers about upcoming vaccination sessions, and encourage attendance (MoHFW, 2018). Official guidance also instructs frontline workers to use the Mother and Child Protection (MCP) card to record the next due date, track missed doses, and support follow-up after missed vaccinations (MoHFW, 2018; MoHFW and MWCD, 2018). The programme distinguishes full immunization within the first year, completed with MCV-1, from complete immunization by age two, which includes the doses due at 16–24 months (MoHFW, 2018, 2020b).

This institutional setting matters for our interpretation because the information and coordination demands of the schedule are not constant across its stages. Around birth and during early infancy, vaccination is more likely to occur during relatively frequent contacts with the health system, so eligibility can often be assessed at the point of care. By contrast, the later doses become due only after a longer interval, and completing them requires that the family, the health worker or both keep track of when the child enters the relevant age window and organize a return.

This asymmetry maps directly into our outcome selection. Birth doses and the primary series provide a benchmark, because their uptake depends less on keeping track of future eligibility. MCV-2 and the first DPT booster, by contrast, become due at 16–24 months, after the primary infant schedule has largely been completed, and their uptake depends more heavily on keeping track of future eligibility and coordinating the return. This institutional feature motivates the grouping of doses by stage of the schedule described in Section 3.2, as well as the age-appropriate samples, the comparison across age cohorts and the within-child completion design described in Sections 4.3 and 4.5.

3.2 NFHS-5 and vaccination outcomes

Our primary data source is the fifth round of the National Family Health Survey (NFHS-5), India’s implementation of the Demographic and Health Surveys (DHS) program. Conducted in 2019–21, NFHS-5 covers a nationally representative sample of 724,115 women aged 15–49 across all states and union territories and provides detailed information on children’s vaccination histories, maternal healthcare utilization, and household socioeconomic characteristics. For geospatial analysis, the DHS program releases displaced longitude and latitude for survey clusters rather than exact household locations. In public-use data, urban clusters are displaced by up to 2 km, rural clusters by up to 5 km, and a small share of rural clusters by up to 10 km, with displacement designed to preserve confidentiality while limiting administrative misclassification.

The unit of analysis is the child. NFHS-5 collects vaccination histories for every living child under 36 months of age listed in the birth history of an interviewed woman, and for no older child; the analytical sample includes all of these children. A natural alternative would

be to keep one child per woman, typically the most recent birth, because survey weights are defined for interviewed women and siblings share the same household and cluster. We do not adopt this restriction, for two reasons. First, because local 3G coverage varies at the survey-cluster level and standard errors are clustered at that level, inference already allows for arbitrary correlation among siblings belonging to the same cluster. Second, selecting the most recent birth would over-represent younger children, many of whom are not yet eligible for the doses due at 16–24 months. If fertility differs with 3G coverage or terrain, the age of the selected child could then differ systematically across locations. Starting from the 132,460 living children under 36 months in the birth histories, we drop the children whose cluster lies outside the extent of the 3G coverage map or lacks released coordinates, and those with incomplete controls. The analytical sample comprises 113,249 children of 101,895 women in 24,553 DHS clusters; 11,817 of these children are older siblings of the most recent birth. Each child carries the survey weight of the mother, as in the DHS children’s recode, normalized to mean one in each estimation sample. Appendix B documents the construction of the sample step by step and compares it with the one-child-per-woman sample. In the analytical sample, neither ruggedness nor instrumented 3G coverage predicts the share of children who have reached 16 months, and the reduced-form relationship between ruggedness and child age is small and statistically insignificant (Appendix Table B2). A modest age gradient remains within the 16–35-month subsample, which is one of the reasons for the exact age-in-month fixed effects included in every specification (Section 4.3).

For each child, NFHS-5 records whether each dose of the Universal Immunization Programme was received, based on the vaccination card when it was available and on the mother’s report otherwise. We code a dose as received when the card records a date or a mark for it or the mother reports it, as not received when neither source does, and as missing when the mother does not know. For the first dose of measles-containing vaccine (MCV-1), NFHS-5 also includes a response category, specific to India, that is used only when the vaccination card was seen, but entries in this category do not contain a vaccination date. Because this India-specific, undated category does not map unambiguously onto the standard receipt categories used for the other doses, we treat it as missing in the baseline coding; it applies to 13,067 of the 84,011 children aged 9–35 months in the analytical sample and accounts for nearly all the children of that age without a usable MCV-1 record. Coding these entries as received or as not received leaves the common completion estimate for the 16–24-month stage positive and statistically significant (at the 10 percent level with district fixed effects when they are coded as not received), and the estimates for MCV-1 small and statistically insignificant (Appendix Table G5).

We group the doses into four stages, defined by the age at which the schedule makes them due (Appendix Table A1): the birth doses (BCG, the birth dose of oral polio vaccine, OPV-0, and the birth dose of hepatitis B vaccine); the primary series due at 6, 10 and 14 weeks (three doses of DPT-containing vaccine and three doses of oral polio vaccine); MCV-1,

due at 9–12 months; and the two doses due at 16–24 months, the second dose of measles-containing vaccine (MCV-2) and the first DPT booster. In NFHS-5, every child recorded as having received a dose of pentavalent vaccine, which combines DPT with the hepatitis B and *Haemophilus influenzae* type b antigens, is also recorded as having received the corresponding doses of DPT and hepatitis B. The DPT indicators therefore cover every DPT-containing dose, and separate indicators for pentavalent vaccine and for hepatitis B doses 1–3 would largely duplicate them: among children recorded as having received a hepatitis B dose of the primary series, more than 99 percent are recorded as having received the corresponding DPT dose. Several other elements of the schedule are not used as outcomes. Rotavirus vaccine was introduced in phases from 2016, and its extension to the whole country was announced only in 2019 (Press Information Bureau, 2019); for many children in the sample, receipt therefore depends on when their state introduced the vaccine rather than on household behavior. Japanese encephalitis (JE) vaccine is part of routine immunization only in endemic districts (MoHFW, 2018). In these districts, which account for more than a third of the children in the analytical sample, terrain is considerably less rugged and ruggedness does not predict 3G coverage (first-stage F -statistics of 0.1 with district fixed effects and 1.2 with state fixed effects), so the instrument carries no information on JE doses (Appendix Table G4). Finally, the public-use NFHS-5 data contain no usable indicator for the inactivated poliovirus vaccine, the pneumococcal conjugate vaccine or the OPV booster (Appendix Table A1).

For each stage, our main outcome is the share of the doses due at that stage that the child has received, measured among children who have reached the minimum age at which the last of these doses becomes due (Section 4.3); for MCV-1, the share coincides with receipt of the single dose. We also use a stricter indicator for having received all the doses of a stage, and we report estimates for MCV-2 and the DPT booster separately. Vaccination coverage is high in the first year of life and drops sharply at the 16–24-month stage. Among age-eligible children in the analytical sample, the weighted average share of doses received is 82.2 percent for the birth doses, where it is lowered by the hepatitis B birth dose (66.7 percent), 87.3 percent for the 6–14-week series and 86.1 percent for MCV-1. For the doses due at 16–24 months, it falls to 57.8 percent: 54.2 percent of children have received MCV-2, 61.3 percent the DPT booster, and 47.5 percent both. Table 1 reports summary statistics.

3.3 Mobile coverage and terrain ruggedness

We measure mobile internet availability using the proprietary Mobile Coverage Explorer (MCE) dataset produced by the GSM Association (GSMA) in partnership with Collins Bartholomew. These data are compiled from submissions by mobile operators for the construction of roaming coverage maps and provide georeferenced information on the spatial footprint of each mobile technology at fine geographic resolution. We use the 2018 release of the 3G coverage layer for India, a raster in the Web Mercator projection with a nominal pixel

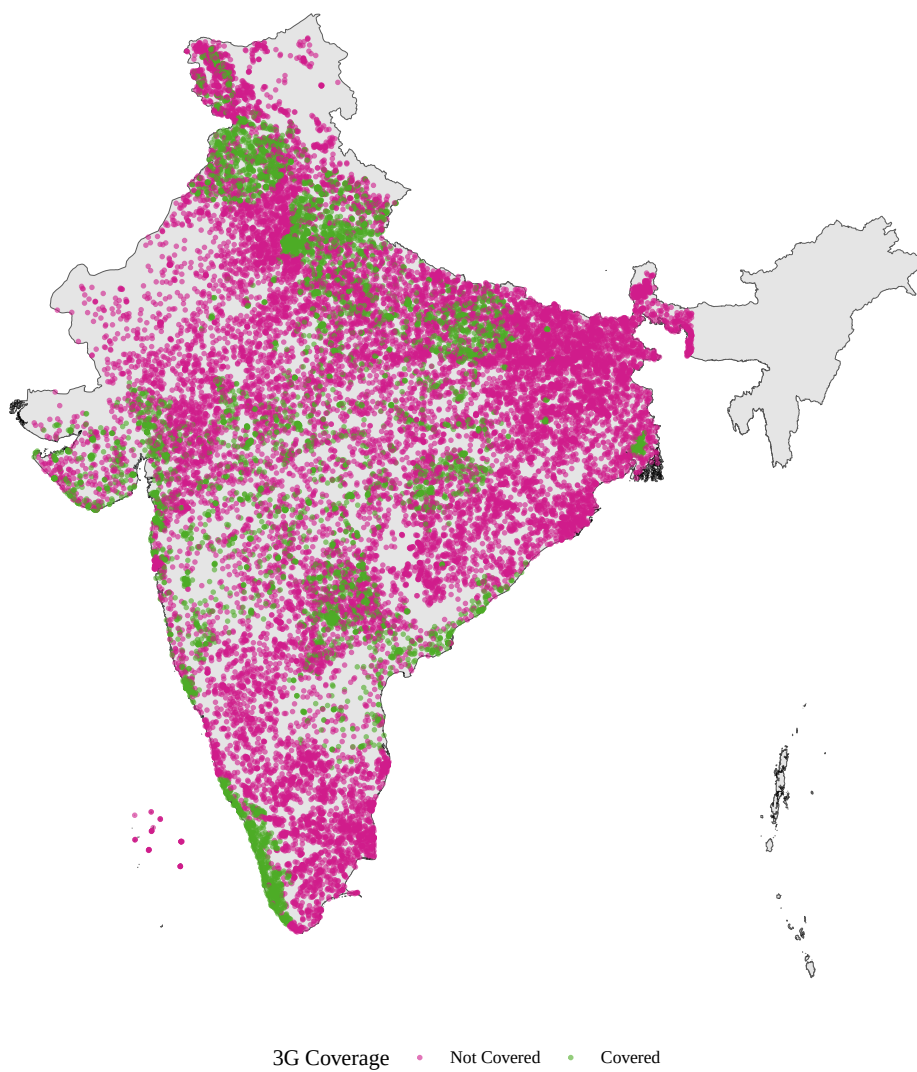


Figure 1: 3G coverage of DHS clusters (2018)

size of 264.6 metres, in which each pixel is coded as covered or not covered. The raster extends to about 90°E, and clusters east of this meridian, including many in the North-Eastern states and in the Andaman and Nicobar Islands, are outside the map and are excluded from the analysis (Appendix Table B1). No earlier release of the 3G layer is available for India. Our analysis therefore exploits cross-sectional variation in local 3G availability rather than its rollout over time.

Our baseline measure of local 3G availability is binary point coverage: for each DHS cluster, $3G_c$ equals one if the raster pixel containing the released cluster coordinate is covered by a 3G signal, and zero otherwise. This measure records whether a 3G signal was available at the released location of the cluster, is the simplest possible definition, and does not depend on any choice of buffer radius. In the analytical sample, 29 percent of children live in covered clusters; the share is 60 percent in urban clusters and 18 percent in rural clusters. Figure 1 shows the spatial distribution of covered and non-covered clusters.

Because the released coordinates are displaced by up to 2 km in urban areas and up to 5 km in rural areas, with a small share of rural clusters displaced by up to 10 km, we also construct four alternative measures. Three of them use a buffer equal to the standard DHS displacement radius, 2 km for urban and 5 km for rural clusters: the share of the buffer’s area covered by 3G; the share of the buffer’s population covered by 3G, weighting each raster pixel by the population of the WorldPop 2018 gridded population data (WorldPop, 2020), so that unpopulated areas receive no weight; and an indicator for at least one covered pixel within the buffer. The fourth is the share of the area covered within a 10-km buffer. Averaged over the children in the analytical sample, coverage is 0.27 with the area share, 0.30 with the population share, 0.49 with the indicator for any covered pixel and 0.22 with the 10-km area share. Across clusters, the correlation with the baseline point measure is 0.84 for both the area and the population shares within the displacement buffer, 0.63 for the indicator for any covered pixel and 0.73 for the 10-km area share. Section 5.2 reports the main results under each of these definitions.

Our instrument is a terrain ruggedness index in the spirit of Riley et al. (1999), which measures local topographic irregularity independently of average elevation. We compute it from the Copernicus GLO-90 digital elevation model (European Space Agency and Airbus, 2022), aggregated to cells of 12 arc-seconds (about 360 metres). For each cell, the index is the mean absolute elevation difference, in metres, between the cell and its eight neighbours; the value for a DHS cluster is the average over the four-by-four block of cells around the released coordinate, a window of about 1.4 km. Terrain ruggedness is therefore measured in the immediate surroundings of the cluster, at the same displaced location as the point coverage measure. The index is highly skewed: across clusters its median is 2.4 and its mean 9.6, with a standard deviation of 23.8; in the regressions it enters in units of 10. Because rugged terrain increases the cost of deploying and maintaining cellular infrastructure, it provides a natural source of variation in local 3G coverage. We discuss the identifying assumptions behind this

strategy in Section 4.

3.4 Controls and additional data sources

Controls. The baseline specifications include a vector of individual- and cluster-level controls to absorb observable determinants of both 3G coverage and vaccination. Individual controls include the mother’s age and its square, years of schooling, and household wealth quintile based on the DHS asset index. Geographic controls include elevation, nighttime lights, mean temperature and precipitation, an indicator for urban clusters, and travel time to the nearest city. The baseline nighttime-lights control is the 2015 VIIRS annual composite in the DHS geospatial covariates released with NFHS-5; the value is extracted at the displaced cluster coordinate from a raster resampled to a 5-km grid (Mayala and Donohue, 2022). Because this composite refers to 2015, when 3G services were already available in parts of India, we also re-estimated the main specifications without it: the estimates change by at most 0.01. Every specification for vaccination outcomes also includes fixed effects for the child’s exact age in completed months (Section 4.3) and for the month of interview, defined separately by calendar month and year, together with district fixed effects or, in robustness checks, state fixed effects. NFHS-5 interviews took place between June 2019 and April 2021, with fieldwork suspended between April and October 2020 during the COVID-19 pandemic. Over this period, the pandemic and the associated restrictions may have affected both vaccination behavior and the provision of health services. The interview-month fixed effects absorb shocks common to all children interviewed in the same month-year, as well as other systematic differences associated with the timing of the interview.

Travel time to healthcare. To assess whether our results are sensitive to differences in physical access to care, we use motorized travel time to the nearest healthcare facility from the Malaria Atlas Project (Weiss et al., 2020). This raster, available at a resolution of approximately 1 km, captures accessibility to the nearest hospital or clinic based on a global travel-time surface that combines healthcare facility and road network information from OpenStreetMap, Google Maps, and related geospatial sources with data on terrain and land cover.

Earlier survey round. We also use NFHS-4 (2015–16), the only earlier NFHS round for which public-use cluster coordinates are available. We use its vaccination histories for the doses observed in both rounds, together with the same maternal, household and geographic controls, with the cluster-level controls taken from the DHS geospatial covariates released with NFHS-4. We restrict the sample to living children under three years of age, apply the same age-eligibility and geographic restrictions used for NFHS-5, and compute terrain ruggedness for NFHS-4 clusters using the same procedure. We use this round to examine how the relationship between ruggedness and vaccination has changed over time (Section 5.5).

Mission Indradhanush. To examine whether targeted catch-up campaigns could have attenuated the relationship between ruggedness and vaccination, we compiled the district lists and starting months of the phases of Mission Indradhanush that took place before the NFHS-4 interviews in the districts concerned: April 2015, October 2015 and, in Uttar Pradesh, April 2016, each comprising four monthly rounds. The lists and dates come from the operational guidelines of the Ministry of Health and Family Welfare and from replies to parliamentary questions. We combine these dates with each child’s district and vaccination calendar to identify exposure to the campaign while the child was of catch-up age (Section 5.5).

Nighttime lights before mobile broadband. To measure local development before the diffusion of 3G, we use the harmonized DMSP-OLS nighttime-light series of Li et al. (2020) for 2000–2007, at a resolution of 30 arc-seconds (about 1 km). For each cluster we average light intensity within a 2-km buffer for urban clusters and a 5-km buffer for rural clusters, and use $\log(1 + x)$ of the 2000–02 average and the change in the same transformed measure between 2000–02 and 2005–07.

Floods and rainfall. We draw flood events from the India Flood Inventory (Saharia et al., 2021), which lists each event with its dates and the districts affected; we match events recorded between 2012 and 2021 to the NFHS-5 districts. We obtain monthly rainfall from CHIRPS (Funk et al., 2015), at a resolution of 0.05 degrees, averaged within 5 km of each cluster for 1981–2021; the 1981–2010 period provides the cluster-specific climatology. We define a month of extreme rainfall as one in which rainfall exceeds the cluster’s 1981–2010 95th percentile for that calendar month and is at least 200 mm. Because both sources are dated by month, we can measure the conditions in each child’s cluster, or district for floods, during the months in which the later dose of each pair of vaccinations fell due (Section 5.5).

Frontline health workers. NFHS-5 asks mothers whether they met an auxiliary nurse midwife or lady health visitor (ANM/LHV), or an ASHA or Anganwadi worker, in the three months before the interview, whether these workers visited the home, and whether the child received most vaccinations at a community-based vaccination site rather than at a health facility. NFHS-5 also records whether the mother received the Mother and Child Protection card after registering the pregnancy and, among children receiving Anganwadi services, whether they received immunization through the centre. We use these measures to characterize observed access to vaccination services and frontline-worker outreach, and to assess the sensitivity of the completion estimates to these observed dimensions of access and outreach.

Household access to mobile phones and the internet. The NFHS-5 household questionnaire asks every household whether it has internet. Whether a woman has a mobile phone that she herself uses and whether she has ever used the internet are asked only in

the households selected for the state module, about 15 percent of households in every state; 15,490 mothers in our sample answered these questions. We also measure basic mobile (2G) coverage in the same way as 3G coverage, from the 2G layers of the 2018 and 2014 releases of the Mobile Coverage Explorer. In our sample, 15 percent of children live in clusters with no mobile coverage in 2018, 56 percent in clusters covered by 2G but not by 3G, and 29 percent in clusters covered by 3G, almost all of which are also covered by 2G.

Table 1: Descriptive statistics

Variable	(1) <i>N</i>	(2) Mean	(3) SD	(4) Min	(5) Max
<i>Panel A: Individual doses on the age-appropriate samples (0/1)</i>					
BCG (Birth), age ≥ 0 m	113,171	0.945	0.227	0	1
OPV-0 (Birth), age ≥ 0 m	113,145	0.852	0.355	0	1
HepB-0 (Birth), age ≥ 0 m	112,279	0.667	0.471	0	1
DPT-1 (6 wks), age ≥ 2 m	106,625	0.917	0.277	0	1
DPT-2 (10 wks), age ≥ 3 m	103,193	0.889	0.314	0	1
DPT-3 (14 wks), age ≥ 4 m	99,759	0.845	0.362	0	1
OPV-1 (6 wks), age ≥ 2 m	106,778	0.902	0.297	0	1
OPV-2 (10 wks), age ≥ 3 m	103,341	0.859	0.348	0	1
OPV-3 (14 wks), age ≥ 4 m	99,904	0.781	0.414	0	1
MCV-1 (9–12 mo), age ≥ 9 m	70,358	0.861	0.346	0	1
MCV-2 (16–24 mo), age ≥ 16 m	61,313	0.542	0.498	0	1
DPT booster (16–24 mo), age ≥ 16 m	60,945	0.613	0.487	0	1
<i>Panel B: Stages of the schedule</i>					
Birth doses: share received, age ≥ 0 m	112,227	0.822	0.283	0	1
Birth doses: all received, age ≥ 0 m	112,227	0.652	0.476	0	1
Primary series: share received, age ≥ 4 m	99,720	0.873	0.268	0	1
Primary series: all received, age ≥ 4 m	99,720	0.750	0.433	0	1
MCV-1: share received, age ≥ 9 m	70,358	0.861	0.346	0	1
16–24-month doses: share received, age ≥ 16 m	60,838	0.578	0.439	0	1
16–24-month doses: all received, age ≥ 16 m	60,838	0.475	0.499	0	1
<i>Panel C: Child, mother and household</i>					
Child age (months)	113,249	17.3	10.4	0	35
Child: female (=1)	113,249	0.483	0.500	0	1
Mother’s age (years)	113,249	26.1	4.6	15	49
Mother’s schooling (years)	113,249	8.10	5.21	0	20
Wealth quintile (1–5)	113,249	2.84	1.41	1	5
Urban cluster (=1)	113,249	0.265	0.441	0	1
<i>Panel D: Cluster-level variables (one observation per DHS cluster)</i>					
3G coverage at the cluster point (0/1)	24,553	0.296	0.457	0	1
Terrain Ruggedness Index	24,553	9.59	23.79	0.04	210.35
Elevation (m)	24,553	374	528	1	5,659
Nighttime lights	24,553	3.21	8.47	0	97
Mean temperature 2020 (°C)	24,553	25.1	4.0	−2.3	29.8
Precipitation 2020 (mm/month)	24,553	96.3	42.8	14.4	304.9
Travel time to city (min)	24,553	25.8	49.6	0	1,575

Notes. Analytical sample: every living child under 36 months of an interviewed woman in NFHS-5 (2019–21) inside the extent of the 3G raster, with terrain ruggedness, 3G coverage and all controls observed: 113,249 children in 24,553 DHS clusters. Panel A describes each dose among children who have reached the minimum age at which it becomes due (completed months). Panel B describes, for each stage of the schedule, the share of the stage’s doses received and an indicator for all of them received, among children old enough for every dose of the stage (birth doses: BCG, OPV-0, HepB-0; primary series: DPT-1 to DPT-3 and OPV-1 to OPV-3; 16–24-month doses: MCV-2 and DPT booster; for MCV-1 the two coincide). The pentavalent doses are covered by the DPT indicators; rotavirus and Japanese encephalitis doses are excluded (Section 3.2). Panels A–C use DHS survey weights (v005) normalized to mean 1. Panel D describes the cluster-level variables once per cluster, unweighted: 3G coverage and the Terrain Ruggedness Index are defined in Section 3.3; nighttime lights are the 2015 VIIRS annual composite of the DHS geospatial covariates (Section 3.4).

4 Empirical strategy

This section presents the empirical strategy used to identify the effect of local 3G coverage on childhood vaccination. We first describe the baseline and instrumental-variable specifications,

and then the age-appropriate samples and the age-cohort design, the exclusion restriction, the within-child completion design, and the heterogeneity analyses.

4.1 Baseline specification

As a descriptive benchmark, we estimate linear regressions of the form

$$Y_{icd} = \mu_d + \beta^{\text{OLS}} 3G_c + \tilde{X}'_{ic} \gamma + \varepsilon_{icd}, \quad (1)$$

where Y_{icd} is a vaccination outcome for child i in cluster c and district d (receipt of a dose, the share of the doses due at a stage that the child has received, or an indicator for having received all of them; Section 3.2), $3G_c$ is local 3G coverage, equal to one if the raster pixel containing the released coordinates of cluster c is covered by 3G (Section 3.3), μ_d denotes district fixed effects (state fixed effects in the robustness specification; Section 4.2), and $\tilde{X}_{ic}$ is the vector of individual and geographic controls described in Section 3.4, together with fixed effects for the child's exact age in completed months (Section 4.3) and for the calendar month of interview (Section 3.4). Standard errors are clustered at the DHS cluster level, and all regressions are weighted using normalized DHS survey weights.

These estimates should be interpreted cautiously. Even conditional on rich controls, 3G coverage is likely to remain correlated with unobserved features of local development. We address this issue by means of an instrumental variable strategy.

4.2 Instrumental variable strategy

The main empirical challenge is that mobile internet coverage is not randomly assigned. Areas with better connectivity are also likely to differ systematically in income, education, remoteness, and health infrastructure. Simple comparisons between covered and uncovered areas may therefore conflate the effect of digital connectivity with broader differences in local development.

We estimate the causal effect of 3G coverage using two-stage least squares (2SLS), instrumenting local 3G coverage with the Terrain Ruggedness Index (TRI). The first stage is

$$3G_c = \mu_d^{(f)} + \pi TRI_c + \tilde{X}'_{ic} \gamma_f + v_{icd}, \quad (2)$$

where TRI_c denotes terrain ruggedness in cluster c . The second stage is

$$Y_{icd} = \mu_d^{(s)} + \beta^{\text{IV}} \widehat{3G}_{ic} + \tilde{X}'_{ic} \gamma_s + u_{icd}, \quad (3)$$

where $\widehat{3G}_{ic}$ is the fitted value from the first stage, and $\tilde{X}_{ic}$ includes, as in equation (1), the individual and geographic controls and the fixed effects for the child's exact age in completed months and for the calendar month of interview.

A natural concern is that rugged terrain may also be correlated with broader features of local development, including remoteness, urbanization, local economic conditions and physical access to health care. Our specifications condition on a rich set of individual and geographic controls, including nighttime lights, an indicator for urban clusters and travel time to the nearest city, together with district fixed effects in the benchmark specification. The main results are also robust to adding motorized travel time to the nearest health facility. Conditional on these controls and fixed effects, terrain ruggedness provides the variation we use to identify the effect of local 3G coverage. Section 4.4 discusses the remaining threats to the exclusion restriction and how we address them, including the within-child completion design of Section 4.5.

Our benchmark specification includes district fixed effects, which absorb all time-invariant differences between districts, including local policy environments, health infrastructure and broad socio-economic conditions, so that the effect of 3G coverage is identified from differences in terrain and coverage across clusters of the same district. The analytical sample covers 608 districts. Next to each benchmark estimate, we report the corresponding estimate with state fixed effects, which additionally uses variation across districts within the same state. The state-fixed-effects estimates are generally larger, and they are reported as a robustness check. We also report the main estimates with the four alternative measures of local 3G coverage described in Section 3.3 (Section 5.2). In the main estimation samples, the first stage is comfortably above conventional weak-instrument thresholds (Section 5.1).

4.3 Child age, eligibility and timing of effects

Vaccination receipt varies systematically with child age, creating two distinct challenges for estimating the effect of 3G coverage. First, including children below the eligible age would attenuate the estimate, because they have not yet had an opportunity to receive the vaccination. Second, among children who are already age-eligible, the probability of receipt still increases with age. If child age is correlated with local 3G coverage or terrain ruggedness, differences in age composition can therefore bias the estimated effect.

We address the first challenge by estimating the effect of 3G coverage only among children who have reached the eligible age for the vaccination outcome considered. The sample includes all children for the birth doses; children aged at least 2, 3 and 4 completed months for the doses scheduled at 6, 10 and 14 weeks; children aged at least 9 months for MCV-1; and children aged at least 16 months for the doses scheduled at 16–24 months. The upper age limit is always 35 months, the last age covered by the vaccination module. These age-appropriate samples avoid mechanically diluting the estimates with children below the eligible age. They are used for all main estimates by dose and by stage of the schedule; the age-cohort analysis described below deliberately also considers the later doses among younger children.

We address the second challenge by including fixed effects for the child’s exact age in completed months in every specification for vaccination outcomes. Even in an analytical sample that retains all living children under 36 months, ruggedness is associated with a slightly younger age among children aged 16–35 months: the reduced-form coefficient is small and statistically insignificant with district fixed effects and statistically significant with state fixed effects (Appendix B, Table B2). Because younger children have had less time to receive the doses due at 16–24 months, this difference could associate ruggedness with lower vaccination for reasons unrelated to connectivity. This source of bias would inflate a positive instrumental-variable estimate. The fixed effects for the child’s exact age in completed months compare children of the same age and allow the probability of vaccination to differ freely from one month of age to the next, without assuming that it rises linearly, quadratically or in any other predetermined way. Differences in age composition across completed months therefore cannot bias the estimated effect of 3G coverage.

Finally, we estimate the effect of 3G coverage separately by age of the child, to establish when the effect emerges relative to the immunization schedule. We divide the age range covered by the vaccination module into five bins that follow the schedule and the observed profile of receipt: 0–8 months, before MCV-1 is due; 9–12 months, the window of MCV-1; 13–15 months, after that window and before the later doses are due; 16–24 months, the window of MCV-2 and the DPT booster; and 25–35 months, after the end of that window. Within each bin we estimate the two-stage least squares specification of Section 4.2, with fixed effects for the child’s exact age in completed months, and report the cluster-robust first-stage F -statistic of each subsample. For the doses due at 16–24 months, we deliberately estimate the effect also in the three bins of children who have not yet reached the eligible age. An effect appearing before these doses become due would be difficult to reconcile with the timing prediction of Section 2, which implies that the effect should emerge when children enter the eligible age range.

To test whether the effects differ across age bins, we estimate a fully interacted model for each pair of bins. The joint specification reproduces the coefficients of the separate regressions and allows us to test the differences between age bins while accounting for the correlation between the estimates within DHS clusters (Appendix Table C5). The 25–35-month bin shows whether the effect remains visible after the recommended window. NFHS-5 does not record vaccination histories beyond 35 months, so vaccination later in childhood cannot be observed.

Narrower age bins would provide a finer view of when the effect emerges, but at that resolution the subsamples are too small for informative two-stage least squares estimates. We therefore complement the age-bin analysis with reduced-form regressions of each outcome on ruggedness in two-month age bins, which do not require estimating a first stage separately in every narrow bin. Because ruggedness predicts lower 3G coverage, a negative reduced-form coefficient has the sign implied by a positive effect of coverage. These estimates are reported

in Appendix Table C4.

4.4 Exclusion restriction

The key identifying assumption is that, conditional on controls and fixed effects, terrain ruggedness affects vaccination only through local 3G coverage. The most important threat to this assumption is that rugged terrain may make vaccination physically harder to obtain. Outreach sessions may be more difficult to organize, frontline health workers may visit households less often, and travel to health facilities may be longer or more frequently interrupted. If these channels operated independently of connectivity, ruggedness would affect vaccination directly. The IV estimates would then conflate the effect of mobile internet with that of physical access to care.

A natural way to address this concern would be to compare the relationship between ruggedness and vaccination before and after the arrival of mobile broadband. The available coverage data do not provide usable pre-3G cluster-level variation for India, and the only earlier DHS round with cluster coordinates, NFHS-4 (2015–16), was fielded after 3G networks had already diffused widely across the country (GSMA, 2015). We therefore use NFHS-4 to examine how the relationship between ruggedness and vaccination has changed across survey rounds (Section 5.5), and pursue three complementary strategies centred on the NFHS-5 analysis.

First, we use the pattern of the estimates across the schedule to assess access-based explanations. If ruggedness affected vaccination mainly through a generic disadvantage in reaching vaccination services, its consequences should not be confined to particular stages of the vaccination schedule. We therefore compare the estimates, obtained on the age-appropriate samples of Section 4.3, across the birth doses, the primary series, MCV-1 and the doses due at 16–24 months (Section 5.2).

Second, we introduce a within-child completion design (Section 4.5). By comparing, for the same child, a later dose with an earlier dose of the same vaccine or, for the scheduled return around 9 months, MCV-1 with BCG, the design removes any effect of terrain that is common to the two contacts with vaccination services. In this design, the identifying assumption is that ruggedness has no direct effect that is specific to the later contact.

Third, we examine directly the most plausible sources of such a contact-specific effect: differences in local development trajectories measured before the diffusion of mobile broadband, temporary disruptions of physical access caused by floods and extreme rainfall, and the observable access and outreach conditions through which terrain could affect immunization delivery (Section 5.5).

4.5 Within-child completion design

We construct within-child contrasts between vaccinations scheduled at successive stages of the immunization calendar. For the multi-dose vaccine series, these contrasts compare an earlier and a later dose of the same antigen; we also use the transition from BCG to MCV-1 to capture completion of the scheduled return around 9 months. Consider a dose pair k with an earlier vaccination $e(k)$ and a later vaccination $l(k)$. For child i in cluster c , we estimate

$$Y_{i,l(k)} - Y_{i,e(k)} = \mu_{g(c)}^k + \beta_k^C 3G_c + \tilde{X}_{ic}' \gamma_k + u_{ik}, \quad (4)$$

where $Y_{i,v}$ equals one if child i received vaccination v , and $\mu_{g(c)}^k$ denotes district fixed effects in the benchmark specification and state fixed effects in the robustness specification. The dependent variable takes the value -1 when the child received the earlier vaccination but not the later one, zero when the child received both or neither, and one when only the later vaccination is recorded, which occurs for less than 2 percent of children in every pair. Local 3G coverage is instrumented by terrain ruggedness as in equation (2). The coefficient β_k^C measures the effect of 3G coverage on receipt of the later vaccination relative to the earlier one. The controls $\tilde{X}_{ic}$ include fixed effects for the child's exact age in completed months. Because vaccination receipt rises with age even among children who have reached the recommended age, these fixed effects absorb the remaining within-eligibility age profile without imposing a functional form. In pooled models, the age effects are allowed to differ across dose pairs.

Using the same sample of children and the same survey weights, equation (4) yields exactly the same 2SLS coefficient as a stacked specification with one observation per child and vaccination, $v \in \{e(k), l(k)\}$,

$$Y_{iv} = \alpha_i + \lambda_v + \beta_k^C (3G_c \times L_v) + (\mu_{g(c)}^k + \tilde{X}_{ic}' \gamma_k) L_v + \varepsilon_{iv}, \quad (5)$$

in which L_v indicates the later vaccination, α_i are child fixed effects, λ_v are vaccination fixed effects, and $3G_c \times L_v$ is instrumented by $TRI_c \times L_v$. The controls of equation (4), including the age-in-month indicators, enter interacted with L_v ; in pooled models, these interactions are pair-specific. Their main effects are absorbed by the child fixed effects. The child fixed effects absorb all characteristics that enter identically in the two observations of the same child, including those of the household and of the survey cluster, and in particular any terrain-related component of access to care that is common to the two vaccinations. In this completion design, the exclusion restriction is considerably narrower than in the level specification: ruggedness must not have a direct effect on the later vaccination that differs from its effect on the earlier one.

The dose pairs are defined by the vaccination schedule before looking at the data. The primary-series pairs compare the first and the third dose of DPT and of oral polio vaccine,

due at 6 and 14 weeks. To capture the return visit around 9 months, we compare BCG with MCV-1. The late completion pairs compare MCV-1 with MCV-2 and DPT-3 with the DPT booster, whose later vaccination is scheduled at 16–24 months. Completion is measured among children who have had a reasonable opportunity to receive the later vaccination in each pair: children aged 12–35 months when the later vaccination falls within the first year of life, including the 9–12 month window for MCV-1, and children aged 16–35 months when the later vaccination is scheduled at 16–24 months.

Because our hypothesis concerns stages of the schedule rather than specific vaccines, we also estimate a common coefficient across dose pairs whose later vaccination falls in the same stage of the schedule. We stack the child-level differences in equation (4) for all the pairs of a stage, allow controls and fixed effects to differ by pair, and estimate a common coefficient on 3G coverage, instrumented by terrain ruggedness. In the stacked representation of equation (5), this corresponds to child-by-pair fixed effects and a common coefficient on the interaction between 3G coverage and the later-vaccination indicator, instrumented by the corresponding interaction between terrain ruggedness and the later-vaccination indicator. In a joint model with one coefficient per stage, we then test formally whether the effect on completion at 16–24 months differs from the effect on the primary series and on the return visit around 9 months. Standard errors are clustered at the DHS cluster level, which contains all the observations of each child.

Under the framework of Section 2, 3G coverage should raise completion of the dose pairs whose later vaccination is scheduled at 16–24 months, in the second year of life and after the infant schedule has been completed, and leave completion within the first year of life essentially unchanged. The design removes any terrain-related disadvantage that affects the two vaccinations similarly; the remaining assumption, that ruggedness has no direct effect specific to the later vaccination, is examined in Section 5.5 through cross-stage comparisons and direct tests of historical development trajectories, temporary access disruptions, and observed access and outreach conditions.

4.6 Heterogeneity analyses

We next examine whether the effect of 3G coverage differs across households and local environments. We estimate the IV specification separately in two groups defined by maternal schooling (fewer than 8 years or 8 or more) and, in the appendix, by household wealth (the bottom two quintiles of the DHS wealth index or the top three) and by reported diarrhoea and fever among the other sampled children in the same cluster. Within each group, we estimate separately the coefficients on the controls and on all fixed effects. To test whether the effects differ between groups, we estimate the two group equations jointly in a fully interacted stacked model, in which the treatment, the instrument, the controls and all fixed effects are group-specific. The group coefficients coincide with those of the separate regressions, and the

standard error of their difference allows for correlation between the two groups within DHS clusters.

The split by maternal schooling follows the third prediction of Section 2: if connectivity and households' own information resources are substitutes in reducing information and coordination frictions, the effect may be larger where households have fewer such resources. Household wealth provides a complementary measure of household resources. These splits show where the effect of coverage is concentrated. Because less educated and poorer households differ in many other respects, including access to mobile phones and the internet, they do not by themselves identify the channel through which coverage operates. The symptom-based splits are exploratory and examine whether the effect varies with the local disease environment. Reported diarrhoea and fever are syndromic proxies and do not measure the diseases prevented by the doses we study.

5 Results

We begin with the first stage of the instrumental variable strategy. We then report the effects of 3G coverage at each stage of the immunization schedule, examine when the effect appears as children age, and turn to the within-child completion estimates and to the threats to identification. We conclude with the heterogeneity of the effects by household resources.

5.1 First stage

The first stage confirms that terrain ruggedness is a strong predictor of local 3G coverage in the main estimation samples (Table 2). With district fixed effects, an increase of 10 units in the Terrain Ruggedness Index is associated with a 2.8-percentage-point lower probability of 3G coverage at the released cluster coordinate in the analytical sample, significant at the 1 percent level, against an average coverage of 29 percent. The coefficient is nearly identical in the three age-eligible samples corresponding to the doses due at 14 weeks, 9 months and 16 months, and the cluster-robust F -statistics range between 52 and 57. With state fixed effects, the coefficient ranges from 2.2 to 2.4 percentage points in absolute value, and the F -statistics range between 51 and 57.

Table 2: First stage: terrain ruggedness and local 3G coverage

	(1)	(2)	(3)	(4)
	Full sample	Age ≥ 4 m	Age ≥ 9 m	Age ≥ 16 m
Sample ages (months)	0–35	4–35	9–35	16–35
<i>Dependent variable: 3G coverage at the cluster point (0/1)</i>				
<i>Panel A: District FE (benchmark)</i>				
TRI (per 10 units)	−0.028*** (0.004)	−0.029*** (0.004)	−0.029*** (0.004)	−0.029*** (0.004)
Cluster-robust F	56.1	56.4	57.2	52.1
Mean 3G coverage	0.291	0.293	0.294	0.296
N	113,249	99,996	84,011	61,769
Clusters	24,553	24,270	23,718	22,319
<i>Panel B: State FE</i>				
TRI (per 10 units)	−0.022*** (0.003)	−0.023*** (0.003)	−0.024*** (0.003)	−0.024*** (0.003)
Cluster-robust F	56.8	57.1	56.9	50.7
Mean 3G coverage	0.291	0.293	0.294	0.296
N	113,249	99,996	84,011	61,769
Clusters	24,553	24,270	23,718	22,319

Notes. Weighted OLS of local 3G coverage, an indicator equal to one if the raster pixel containing the released cluster coordinate is covered by 3G, on the Terrain Ruggedness Index (per 10 units), with mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, fixed effects for the child’s exact age in completed months and for the calendar month of interview, and district (Panel A, benchmark) or state (Panel B) fixed effects. Column (1) is the analytical sample; columns (2)–(4) are the age-eligible samples corresponding to the doses due at 14 weeks, 9 months and 16 months. Estimates are weighted with normalized DHS survey weights; standard errors clustered at the DHS cluster level in parentheses. The F -statistic is the square of the cluster-robust t -statistic on the instrument. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The identifying first-stage variation comes from rural clusters (Appendix Table C1). In rural clusters, the first-stage F -statistic is 97 with district fixed effects; in urban clusters, where 60 percent of children live in clusters covered by 3G, ruggedness has no detectable relationship with coverage. The first stage also remains strong in the benchmark district-fixed-effects specification across the groups used in the heterogeneity analyses.

5.2 Estimates across the immunization schedule

Table 3 reports the effects of 3G coverage at each stage of the immunization schedule. Each effect is estimated among the children who have reached the age at which the corresponding doses become due, and every specification includes fixed effects for the child’s exact age in completed months (Section 4.3) and for the month of interview (Section 3.4). Panel A reports the estimates for our main outcome, the share of the doses due at each stage that the child has received; Panel B reports the estimates for having received all the doses of a stage, and Panel C those for each dose separately. Columns (1) and (2) report OLS and 2SLS estimates

with district fixed effects, the benchmark specification, in which the effect is identified only from differences in ruggedness and coverage between clusters of the same district; column (3) reports the 2SLS estimates with state fixed effects. Because the coverage measure is binary, the coefficients are scaled to a change from uncovered to covered status. The first stage is strong in every estimation sample of the table, with F -statistics between 44 and 57.

For the three stages due in the first year of life, the 2SLS estimates are small, and none is statistically significant, even at the 10 percent level, with either district or state fixed effects. The same holds for having received all the doses of the two multi-dose stages (Panel B) and for each of the ten doses due in the first year of life (Panel C). Outcomes that a substantial share of children have not received show the same pattern: among children in uncovered clusters, 66 percent have received all the birth doses, 76 percent all the doses of the primary series and 68 percent the birth dose of hepatitis B, and for these outcomes too the estimates are small and statistically insignificant. They are also precise enough to rule out effects of the size estimated for the doses due at 16–24 months. Under both specifications, the 95 percent confidence intervals for having received all the birth doses or all the doses of the primary series exclude the effect on having received both doses due at 16–24 months, and the interval for the birth dose of hepatitis B excludes the effects on MCV-2 and on the DPT booster.

The pattern changes at the 16–24-month stage. With district fixed effects, 3G coverage increases the share of the two doses due at this stage that the child has received by 0.218, significant at the 10 percent level, against a mean of 0.584 among children in uncovered clusters. The effect on MCV-2 is 0.258 and the probability of having received both doses increases by 0.274, both significant at the 5 percent level; the estimate for the DPT booster, 0.188, is positive but not statistically significant. With state fixed effects, the estimates are larger: 0.327 for the share of doses received and 0.371 for having received both doses, significant at the 1 percent level, and 0.308 for MCV-2 and 0.353 for the DPT booster, significant at the 5 percent level. The contrast with the doses of the first year corresponds to the first prediction of Section 2: the effect of coverage is concentrated at the stage of the schedule that places the greatest information and coordination demands on families and health workers. These estimates pool children who have just reached the eligible age with children observed after the recommended window. Section 5.3 shows that the effect is larger among children aged 16–24 months, the age at which these doses are due, and Section 5.4 shows that 3G coverage also raises completion of this stage within the same child.

OLS estimates are close to zero throughout the schedule, including at the 16–24-month stage. The difference from the 2SLS estimates does not appear to stem from the point measure of coverage: with the area- and population-based measures described in Section 3.3, which summarize coverage around the released cluster coordinate, the OLS estimates remain close to zero (Appendix Table G3). More generally, the endogenous placement of networks may bias OLS in either direction, and when effects are heterogeneous the two estimators need not recover the same parameter. We therefore interpret the 2SLS estimates as local effects

of the variation in 3G coverage generated by terrain, which need not equal the average effect of coverage across all locations.

Alternative measures of 3G coverage. The baseline measure assigns to each cluster the coverage status of the raster pixel containing its released coordinate. Because the DHS displaces the released coordinates by up to 2 km in urban areas and up to 5 km, and occasionally 10 km, in rural areas, coverage at that pixel may differ from coverage at the true location of the cluster. We therefore re-estimate the main specifications with the four alternative measures described in Section 3.3, which characterize coverage in the area within which the true location lies: the shares of the area and of the population covered within the standard DHS displacement radius, an indicator for at least one covered pixel within the same radius, and the share of the area covered within 10 km. The population share gives no weight to unpopulated pixels (Appendix Tables G1 and G2).

Under the three share measures, the estimates show the same contrast between stages as under the point measure. The estimates for the first-year stages remain small and statistically insignificant. The effects on the doses due at 16–24 months remain positive: with state fixed effects, all of them are significant at the 1 or 5 percent level; with district fixed effects, they are less precise, with the effect on MCV-2 significant at the 5 or 10 percent level and the effect on the DPT booster, as in the baseline, statistically insignificant. The completion estimates presented in Section 5.4 show the same stability. The coefficients on the shares refer to a change from no coverage to full coverage of the area or population around the cluster and are not comparable in magnitude with those on the point measure. The indicator for at least one covered pixel, which classifies 49 percent of children as covered against 29 percent under the point measure, has a weak first stage (F between 7 and 11); its weak-instrument-robust Anderson–Rubin confidence sets for MCV-2 and for completion of the 16–24-month stage exclude zero with both sets of fixed effects, but are very wide. Because the alternative measures describe coverage over the area within which the true cluster location lies, the stability of the results indicates that the main estimates are robust to the displacement of the DHS coordinates.

Table 3: Effects of 3G coverage across the immunization schedule

		District FE (benchmark)			State FE		Mean, 3G = 0	N
	Due at / sample age	(1) OLS	(2) 2SLS	F	(3) 2SLS	F		
<i>Panel A: Share of the stage's doses received</i>								
Birth doses	Birth	−0.005 (0.005)	−0.037 (0.056)	56.0	−0.043 (0.061)	56.6	0.826	112,227
Primary series	0–35							
	6–14 wks	−0.014*** (0.005)	+0.021 (0.062)	56.4	+0.016 (0.061)	57.0	0.879	99,720
MCV-1	4–35							
	9–12 mo	−0.005 (0.007)	+0.055 (0.112)	44.5	+0.016 (0.102)	48.2	0.868	70,358
16–24-month doses	9–35							
	16–24 mo	−0.006 (0.008)	+0.218* (0.121)	50.5	+0.327*** (0.123)	50.7	0.584	60,838
<i>Panel B: All of the stage's doses received</i>								
Birth doses	Birth	−0.014* (0.008)	−0.096 (0.096)	56.0	−0.106 (0.105)	56.6	0.664	112,227
Primary series	0–35							
	6–14 wks	−0.022*** (0.007)	+0.030 (0.090)	56.4	−0.010 (0.091)	57.0	0.760	99,720
16–24-month doses	4–35							
	16–24 mo	−0.005 (0.009)	+0.274** (0.140)	50.5	+0.371*** (0.141)	50.7	0.486	60,838
<i>Panel C: Individual doses</i>								
BCG	Birth	−0.003 (0.004)	+0.008 (0.044)	56.2	−0.008 (0.047)	56.7	0.947	113,171
OPV-0	0–35							
	Birth	−0.003 (0.006)	−0.042 (0.059)	56.1	−0.024 (0.066)	56.6	0.851	113,145
HepB-0	0–35							
	Birth	−0.012 (0.008)	−0.080 (0.097)	55.9	−0.097 (0.105)	56.5	0.681	112,279
OPV-1	0–35							
	6 wks	−0.007 (0.005)	+0.026 (0.066)	54.3	+0.057 (0.063)	55.1	0.907	106,778
OPV-2	2–35							
	10 wks	−0.013** (0.006)	+0.062 (0.082)	54.8	+0.088 (0.078)	56.3	0.865	103,341
OPV-3	3–35							
	14 wks	−0.014** (0.007)	+0.087 (0.090)	56.3	+0.059 (0.090)	56.9	0.790	99,904
DPT-1	4–35							
	6 wks	−0.006 (0.004)	−0.030 (0.059)	54.3	−0.046 (0.062)	55.2	0.920	106,625
DPT-2	2–35							
	10 wks	−0.013*** (0.005)	+0.005 (0.064)	54.9	−0.006 (0.069)	56.4	0.894	103,193
DPT-3	3–35							
	14 wks	−0.022*** (0.006)	−0.005 (0.071)	56.4	−0.048 (0.070)	57.1	0.852	99,759
DPT booster	4–35							
	16–24 mo	−0.007 (0.009)	+0.188 (0.139)	50.6	+0.353** (0.145)	50.7	0.617	60,945
MCV-1	16–35							
	9–12 mo	−0.005 (0.007)	+0.055 (0.112)	44.5	+0.016 (0.102)	48.2	0.868	70,358
MCV-2	9–35							
	16–24 mo	−0.003 (0.009)	+0.258** (0.127)	51.3	+0.308** (0.130)	51.1	0.551	61,313
	16–35							

Notes. Each coefficient is the effect of local 3G coverage, an indicator equal to one if the raster pixel containing the released cluster coordinate is covered, on the outcome in the row. In Panel A the outcome is the share of the stage's doses that the child has received (birth doses: BCG, OPV-0 and HepB-0; primary series: DPT-1 to DPT-3 and OPV-1 to OPV-3; 16–24-month doses: MCV-2 and DPT booster); for MCV-1 it is receipt of the single dose. In Panel B it is an indicator for having received all of the stage's doses; MCV-1 is omitted from Panel B because, as the only dose of its stage, this indicator coincides with the Panel A outcome. In Panel C the outcome is an indicator for having received the dose. Each outcome is estimated among children who have reached the minimum age at which the dose, or the last dose of the stage, becomes due (Section 4.3); the second column reports the scheduled age and, below it, the ages in completed months of the children in the estimation sample. Columns (1) and (2) report OLS and 2SLS estimates with district fixed effects, the benchmark specification; column (3) reports 2SLS estimates with state fixed effects. In the 2SLS columns, 3G coverage is instrumented by the Terrain Ruggedness Index (per 10 units), with the cluster-robust first-stage F -statistic in the next column. All specifications include fixed effects for the child's exact age in completed months and for the calendar month of interview, mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, as well as district (columns 1 and 2) or state (column 3) fixed effects. Estimates are weighted with normalized DHS survey weights; means are weighted means of the outcome among children in uncovered clusters (3G = 0) in the corresponding estimation sample. Children with a missing indicator for any dose of a stage are excluded from that stage's outcomes. Standard errors, clustered at the DHS cluster level, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.3 Effects by age of the child

The estimates in Table 3 pool children of all eligible ages. To establish when the effect of 3G coverage appears, we estimate it separately by age, in the five bins defined in Section 4.3. These bins follow the timing of vaccination observed in the data. Most first-year vaccinations are received early: receipt of the birth doses and of the primary series is close to its final level by 9–12 months, and receipt of MCV-1 by 13–15 months. The doses due at 16–24 months follow a different calendar. The share of these doses received remains below 11 percent before 16 months, rises to 50 percent in the 16–24-month bin and reaches 64 percent at 25–35 months (Appendix Figure C1 and Appendix Tables C2 and C3). Figure 2 reports the benchmark 2SLS estimates for each bin, with district fixed effects, for the doses due at 16–24 months (Panel A) and for the three stages of the schedule due in the first year of life (Panel B); Table 4 also reports the estimates with state fixed effects. For the doses due at 16–24 months, the first-stage F -statistics of the age subsamples range between 22 and 52.

Before children reach 16 months, 3G coverage has no detectable effect on the doses due at 16–24 months: in each of the three younger bins, the estimates for the share of the two doses received, and for MCV-2 and the DPT booster separately, are small and statistically insignificant under both specifications. The positive effect emerges in the 16–24-month bin, when the doses become due. With district fixed effects, 3G coverage increases the share of the two doses received by 0.345, against a mean of 0.509 among children in uncovered clusters, and the probability of having received both doses by 0.555 (Appendix Table C6); both estimates are significant at the 5 percent level. The effect on MCV-2, 0.432, is also significant at the 5 percent level, whereas the effect on the DPT booster, 0.280, is positive but not statistically significant. With state fixed effects, all four estimates are statistically significant: 0.387 for the share of doses received, 0.392 for MCV-2 and 0.394 for the DPT booster, at the 5 percent level, and 0.562 for having received both doses, at the 1 percent level.

Two further pieces of evidence locate the change at 16 months. First, formal tests compare the effects before 16 months and at 16–24 months. With district fixed effects, a cluster-robust test rejects their equality at the 10 percent level for the share of doses received and at the 5 percent level for MCV-2, but not for the DPT booster ($p = 0.18$); with state fixed effects, it rejects equality at the 5 percent level for all three outcomes. Tests on the reduced-form coefficients give similar results (Appendix Table C5). Second, the reduced form in two-month age bins traces the timing more finely, because it does not require a first stage in each narrow bin (Appendix Table C4). At each age, it compares receipt of the doses due at 16–24 months in more rugged locations, where 3G coverage is lower, with receipt elsewhere. Before 16 months, children in more rugged locations are as likely as other children to have received these doses. Once they enter the 16–24-month window, they begin to fall behind, and the gap becomes statistically significant mainly between 22 and 27 months, as children have more

time to receive the doses. The gap therefore opens only after the doses become due. Together with the age-bin estimates, this timing corresponds to the second prediction of Section 2: the effect on the later doses emerges when children reach the age at which these doses become due.

Within the same age bins, 3G coverage has no comparable effect on the doses due in the first year of life. Table 4 reports thirty estimates for these doses (three outcomes, five age bins and two specifications). Only one of them is statistically significant, at the 10 percent level, and it is negative. The indicators of having received all the doses of a stage give the same picture, with a single significant coefficient, also negative (Appendix Table C6). Children aged 16–24 months live in the same clusters and face the same terrain whether the outcome is an early dose or a late one; among these children, the positive effect of coverage is concentrated on the doses that become due at that age.

In the 25–35-month bin, in which all children are past the end of the recommended window, the estimates remain positive but are smaller and less precise; only those for the share of doses received and for the DPT booster with state fixed effects are statistically significant, at the 10 percent level. The confidence intervals of the 16–24-month and 25–35-month bins overlap widely, and cluster-robust tests do not reject the equality of the effects in the two bins for any of the three outcomes under either specification, with p -values above 0.30 (Appendix Table C5). The data therefore do not establish whether the effect declines after the recommended window.

For children aged 25–35 months, the dates recorded on the vaccination cards show whether the doses were received within the recommended window or later (Appendix Table C8). A usable card date is available for 82 percent of the received doses of MCV-2 and of the DPT booster. Receipt after 24 months is rare: it concerns 2 to 3 percent of the children, or about 4 percent of the dated doses received, and it is not associated with 3G coverage. We also estimate the effect on receipt by 24 months, treating the received doses without a usable date in three ways: we exclude the children concerned, count the doses as received after 24 months, or count them as received by 24 months. In all three cases, the estimates are positive and similar in size to those for receipt by the interview, although they are imprecise. The evidence therefore gives no indication that the effect reflects catch-up after the recommended window. Because NFHS-5 does not record vaccination histories beyond 35 months, however, we cannot distinguish conclusively between an effect on timely and an effect on eventual vaccination.

The same pattern emerges when the analysis is restricted to one child per woman (Appendix Table C7). In the 16–24-month bin, the effect on the share of the doses due at that age is 0.369 with district fixed effects and 0.424 with state fixed effects, both significant at the 5 percent level, and the estimates before 16 months remain small and statistically insignificant.

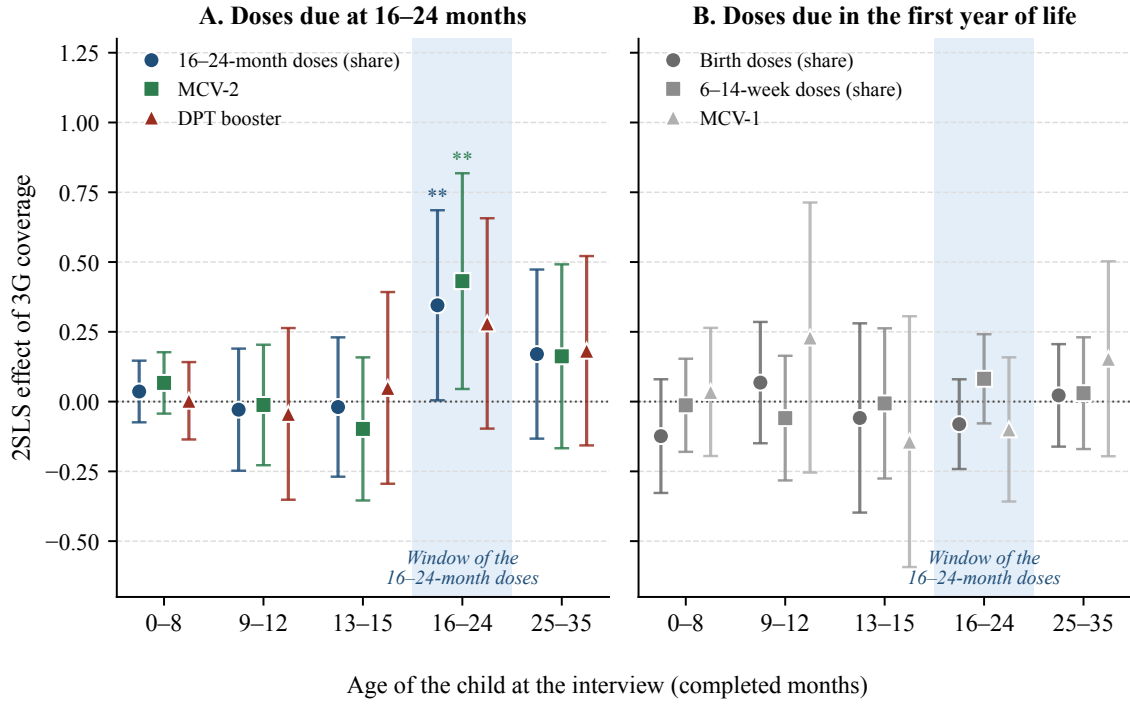


Figure 2: Effects of 3G coverage by age of the child

Notes. 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, estimated separately in each bin of the child's age at the interview (completed months) with district fixed effects (benchmark specification), with 95 percent confidence intervals based on standard errors clustered at the DHS cluster level. Panel A: doses due at 16–24 months (share of the two doses received, MCV-2 and DPT booster). Panel B: doses due in the first year of life (share of the birth doses received, share of the 6–14-week doses received, MCV-1). The shaded area marks the 16–24-month window. Estimates with state fixed effects, first-stage F -statistics and sample sizes are reported in Table 4; Appendix Figure C1 plots both specifications. $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

Table 4: Effects of 3G coverage by age of the child: 2SLS estimates by age bin

Outcome	Age of the child at the interview (completed months)				
	(1) 0–8	(2) 9–12	(3) 13–15	(4) 16–24	(5) 25–35
<i>Birth doses, share received</i>					
District FE	−0.124 (0.104) [32.2]	+0.068 (0.111) [24.4]	−0.059 (0.173) [22.4]	−0.081 (0.082) [33.1]	+0.022 (0.094) [52.6]
State FE	−0.026 (0.118) [28.6]	+0.031 (0.116) [21.6]	−0.104 (0.185) [25.2]	−0.150* (0.088) [34.5]	+0.014 (0.095) [45.8]
Mean, 3G = 0	0.805	0.837	0.847	0.835	0.827
N	29,055	12,470	9,593	27,106	34,003
<i>6–14-week doses, share received</i>					
District FE	−0.013 (0.085) [32.2]	−0.059 (0.114) [24.1]	−0.007 (0.137) [22.6]	+0.082 (0.082) [33.6]	+0.030 (0.102) [51.6]
State FE	−0.032 (0.098) [28.7]	−0.045 (0.109) [21.6]	−0.041 (0.143) [25.6]	+0.050 (0.079) [34.8]	+0.072 (0.095) [45.2]
Mean, 3G = 0	0.543	0.881	0.900	0.901	0.893
N	29,169	12,553	9,641	27,290	34,286
<i>9–12-month dose (MCV-1)</i>					
District FE	+0.035 (0.117) [26.0]	+0.230 (0.247) [20.5]	−0.144 (0.229) [13.4]	−0.100 (0.132) [22.0]	+0.153 (0.178) [45.6]
State FE	−0.041 (0.136) [20.2]	+0.067 (0.201) [23.4]	−0.099 (0.213) [16.0]	−0.140 (0.118) [27.2]	+0.152 (0.169) [36.9]
Mean, 3G = 0	0.060	0.775	0.865	0.886	0.883
N	19,562	8,947	8,010	23,400	30,001
<i>16–24-month doses, share received</i>					
District FE	+0.036 (0.056) [32.7]	−0.029 (0.112) [24.4]	−0.019 (0.127) [23.5]	+0.345** (0.174) [32.2]	+0.170 (0.155) [50.8]
State FE	+0.016 (0.061) [28.8]	+0.007 (0.110) [22.0]	−0.058 (0.165) [24.9]	+0.387** (0.164) [34.5]	+0.286* (0.155) [45.9]
Mean, 3G = 0	0.028	0.072	0.109	0.509	0.646
N	29,069	12,459	9,547	27,026	33,812
<i>MCV-2</i>					
District FE	+0.067 (0.056) [32.6]	−0.012 (0.110) [24.2]	−0.098 (0.131) [23.7]	+0.432** (0.197) [32.8]	+0.162 (0.168) [51.5]
State FE	+0.041 (0.057) [29.0]	+0.039 (0.117) [21.7]	−0.090 (0.161) [25.9]	+0.392** (0.185) [34.8]	+0.251 (0.169) [46.0]
Mean, 3G = 0	0.025	0.063	0.092	0.479	0.609
N	29,109	12,509	9,603	27,207	34,106
<i>DPT booster</i>					
District FE	+0.003 (0.071) [32.8]	−0.044 (0.157) [24.3]	+0.049 (0.175) [23.3]	+0.280 (0.192) [32.2]	+0.182 (0.173) [50.9]
State FE	−0.012 (0.079) [28.9]	−0.026 (0.150) [21.9]	−0.021 (0.207) [24.4]	+0.394** (0.188) [34.3]	+0.326* (0.178) [46.1]
Mean, 3G = 0	0.030	0.081	0.127	0.538	0.682
N	29,092	12,476	9,562	27,064	33,881

Notes. NFHS-5 (2019–21). 2SLS estimates of the effect of local 3G coverage (point coverage at the DHS cluster coordinate), instrumented by the Terrain Ruggedness Index (TRI), in subsamples defined by the child’s age at the interview in completed months; the dependent variable is indicated in the row heading. Standard errors clustered at the DHS cluster level in parentheses; cluster-robust first-stage F -statistic of each subsample in brackets, next to the standard error; “Mean, 3G = 0” is the weighted mean of the outcome among children of the bin in uncovered clusters; N is the number of children with a non-missing outcome in the bin (identical for the two specifications). Each specification includes fixed effects for the child’s exact age in completed months and for the calendar month of interview within the bin, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and district or state fixed effects; estimates are weighted with normalized DHS survey weights. Sample: all living children under 36 months in the analytical sample. The four stages of the schedule follow India’s immunization schedule: birth (BCG, OPV-0, hepatitis B birth dose), 6–14 weeks (DPT-1 to DPT-3, OPV-1 to OPV-3), 9–12 months (MCV-1), 16–24 months (MCV-2, DPT booster); “share received” is the share of the stage’s doses received by the interview; for the single-dose 9–12-month stage it coincides with receipt of MCV-1. Table C2 reports the weighted vaccination rates of the same outcomes in each bin. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.4 Within-child completion

Table 5 reports the estimates from the within-child completion design introduced in Section 4.5. The design compares, for the same child, a later vaccination with an earlier one, and asks whether 3G coverage raises receipt of the later vaccination relative to the earlier one. The framework of Section 2 indicates where such an effect should appear. The returns to vaccination services in the first year of life are embedded in a dense sequence of scheduled vaccinations or, for MCV-1, close the first-year schedule that the programme uses to define full immunization. The return at 16–24 months follows a longer interval and places greater information and coordination demands on families and health workers. Under the first prediction, 3G coverage should therefore raise completion at 16–24 months more than completion in the first year of life.

The estimates follow this pattern. For the three pairs whose later vaccination falls in the first year of life, the effects of 3G coverage are small and statistically indistinguishable from zero (Panel A). This holds for completion of the DPT and oral polio primary series, from the first to the third dose, and for the return around 9 months, from BCG to MCV-1. For the two pairs whose later vaccination is scheduled at 16–24 months, the effects are positive. For measles, the effect on completion from the first to the second dose is 0.271 with district fixed effects, significant at the 10 percent level, and 0.354 with state fixed effects, significant at the 5 percent level. For DPT, the effect on completion from the third dose to the booster is 0.199 with district fixed effects, positive but not statistically significant, and 0.368 with state fixed effects, significant at the 1 percent level.

Because the framework concerns stages of the schedule rather than individual vaccines, Panel B pools the pairs of each stage and estimates a common coefficient (Section 4.5). For the 16–24-month stage, the common coefficient is 0.230 with district fixed effects and 0.362 with state fixed effects, significant at the 5 and 1 percent levels, respectively; for the primary series, it is small and statistically indistinguishable from zero. Panel C tests the differences between stages in a joint model of the five pairs with one coefficient per stage. The completion effect at 16–24 months exceeds the effect for the primary series by 0.199 with district fixed effects and 0.354 with state fixed effects, significant at the 10 and 1 percent levels, respectively. It exceeds the effect for the return around 9 months by 0.208 with district fixed effects, positive but not statistically significant, and by 0.342 with state fixed effects, significant at the 5 percent level. The coefficients for the primary series and for the return around 9 months do not differ from each other.

The completion estimates therefore reproduce, within the same child, the pattern of the level estimates: 3G coverage raises completion at the stage at which the framework locates the largest information and coordination demands, and leaves completion within the first year essentially unchanged. The comparison also matters for identification. The within-child design removes time-invariant child, household and local characteristics that affect

the two vaccinations of a pair similarly, including any disadvantage of rugged locations in reaching vaccination services that is common to both. The first-year pairs, in turn, provide a benchmark based on vaccinations that also require returning to vaccination services. A generic, time-invariant disadvantage of rugged locations in accessing vaccination is therefore difficult to reconcile with the pattern across stages. Section 5.5 examines directly whether terrain instead generates disadvantages specific to the later vaccinations.

Table 5: 3G coverage and within-child completion across the immunization schedule

		(1) 2SLS District FE (benchmark)	(2) 2SLS State FE	(3) <i>N</i>
Dose pair	Later dose due			
<i>Panel A: Dose pairs</i>				
DPT-1 → DPT-3	14 wks	+0.010 (0.047) [59.7]	+0.007 (0.049) [59.1]	74,612
OPV-1 → OPV-3	14 wks	+0.054 (0.068) [59.6]	+0.008 (0.067) [59.0]	74,733
BCG → MCV-1	9 mo	+0.022 (0.064) [44.7]	+0.020 (0.063) [48.2]	64,159
MCV-1 → MCV-2	16–24 mo	+0.271* (0.148) [40.4]	+0.354** (0.145) [42.6]	53,401
DPT-3 → DPT booster	16–24 mo	+0.199 (0.127) [50.4]	+0.368*** (0.137) [50.6]	60,910
<i>Panel B: Common coefficient by stage of the schedule</i>				
Primary series	14 wks	+0.032 (0.050) [59.6]	+0.008 (0.051) [59.1]	149,345
16–24-month stage	16–24 mo	+0.230** (0.113) [46.7]	+0.362*** (0.116) [47.9]	114,311
<i>Panel C: Differences between stages (joint model)</i>				
16–24-month stage minus primary series		+0.199* (0.118)	+0.354*** (0.123)	
16–24-month stage minus return at 9 months		+0.208 (0.135)	+0.342** (0.133)	
Return at 9 months minus primary series		−0.009 (0.067)	+0.012 (0.066)	

Notes. 2SLS estimates of equation (4). The dependent variable is the difference between the indicators for the later and the earlier vaccination of each pair (−1, 0 or 1). Local 3G coverage (point coverage at the DHS cluster coordinate) is instrumented by the Terrain Ruggedness Index (TRI). Column (1) reports the coefficients with district fixed effects, the benchmark specification, and column (2) those with state fixed effects, with standard errors in parentheses and cluster-robust first-stage *F*-statistics in brackets. Children aged 12–35 months for the pairs whose later vaccination falls within the first year of life, and 16–35 months for the pairs whose later vaccination is scheduled at 16–24 months. Panel B stacks the child-level differences of the pairs of each stage (primary series: DPT-1 → DPT-3 and OPV-1 → OPV-3; 16–24-month stage: MCV-1 → MCV-2 and DPT-3 → DPT booster), with pair-specific controls and fixed effects and a common coefficient on 3G coverage; *N* is the number of child-pair observations. Panel C reports differences between the stage coefficients of a joint stacked model of the five pairs with one coefficient per stage (the primary series and the 16–24-month stage as in Panel B, the return at 9 months as in Panel A), so that the tests account for the covariance between the estimates. All specifications include fixed effects for the child’s exact age in completed months and for the calendar month of interview (specific to each pair in the stacked models), mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and are weighted with normalized DHS survey weights. Standard errors are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.5 Threats to identification

The within-child design removes terrain-related disadvantages that affect the two vaccinations of each pair similarly. It would not remove a direct effect of ruggedness specific to the later vaccinations, if one existed. Such an effect could arise in three ways: rugged places may have followed slower development paths, rugged terrain may make vaccination services harder to reach or to deliver, and outreach by frontline health workers may be weaker there. For each possibility, we ask what it would imply for the data and whether accounting for it changes the completion estimates. We then describe how the relationship between ruggedness and vaccination has changed since the previous round of the survey. Table 6 reports the common coefficients for the 16–24-month stage and for the primary series under each check; the detailed diagnostics are reported in Appendix D.

Development trajectories before mobile broadband. Rugged places may have been on slower development paths before the arrival of 3G, and slower development could weigh more on the later, less routine vaccinations than on earlier ones. If so, the completion estimate would partly reflect differences in development rather than in connectivity. To account for this possibility, we allow measures of local development before 3G to affect the later vaccination of each pair differently from the earlier one, which is the margin on which the within-child design could fail. If the completion estimate reflected pre-existing differences in development, the estimate should shrink once these measures are included. We measure local development with harmonized DMSP-OLS nighttime lights for 2000–2007 (Li et al., 2020), a period that ends before the commercial launch of 3G services in India (GSMA, 2015), using the 2000–02 level and its change to 2005–07; these pre-3G lights are distinct from the 2015 VIIRS composite used as a baseline control. The completion estimate does not shrink. The common coefficient for the 16–24-month stage is 0.282 with district fixed effects and 0.376 with state fixed effects, significant at the 5 and 1 percent levels, respectively, slightly larger than in the baseline (row 2). The check is informative because the pre-3G lights do capture a difference between rugged and other locations: rugged clusters were less bright in 2000–02, and their lights grew more slowly afterwards. Conditional on the initial level, a one-standard-deviation increase in ruggedness is associated with a reduction of 0.14 to 0.15 standard deviations in light growth between 2000–02 and 2005–07, significant at the 1 percent level with both district and state fixed effects (Appendix Table D1). This difference in development, however, does not account for the effect of 3G coverage on completion.

Temporary disruptions of physical access. A second possibility is that rugged terrain directly makes vaccination services harder to reach or to deliver, independently of 3G coverage. Floods and extreme rainfall offer a way to probe this possibility, because they temporarily worsen the conditions under which families travel and health workers conduct outreach. If ruggedness directly impaired access to vaccination, its negative consequences

should be most visible when such disruptions occur. Because we measure the disruptions in the window in which the later vaccination of each pair falls due, a direct effect of terrain on access would then lower completion in rugged locations hit by a shock. We test this implication with the flood and rainfall measures described in Section 3.4, estimating reduced-form regressions of completion in which ruggedness is interacted with exposure to a flood or to a month of extreme rainfall in that window. The test is particularly informative for the first-year pairs, for which the estimated effect of 3G coverage on completion is close to zero: if ruggedness became more detrimental during disruptions for these pairs, the pattern would point to a direct effect of terrain rather than to connectivity.

For all first-year pairs, the interactions between ruggedness and either shock are small and statistically insignificant (Appendix Table D2). For the 16–24-month pairs, the interaction is less directly interpretable, because connectivity may itself help families or health workers cope with a disruption. Even so, none of these estimates indicates that ruggedness becomes significantly more detrimental during floods or months of extreme rainfall. The reduced-form estimates therefore show no sign that ruggedness becomes more detrimental to completion when travel and outreach are disrupted.

We next ask whether exposure to these shocks can account for the completion estimates themselves. To address the possibility that rugged places experience such shocks more often, we add to the completion equation indicators for a flood in the child’s district and for a month of extreme rainfall around the child’s cluster in the window of the later vaccination. The estimated effects of 3G coverage on completion remain essentially unchanged (row 3).

Finally, we re-estimate the completion equation after removing the vaccination windows affected by extreme rainfall. Because rainfall is observed around each cluster, whereas floods are recorded only by district, we exclude every child-pair observation whose later-vaccination window contains a month of extreme rainfall at the cluster. If the estimated effect at 16–24 months reflected a disadvantage of rugged locations in access to vaccination that becomes more consequential under adverse physical conditions, the estimated effect should decline once these windows are removed. Instead, the common coefficient for the 16–24-month stage is 0.312 with district fixed effects and 0.370 with state fixed effects, significant at the 5 and 1 percent levels, respectively, at least as large as in the baseline (row 4). Taken together, the evidence from floods and extreme rainfall gives no indication that the estimated completion effect reflects a direct effect of ruggedness on access to vaccination.

Access and outreach conditions. A third possibility is that rugged locations face persistently worse access to vaccination services or weaker outreach by frontline health workers, so that terrain could affect the later vaccination more strongly than the earlier one through channels unrelated to 3G coverage. We first examine physical access, which we measure with motorized travel time to the nearest health facility from the Malaria Atlas Project (Weiss et al., 2020), a raster that combines the location of health facilities and road networks with

terrain and land cover (Section 3.4). Ruggedness strongly predicts longer travel time: with district fixed effects, an increase of 10 units in the index is associated with 0.114 higher log travel time, significant at the 1 percent level (Appendix Table D3). Travel time therefore captures an observed disadvantage of rugged locations that could make repeated returns for vaccination more difficult. We examine whether this disadvantage can account for the effect of coverage on the later doses, both in the within-child completion design and in the level estimates. When travel time is allowed to affect the later vaccination differently from the earlier one, the completion effect for the 16–24-month stage remains positive and significant, at the 10 percent level with district fixed effects and at the 1 percent level with state fixed effects, while the coefficient for the primary series remains small and statistically insignificant (row 5). When travel time is added to the controls of the level estimates, the effects on the share of the doses due at 16–24 months and on MCV-2 remain significant at the 10 percent level or better with both sets of fixed effects, the effect on the DPT booster remains significant only with state fixed effects, as in the baseline, and the estimates for the first-year stages remain statistically insignificant (Appendix Table D7). In both designs, the coefficients on the later doses become larger and less precise. The loss of precision is expected, because travel time is closely related to ruggedness, and holding travel time fixed weakens the first stage. The estimated effect of coverage on the later doses thus persists once we account for the greater difficulty of reaching health facilities from rugged locations. This persistence is reassuring for the exclusion restriction: if the later-dose effects reflected poorer physical access, they would be expected to weaken once travel time is held fixed.

NFHS-5 also records whether the mother met an auxiliary nurse midwife or lady health visitor (ANM/LHV), or an ASHA or Anganwadi worker, in the three months before the interview, whether these workers visited the home, and where the child received most vaccinations (Section 3.4). Unlike travel time, these measures cannot provide a clean test of the exclusion restriction, because health-worker contacts may themselves respond to connectivity. A negative association between ruggedness and these contacts could therefore reflect either a direct disadvantage of rugged locations or an effect operating through their lower 3G coverage, while the absence of an association would be equally difficult to interpret. We therefore report these relationships descriptively, rather than treating either significant or insignificant coefficients as evidence for or against the instrument. Descriptively, most measures show no adverse association with ruggedness, while ruggedness is associated with fewer home visits by ASHA and Anganwadi workers, significant at the 5 percent level with district fixed effects and at the 1 percent level with state fixed effects (Appendix Table D3). NFHS-5 does not record other dimensions of outreach, such as the frequency and reliability of outreach sessions, the tracking of missed doses, access to the cold chain or the overall quality of immunization delivery.

As a sensitivity exercise, we also allow the indicators for meetings with these workers and for their home visits to affect the later vaccination differently from the earlier one.

Because these contemporaneous contact measures may themselves lie on the pathway from connectivity to vaccination, we do not interpret this adjustment as an additional test of the instrument. The common completion coefficient for the 16–24-month stage is essentially unchanged, at 0.240 with district fixed effects and 0.364 with state fixed effects, significant at the 5 and 1 percent levels, respectively (row 6), while the coefficient for the primary series remains small and statistically indistinguishable from zero. The completion effect therefore remains robust to conditioning on the clearest observed physical-access disadvantage of rugged locations, travel time to health facilities, and is insensitive to the inclusion of these contact indicators.

Ruggedness and vaccination across survey rounds. A further concern is that ruggedness could mark a persistent disadvantage in access to vaccination services, independent of 3G coverage. If this disadvantage were an important source of the reduced-form relationship, the adverse association between ruggedness and routine vaccination should display some persistence over time, particularly for the first-year vaccinations, which rely on the same local services. We examine this implication with NFHS-4 (2015–16), the only earlier survey round with public-use cluster coordinates, constructing ruggedness in the same way and using comparable age-appropriate samples and controls (Section 3.4). NFHS-4 cannot provide a pre-3G benchmark, because 3G networks had already diffused widely across India by 2015–16 (GSMA, 2015), so the comparison does not identify the effect of the subsequent expansion of coverage. Because NFHS-4 does not record the doses due at 16–24 months, MCV-2 and the DPT booster, the comparison concerns the first-year vaccinations. In 2015–16, ruggedness was associated with lower receipt of several first-year doses, including OPV-0, DPT-2, OPV-2 and MCV-1, with generally stronger associations under state fixed effects, and with lower completion of the return from BCG to MCV-1, while it did not predict completion of the primary series (Appendix Table D4). By 2019–21, ruggedness is not significantly associated with any of these first-year doses or with completion of any first-year pair. The first-year ruggedness gradient observed in 2015–16 therefore does not persist into the period of our main analysis. This pattern weakens one possible interpretation of ruggedness, as a stable, generic disadvantage in routine vaccination.

One possible explanation for the disappearance of the first-year gradient is that targeted vaccination campaigns attenuated terrain-related disparities between the two surveys. We examine this possibility using Mission Indradhanush, the national catch-up immunization campaign launched in 2015 in districts with low vaccination coverage. We compiled the district lists and starting months of the campaign phases that took place before the NFHS-4 interviews in the districts concerned (Section 3.4) and matched them to each child’s district and vaccination calendar. A child is classified as exposed when a campaign round took place in the child’s district before the interview while the child was between the scheduled age of the dose and 23 months, the age range targeted by the catch-up rounds. Within

NFHS-4, we then test whether the ruggedness gradient is weaker among exposed children. If campaign exposure were offsetting a terrain-related disadvantage, the negative association between ruggedness and vaccination should be attenuated among them. The interactions between ruggedness and exposure are small and statistically insignificant for DPT-3, OPV-3, MCV-1 and receipt of all eight basic doses, and show no systematic attenuation when the relationship between ruggedness and vaccination is also allowed to vary by birth cohort and age (Appendix Table D6). Because campaign placement was non-random, the exercise is a diagnostic rather than an evaluation of the programme. We find no evidence within NFHS-4 that exposure to the campaign attenuated the ruggedness gradient in the way required to explain its subsequent disappearance.

Table 6: Within-child completion and threats to identification

Specification	16–24-month stage		Primary series		<i>N</i>	
	(1)	(2)	(3)	(4)	(5)	(6)
	District FE	State FE	District FE	State FE	16–24 mo	Primary
(1) Baseline	+0.230** (0.113) [46.7]	+0.362*** (0.116) [47.9]	+0.032 (0.050) [59.6]	+0.008 (0.051) [59.1]	114,311	149,345
(2) Pre-3G nightlights (DMSP)	+0.282** (0.140) [39.2]	+0.376*** (0.120) [48.7]	+0.040 (0.061) [50.7]	+0.007 (0.054) [60.3]	114,311	149,345
(3) Flood and extreme-rainfall exposure	+0.230** (0.113) [46.7]	+0.358*** (0.115) [48.1]	+0.032 (0.050) [59.7]	+0.008 (0.051) [59.1]	114,300	149,345
(4) Clean windows: no extreme rainfall	+0.312** (0.146) [36.1]	+0.370*** (0.140) [40.0]	+0.032 (0.055) [58.4]	+0.019 (0.055) [59.5]	87,984	130,821
(5) Travel time to health facility	+0.369* (0.189) [22.1]	+0.491*** (0.164) [30.2]	+0.049 (0.080) [29.1]	+0.011 (0.069) [37.6]	114,253	149,271
(6) Meetings and home visits by health workers	+0.240** (0.114) [46.5]	+0.364*** (0.116) [47.7]	+0.036 (0.049) [59.5]	+0.007 (0.050) [59.2]	114,165	149,133

Notes. 2SLS estimates of the common coefficient on 3G coverage for the dose pairs of each stage (Table 5, Panel B), with standard errors in parentheses and cluster-robust first-stage *F*-statistics in brackets. Columns (1) and (3) use district fixed effects, the benchmark specification; columns (2) and (4) use state fixed effects. Row (1) reproduces the baseline of Table 5. Row (2) adds $\log(1+x)$ of mean DMSP nighttime-light intensity around the cluster in 2000–02 and the change in the same transformed measure between 2000–02 and 2005–07. Row (3) adds indicators for a flood recorded in the district and for a month of extreme rainfall at the cluster (rainfall above the cluster’s 1981–2010 95th percentile for that calendar month and at least 200 mm) in the window of the later vaccination of each pair (ages 1–4 months for the primary series, 16–24 months for the late pairs). Row (4) drops the child-pair observations whose window contains a month of extreme rainfall at the cluster. Row (5) adds $\log(1+x)$ of motorized travel time, in minutes, to the nearest health facility. Row (6) adds indicators for whether the mother met an ANM/LHV or an ASHA/Anganwadi worker in the last three months and whether each of them visited the home. In the differenced specification, these controls are equivalent to their interactions with the later-vaccination indicator in the stacked specification with child fixed effects. Controls, fixed effects for the child’s exact age in completed months and for the calendar month of interview, weights and samples otherwise as in Table 5; *N* is the number of child-pair observations. Standard errors are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.6 Heterogeneity by household resources

If connectivity and households' own information resources are substitutes in reducing information and coordination frictions, the case considered in the third prediction of Section 2, coverage should have greater scope to raise vaccination where households have fewer such resources. Maternal schooling is a natural measure of these resources: in developing countries, much of the effect of mothers' schooling on child health operates through their ability to acquire and use health information (Thomas et al., 1991; Glewwe, 1999). Consistent with this role of schooling, children of less educated mothers are less likely to receive the later doses: among children in uncovered clusters, the share of the doses due at 16–24 months received is 0.534 for children of mothers with fewer than 8 years of schooling and 0.622 for children of mothers with 8 or more years (Table 7). Heterogeneity by maternal schooling is therefore informative both about the substitution case and about whether the gains from connectivity reach the children with lower rates of receipt.

The effects of 3G coverage on the doses due at 16–24 months are concentrated among children of less educated mothers. With district fixed effects, the effect on the share of these doses received is 0.771 among children of mothers with fewer than 8 years of schooling, significant at the 1 percent level, and small and statistically insignificant among children of more educated mothers; the difference between the two groups, 0.793, is significant at the 1 percent level. The same pattern holds for having received both doses, for MCV-2 and for the DPT booster, with differences significant at the 1 or 5 percent level. The pattern also holds within the same child: the effect on completion of the 16–24-month stage is 0.716 in the less educated group and small and statistically insignificant in the more educated group, and the difference is significant at the 5 percent level (Panel B). With state fixed effects, the estimates in the less educated group are larger and all the differences are significant at the 5 percent level, but the first stage in this group is weaker (F about 17), and we rely on the benchmark specification.

Table 7: Heterogeneity by maternal schooling

	District FE (benchmark)			State FE			Mean, 3G = 0 (N)	
	(1) <8 yrs	(2) ≥8 yrs	(3) Diff.	(4) <8 yrs	(5) ≥8 yrs	(6) Diff.	<8 yrs	≥8 yrs
<i>Panel A: Doses due at 16–24 months</i>								
Share of the two doses received	+0.771*** (0.269) [21.7]	−0.022 (0.110) [43.8]	+0.793*** (0.281) {0.005}	+0.945*** (0.354) [17.7]	+0.099 (0.107) [44.5]	+0.845** (0.358) {0.018}	0.534 24,395	0.622 36,443
Both doses received	+0.965*** (0.314) [21.7]	−0.025 (0.135) [43.8]	+0.990*** (0.328) {0.003}	+1.145*** (0.404) [17.7]	+0.100 (0.130) [44.5]	+1.045** (0.409) {0.011}	0.441 24,395	0.520 36,443
MCV-2	+0.760*** (0.289) [21.7]	+0.043 (0.124) [44.9]	+0.718** (0.302) {0.018}	+0.935** (0.379) [17.5]	+0.095 (0.122) [45.1]	+0.840** (0.386) {0.030}	0.503 24,641	0.587 36,672
DPT booster	+0.813*** (0.299) [22.0]	−0.083 (0.128) [43.8]	+0.896*** (0.316) {0.005}	+1.001** (0.402) [17.6]	+0.102 (0.123) [44.5]	+0.900** (0.406) {0.027}	0.565 24,435	0.656 36,510
<i>Panel B: Within-child completion</i>								
16–24-month stage	+0.716*** (0.275) [19.2]	+0.039 (0.105) [41.2]	+0.676** (0.277) {0.015}	+1.006*** (0.344) [17.0]	+0.166 (0.102) [42.0]	+0.840** (0.343) {0.014}	−0.285 45,996	−0.256 68,315
Primary series	−0.038 (0.098) [26.8]	+0.055 (0.056) [50.0]	−0.093 (0.115) {0.421}	−0.165 (0.121) [24.2]	+0.048 (0.054) [49.8]	−0.213 (0.135) {0.113}	−0.093 59,496	−0.060 89,849
<i>Panel C: Doses due in the first year of life</i>								
Birth doses, share received	+0.069 (0.135) [25.7]	−0.096* (0.058) [47.5]	+0.166 (0.150) {0.270}	+0.021 (0.197) [22.6]	−0.071 (0.054) [49.1]	+0.091 (0.207) {0.659}	0.793 43,393	0.850 68,834
Primary series, share received	+0.186 (0.132) [25.2]	−0.053 (0.054) [47.4]	+0.240* (0.141) {0.090}	+0.025 (0.185) [22.9]	−0.012 (0.051) [48.9]	+0.037 (0.190) {0.844}	0.844 38,892	0.903 60,828

Notes. The sample is split by the mother's years of schooling: fewer than 8 (43,903 children) or 8 or more (69,346). Columns (1), (2), (4) and (5): 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, estimated separately in each group, with standard errors clustered at the DHS cluster level in parentheses and the group's cluster-robust first-stage F in brackets. Columns (3) and (6): difference between the two group coefficients (column 1 minus column 2; column 4 minus column 5) from a fully interacted stacked 2SLS model, in which treatment, instrument, controls, fixed effects for the child's exact age in completed months and for the calendar month of interview and district or state fixed effects are all group-specific, so that the group coefficients coincide with the separate estimates; standard error clustered at the DHS cluster level in parentheses and stars from that test; in braces, the p -value of that test. Levels are estimated among the children who have reached the minimum age of every dose of the stage (16–35 months for the doses due at 16–24 months, 4–35 months for the primary series and 0–35 months for the birth doses). Panel B reports the common coefficient of the stacked within-child differences of the stage's dose pairs (MCV-1 → MCV-2 and DPT-3 → DPT booster, children aged 16–35 months; DPT-1 → DPT-3 and OPV-1 → OPV-3, children aged 12–35 months), with pair-specific controls and fixed effects; its N counts child-pair observations and its mean is the mean within-child difference. All specifications include the controls of Table 3 and fixed effects for the child's exact age in completed months and for the calendar month of interview; estimates are weighted with normalized DHS survey weights. The last two columns report the weighted mean of the outcome in uncovered clusters and the number of observations in each group. Because these are linear 2SLS coefficients, subgroup estimates are not constrained to the unit interval. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The education gradient is itself concentrated at the later stage of the schedule. For the first-year outcomes, none of the group-specific estimates and none of the differences between groups is significant at the 5 percent level, and there is no comparable pattern of larger positive effects among children of less educated mothers. The difference between the two groups therefore appears at the same stage as the overall effect of coverage, for the doses due at 16–24 months. The estimated gains are concentrated in the group with the lower baseline vaccination rate, a pattern consistent with coverage narrowing the difference in receipt of these doses between children of less and more educated mothers. The magnitudes in the less educated group are large relative to the mean in uncovered clusters, and their confidence intervals are wide; as in the pooled estimates, these are IV estimates identified from terrain-induced variation in coverage, and the contrast between groups is more informative than the

magnitude of either group-specific coefficient.

Household wealth provides a complementary measure of household resources. Appendix Table E1 compares children in the bottom two quintiles of the DHS wealth index with those in the top three. The pattern is similar. With district fixed effects, the effect on the share of the doses due at 16–24 months is 0.643 in poorer households, significant at the 1 percent level, and small and statistically insignificant in the others. The difference between the two groups is significant at the 1 percent level, both for this share and for within-child completion of the 16–24-month stage. Because schooling and wealth are closely related, the two splits cannot separate their roles. Taken together, they indicate that the effect of coverage is concentrated among households with fewer educational or economic resources.

This resource gradient corresponds to the substitution case of the third prediction. The NFHS-5, however, does not record which household member uses mobile internet, nor the connectivity of the frontline health workers who serve the household, so the gradient does not allow us to distinguish who uses the additional connectivity. At least two pathways are consistent with the gradient. Families with fewer resources of their own may gain more from information they obtain directly, for instance about when a dose is due. Alternatively, reminders, tracking and follow-up by better-connected frontline health workers may matter most for the families that would otherwise be least likely to return. The connectivity measures available in the NFHS-5 state-module subsample show how different the two groups of mothers are in this respect: 43 percent of mothers with fewer than 8 years of schooling report having a mobile phone that they themselves use and 11 percent report ever having used the internet, against 68 and 48 percent among more educated mothers. These differences make the schooling gradient difficult to reconcile with a pathway operating only through mothers' own internet use, and are consistent with information reaching the household through other family members, through frontline health workers, or both. Section 6 examines what the available data on household connectivity, basic mobile coverage and the digital tools of frontline health workers can say about these pathways.

6 Household and provider channels

The results of Section 5 are consistent with local connectivity reducing the information and coordination frictions involved in completing the later stage of the schedule. In the framework of Section 2, these frictions arise on both sides of the vaccination process. Families need to know when the next dose is due and to arrange the return visit, while frontline health workers identify eligible children, maintain due lists, organize vaccination sessions and follow up missed doses. Connectivity can ease these tasks on either side. The tasks are most demanding for the doses due at 16–24 months, which follow a longer interval without a scheduled

vaccination contact, so the potential gains from connectivity are largest at this stage. This section examines the evidence available on the household and the provider pathways.

The data are richer on the household side. NFHS-5 records whether every household has internet and, in the state-module subsample, whether the mother has a mobile phone that she herself uses and whether she has ever used the internet (Section 3.4). We relate these measures to local 3G coverage with the IV design used for vaccination, and we use the 2G coverage maps to ask whether the vaccination effects can be attributed to basic mobile service. No survey records the connectivity of frontline workers or their use of digital tools, and the administrative sources available to us do not report the adoption of these tools at a geographic level that could be matched to DHS clusters. For the provider side, we therefore combine NFHS-5 evidence on how vaccination is delivered with official documentation of the digital tools available to frontline workers during the survey period.

The measures of the mother’s own connectivity are available only for 15,490 mothers, and in this subsample the first stage is much weaker than in the full sample (F about 11). The IV estimates for her phone ownership and internet use have Anderson–Rubin confidence sets too wide to exclude either no effect or large effects (Table 8, Panel A), and the split by maternal phone ownership is similarly imprecise (Appendix Table H1). The household measure, available for all mothers, is more informative. Local 3G coverage raises the probability that the household reports having internet by 0.247 with district fixed effects and 0.239 with state fixed effects, against a mean of 0.49 in uncovered clusters; both estimates are significant at the 5 percent level, and their Anderson–Rubin confidence sets exclude zero (Panel B). These specifications omit the DHS wealth index, which includes internet and telephones among its assets. With an asset index that excludes these items, the estimates are smaller and statistically insignificant. Because these assets are measured at the time of the survey and may themselves respond to coverage, we treat this comparison as a sensitivity exercise and the household result as suggestive evidence that local 3G coverage increased household internet access.

Reminders by calls and text messages require only basic mobile service, so the estimated effect of 3G coverage could reflect the more basic difference between having and not having a mobile network. This possibility is relevant in our setting, where 56 percent of children live in clusters covered by 2G but not by 3G. We add 2G coverage, from the 2018 or the 2014 release of the Mobile Coverage Explorer, to the controls, and we restrict the sample to clusters already covered by 2G, where covered and uncovered locations alike have basic mobile service (Appendix Table H2). The 2G control leaves the estimates for the doses due at 16–24 months essentially unchanged. In the 2G-covered samples, the estimates are less precise. With state fixed effects, the effects on the share of the later doses received and on completion of the 16–24-month stage remain significant at the 10 percent level or better; with district fixed effects, the point estimates remain close to the benchmark with the 2018 release and are smaller with the 2014 release. The effect of 3G coverage on the later doses thus persists in

most comparisons among clusters that all have basic mobile service, which suggests a role for the additional connectivity of 3G beyond calls and text messages. Because the deployment of 2G is itself related to terrain and to network investment, these comparisons address this alternative interpretation without decomposing the effects of the two technologies.

On the provider side, frontline workers are central to the tracking, reminders and follow-up that become especially salient for the later doses (Section 3). Vaccination depends heavily on this delivery channel: in NFHS-5, among children aged 16–35 months who had received at least one vaccination, 70 percent received most of their vaccinations at a community-based site, such as a sub-centre or ANM session, an Anganwadi centre, a mobile clinic, a camp or a pulse polio booth, including 55 percent at an Anganwadi centre. The survey also records the mother’s meetings with these workers in the three months before the interview, but these contemporaneous measures may themselves respond to connectivity and contain no information on digital tools, so Section 5.5 uses them only to describe access and outreach conditions.

Official documents show that, during the NFHS-5 period, the health system was introducing digital tools for these tasks. The Reproductive and Child Health (RCH) portal, a web-based system for name-based tracking of mothers and children used in 34 of the 36 States and Union Territories, identifies the children due for immunization and helps health workers draw up their work plans (MoHFW, 2020b, 2021). In a growing number of States, the AN-MOL tablet application let ANMs update beneficiary records in real or near-real time, gave them due lists and supported the planning of village health and nutrition days and of the vaccines these sessions require (MoHFW, 2020b, 2021, 2020a). These tools serve the tasks that become more demanding at the 16–24-month stage, when children must be identified as due after a long interval and their families brought back. Their diffusion during the period we study provides a concrete institutional pathway through which better local mobile coverage could improve the tracking and coordination of the later vaccinations.

Taken together, the evidence presented in this section fits the information-and-coordination interpretation of the vaccination effects. The household evidence suggests that local 3G coverage increased household internet access, and the 2G exercises show that the effect on the later doses generally persists where basic mobile service is already available. On the provider side, vaccination relies heavily on frontline delivery, and during the period we study the health system was deploying digital tools for beneficiary tracking, due lists and session planning. Together with the concentration of the effects among households with fewer resources of their own (Section 5.6), this evidence is consistent with connectivity facilitating the information and coordination needed to complete the later stage of the schedule, through families, frontline health workers, or both.

Table 8: Local 3G coverage and household connectivity

	(1) Mean, 3G = 0	(2) OLS District FE	(3) Reduced form District FE	(4) 2SLS District FE	(5) 2SLS State FE	(6) N
<i>Panel A: Mother's own connectivity (state-module subsample)</i>						
Owens a mobile phone	0.567	−0.010 (0.015)	−0.0117* (0.0062)	+0.582 (0.359) [10.6] [−0.02, +1.84]	+0.367 (0.334) [10.6] [−0.29, +1.38]	15,490
Has ever used the internet	0.296	−0.012 (0.013)	−0.0036 (0.0060)	+0.180 (0.302) [10.6] [−0.50, +0.98]	+0.035 (0.293) [10.6] [−0.76, +0.67]	15,490
<i>Panel B: Household has internet (all households)</i>						
Baseline controls	0.491	+0.030*** (0.007)	−0.0070** (0.0031)	+0.247** (0.107) [58.0] [+0.04, +0.46]	+0.239** (0.102) [60.1] [+0.04, +0.45]	101,895
+ asset index excluding connectivity items	0.491	+0.008 (0.007)	−0.0030 (0.0027)	+0.108 (0.096) [57.5] [−0.08, +0.30]	+0.050 (0.097) [57.9] [−0.14, +0.24]	101,895

Notes. One observation per mother in the analytical sample. Each row reports OLS and IV estimates relating local 3G coverage (an indicator equal to one if the raster pixel containing the released cluster coordinate is covered) to the outcome in the row, together with the reduced-form coefficient of the outcome on terrain ruggedness. Column (1): weighted mean of the outcome among mothers in uncovered clusters. Column (2): OLS. Column (3): reduced form, coefficient on the Terrain Ruggedness Index (per 10 units). Columns (4) and (5): 2SLS, with 3G coverage instrumented by ruggedness, with the cluster-robust first-stage F -statistic in brackets and, in the last row of each block, the Anderson–Rubin 95 percent confidence set for the 2SLS coefficient, which remains valid when the instrument is weak. Panel A: items asked only to women in the households selected for the NFHS-5 state module, a subsample of about 15 percent of the households interviewed in each state: whether the woman has a mobile phone that she herself uses, and whether she has ever used the internet; controls: mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and fixed effects for the calendar month of interview. Panel B: item of the household questionnaire, asked in every household, on whether the household has internet; it does not record who uses it or for what. Because the DHS wealth index is built from household assets that include internet and mobile telephones, the baseline row uses the same controls as Panel A without the wealth quintile; the second row adds quintiles of an alternative asset index, constructed as the first principal component of 41 household assets and housing characteristics, excluding the connectivity items (mobile and landline telephones, internet and computers). All specifications include district (columns 2–4) or state (column 5) fixed effects and are weighted with normalized DHS survey weights. Standard errors, clustered at the DHS cluster level, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

7 Conclusions

This paper studies whether local mobile internet coverage helps complete the childhood immunization schedule in a setting where the doses due in the second year of life are received

far less often than the doses of the first year. Using georeferenced data on about 113,000 children from India’s National Family Health Survey and terrain ruggedness as an instrument for local 3G coverage, we find that the effects of coverage are concentrated at the stage of the schedule at which completion requires a return after a longer interval without a scheduled vaccination contact. For the doses due at birth, at 6–14 weeks and at 9–12 months, the estimated effects of coverage are small and statistically insignificant, including for outcomes that a substantial share of children have not received, such as all the birth doses or all the doses of the primary series. For the two doses due at 16–24 months, coverage raises receipt, and the effect emerges when children reach the age at which these doses become due. A within-child design, which compares earlier and later vaccinations of the same child and thereby removes any disadvantage of rugged locations common to both, shows that coverage raises completion of the 16–24-month stage but not of the primary series. The completion estimate remains positive and statistically significant when we account for local development before the diffusion of mobile broadband, for floods and extreme rainfall when the later dose is due, and for travel time to health facilities and observed outreach conditions. The effects are concentrated among children of less educated mothers, and a similar pattern holds by household wealth.

These results accord with the information-and-coordination mechanism of the conceptual framework. The effect appears at the stage at which families and health workers must keep track of a child after a longer interval without a scheduled vaccination contact, and the larger response among households with fewer resources of their own is consistent with the substitution case of the framework’s third prediction. The evidence on channels points in the same direction. Local 3G coverage is associated with greater household internet access, the effects on the later doses generally persist where basic mobile service is already available, and during the period we study the health system was introducing digital tools that frontline workers use for beneficiary tracking, due lists and session planning. Together, these findings point to digital connectivity improving the information and coordination environment surrounding completion of the later stage of the schedule, through families, frontline health workers, or both.

Research on vaccination has emphasized prices, incentives, beliefs and, more recently, the role of digital media in spreading vaccine hesitancy. Our results draw attention to a distinct barrier, the difficulty of following a prolonged schedule once scheduled vaccination contacts become less frequent, and the effects of connectivity are larger among families with fewer information resources of their own. More generally, the findings indicate that general-purpose connectivity can affect the use of a public health service selectively, at the stage of the schedule that places the greatest demands on acquiring, retaining and acting on information about when a dose is due.

Several qualifications delimit the interpretation of these results. The IV estimates are identified from terrain-induced differences in coverage, which arise mainly in rural clusters,

and therefore need not coincide with the average effect of expanding 3G coverage in all locations. The within-child design narrows the identifying assumption to the absence of a direct effect of terrain specific to the later doses, and Section 5.5 addresses the most plausible channels for such an effect. The data are cross-sectional, and the NFHS-5 vaccination module covers children only through 35 months. Within this window, receipt of the later doses after 24 months is rare and not significantly associated with coverage, but the data cannot show whether the differences persist later in childhood. The measures of the mother’s own connectivity are available only for a small subsample, and no survey records the connectivity of frontline workers, so the data do not allow us to determine the relative contribution of the household and provider pathways. Finally, the relevance of the results to other settings depends on how immunization schedules are organized and on how health systems follow children between scheduled vaccination contacts.

The findings have a practical implication for immunization policy. Where the later doses follow a long interval without scheduled vaccination contacts, keeping track of the schedule may itself be a barrier to completion, and digital tools that ease this task can complement investments in physical access and service delivery. Reminders to families, better tracking of beneficiaries and more effective follow-up by frontline workers may be most valuable at the points of the schedule where scheduled vaccination contacts become sparse and among households with fewer resources for keeping track of the schedule on their own.

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Appendix

A Vaccination schedule

Table A1: Vaccination indicators available in the public-use NFHS-5 data and their use in the analysis

Vaccine/dose	Recommended age	Use in the analysis
<i>At birth</i>		
BCG	At birth	Birth doses
OPV-0	At birth	Birth doses
HepB birth dose	At birth	Birth doses
<i>6–14 weeks</i>		
DPT-1 to DPT-3	6, 10, 14 weeks	Primary series
OPV-1 to OPV-3	6, 10, 14 weeks	Primary series
Pentavalent-1 to -3	6, 10, 14 weeks	Not used separately: every pentavalent dose recorded in NFHS-5 is also recorded as a DPT and a HepB dose
HepB-1 to HepB-3	6, 10, 14 weeks	Not used separately: delivered with DPT through the pentavalent vaccine; more than 99 percent of the children recorded as having received a HepB dose of the primary series are recorded as having received the corresponding DPT dose
Rotavirus-1 to -3	6, 10, 14 weeks	Excluded: introduced in phases from 2016; extension to the whole country announced only in 2019
<i>9–12 months</i>		
MCV-1	9–12 months	MCV-1
JE-1	9–12 months	Excluded: part of routine immunization only in endemic districts, where ruggedness does not predict 3G coverage (Appendix Table G4)
<i>16–24 months</i>		
MCV-2	16–24 months	16–24-month doses
DPT booster	16–24 months	16–24-month doses
JE-2	16–24 months	Excluded (as JE-1)

Notes. The table lists the vaccination indicators of the Universal Immunization Programme available for analysis in the public-use NFHS-5 (2019–21) data and their use in the paper. The NFHS-5 questionnaire includes card-transcription items for fractional doses of the inactivated poliovirus vaccine, but the corresponding variables in the public-use recode contain no usable observations; the public-use data likewise provide no usable indicator for the pneumococcal conjugate vaccine or the OPV booster. Recommended ages follow India’s National Immunization Schedule and operational guidelines (MoHFW and MWCD, 2018; MoHFW, 2018). The four stages of the schedule and the exclusions are described in Section 3.2, and the national extension of rotavirus vaccine is documented in Press Information Bureau (2019); Appendix Table G4 documents the JE-programme districts. Table 1 reports descriptive statistics for the doses used in the analysis.

B Sample construction and selection

Table B1 reports the construction of the analytical sample from the NFHS-5 birth histories, next to the one-child-per-woman construction (the most recent birth of each interviewed woman, if alive). The NFHS-5 vaccination module covers children under 36 months only, so the analytical sample consists of all living children under 36 months whose cluster lies in the extent of the 3G coverage map and has released coordinates, with complete controls. Table B2 asks whether local 3G coverage or terrain ruggedness predicts the age of the child or the fertility of the mother, which could mechanically affect vaccination rates. Selecting the youngest child can make the age of the selected observation depend on fertility patterns, and hence potentially on 3G coverage or its instrument. In the one-child-per-woman sample of children under 60 months (Panel A), ruggedness predicts a slightly younger child and more siblings under five, and the 2SLS estimates suggest an older child and fewer other children under five in covered clusters, significant at the 5 or 10 percent level under both specifications; the 2SLS estimate for births in the last five years is significant at the 10 percent level with district fixed effects only. Moving to children under 36 months substantially attenuates these patterns. In the analytical sample (Panel C), neither 3G coverage nor ruggedness is significantly associated with the age of the child with district fixed effects; with state fixed effects, the OLS association is small (+0.20 months) and significant only at the 10 percent level, while the reduced-form and 2SLS estimates are statistically insignificant. Neither ruggedness nor instrumented 3G coverage predicts the share of children who have reached 16 months, and the 2SLS estimates for recent fertility are statistically insignificant. A small reduced-form association between ruggedness and the number of other children under five remains significant at the 10 percent level with state fixed effects, as do the small OLS associations between coverage and this variable under both specifications. Because the analytical sample retains all eligible children, however, differences in family size no longer mechanically determine which child enters the vaccination regressions. Within the sample aged 16–35 months (Panel D), ruggedness is associated with a slightly younger age: the reduced-form coefficient is small and statistically insignificant with district fixed effects and equal to -0.065 months per 10 units of the index with state fixed effects, significant at the 5 percent level. The fixed effects for the child’s exact age in completed months, included in every specification for vaccination outcomes (Section 4.3), directly address this remaining compositional difference.

Table B1: Sample construction

	(1) One child per woman (most recent birth)	(2) All living children under 36 months
Women interviewed in NFHS-5	724,115	
Living children under 60 months in the birth histories	224,238	
Most recent birth of each woman, if alive, under 60 months	172,442	–
in the extent of the 3G coverage map, with ruggedness observed ^a	146,150	–
of which aged 0–35 months (vaccination module)	101,869	–
Living children aged 0–35 months	–	132,460
in the extent of the 3G coverage map, with ruggedness observed ^a	–	113,710
Analytical sample: complete individual and cluster-level controls	101,432	113,249
women	101,432	101,895
DHS clusters	24,544	24,553
children aged 16–35 months with MCV-2 observed	50,248	61,313
children aged 16–35 months with the DPT booster observed	49,979	60,945

Notes. The NFHS-5 vaccination module is administered for children under 36 months of age; no vaccination information exists for older children. Column (1) follows the one-child-per-woman construction: the most recent birth of each interviewed woman, if alive. Column (2) is the analytical sample of the paper: every living child under 36 months listed in the birth history of an interviewed woman (at most four children per woman; 11,817 children in column (2) are not the most recent birth of their mother: 10,906 are older siblings and 911 are twins of the most recent birth). Sample sizes for individual doses differ because of item non-response and because each dose is estimated among children who have reached its recommended age (Section 4.3). Each child carries the survey weight of the mother, as in the DHS children’s recode; weights are normalized to mean one in each estimation sample, and standard errors are clustered at the DHS cluster level, which contains all the children of a woman.

^a Of the 132,460 living children under 36 months, 426 (in 104 clusters) belong to clusters whose GPS coordinates are not released, and 18,324 (in 3,992 clusters) to clusters located east of the eastern edge of the 2018 coverage raster, at approximately 90°E, a group that includes many clusters in the North-Eastern states and in the Andaman and Nicobar Islands. Every remaining cluster has a value of both terrain ruggedness and 3G coverage.

Table B2: Does local 3G coverage predict the age of the child or fertility?

Dependent variable	District FE (benchmark)			State FE			Mean, uncovered clusters	N
	(1) OLS	(2) Reduced form	(3) 2SLS	(4) OLS	(5) Reduced form	(6) 2SLS		
<i>Panel A: One child per woman (most recent birth), under 60 months</i>								
Age of the youngest child (months)	+0.09 (0.18)	−0.1552** (0.0708)	+5.17** (2.51)	+0.09 (0.18)	−0.1103* (0.0582)	+5.06* (2.84)	25.16	145,450
Youngest child aged 16 months or more (=1)	+0.003 (0.005)	−0.0024 (0.0021)	+0.079 (0.071)	+0.003 (0.005)	−0.0016 (0.0017)	+0.075 (0.080)	0.64	145,450
Other living children under 60 months	+0.006 (0.005)	+0.0040* (0.0022)	−0.134* (0.076)	+0.006 (0.005)	+0.0035** (0.0017)	−0.160* (0.084)	0.31	145,450
Births in the last five years	+0.003 (0.006)	+0.0042* (0.0022)	−0.139* (0.079)	+0.003 (0.006)	+0.0031* (0.0018)	−0.141 (0.086)	1.34	145,450
Children ever born	−0.001 (0.011)	+0.0056 (0.0043)	−0.186 (0.147)	−0.004 (0.011)	+0.0044 (0.0035)	−0.201 (0.162)	2.22	145,450
<i>Panel B: One child per woman (most recent birth), under 36 months</i>								
Age of the youngest child (months)	+0.09 (0.13)	−0.0300 (0.0537)	+1.07 (1.90)	+0.17 (0.13)	−0.0685 (0.0424)	+3.23 (2.04)	15.99	101,432
Youngest child aged 16 months or more (=1)	+0.003 (0.007)	−0.0000 (0.0028)	+0.000 (0.099)	+0.003 (0.007)	−0.0006 (0.0023)	+0.030 (0.107)	0.49	101,432
Other living children under 60 months	+0.011 (0.007)	+0.0035 (0.0028)	−0.126 (0.101)	+0.012* (0.007)	+0.0038* (0.0022)	−0.181* (0.109)	0.43	101,432
Births in the last five years	+0.006 (0.007)	+0.0035 (0.0028)	−0.125 (0.103)	+0.007 (0.007)	+0.0031 (0.0023)	−0.147 (0.110)	1.46	101,432
Children ever born	−0.003 (0.013)	+0.0040 (0.0045)	−0.143 (0.163)	+0.002 (0.013)	+0.0033 (0.0038)	−0.157 (0.180)	2.14	101,432
<i>Panel C: All living children under 36 months (analytical sample)</i>								
Age of the child (months)	+0.13 (0.12)	−0.0113 (0.0453)	+0.41 (1.63)	+0.20* (0.12)	−0.0443 (0.0365)	+2.10 (1.76)	17.24	113,249
Child aged 16 months or more (=1)	+0.005 (0.006)	+0.0002 (0.0024)	−0.008 (0.085)	+0.004 (0.006)	−0.0001 (0.0020)	+0.002 (0.093)	0.54	113,249
Other living children under 60 months	+0.014* (0.009)	+0.0027 (0.0032)	−0.096 (0.117)	+0.016* (0.009)	+0.0044* (0.0026)	−0.207 (0.130)	0.51	113,249
Births in the last five years	+0.009 (0.009)	+0.0028 (0.0033)	−0.099 (0.119)	+0.010 (0.009)	+0.0033 (0.0027)	−0.157 (0.130)	1.55	113,249
Children ever born	−0.001 (0.013)	+0.0045 (0.0048)	−0.160 (0.173)	+0.004 (0.014)	+0.0036 (0.0041)	−0.173 (0.196)	2.22	113,249
<i>Panel D: Age in months within the age-appropriate samples (all living children)</i>								
Age (months), children aged 16–35 months	+0.08 (0.09)	−0.0546 (0.0388)	+1.88 (1.40)	+0.15 (0.09)	−0.0651** (0.0316)	+2.98* (1.54)	25.46	61,769
Age (months), children aged 9–35 months	+0.14 (0.10)	−0.0546 (0.0414)	+1.88 (1.45)	+0.15 (0.10)	−0.0355 (0.0345)	+1.60 (1.57)	21.84	84,011
Age (months), children aged 4–35 months	+0.14 (0.11)	−0.0291 (0.0450)	+1.01 (1.57)	+0.16 (0.11)	−0.0324 (0.0362)	+1.49 (1.67)	19.31	99,996

Notes. Each cell comes from a separate regression of the dependent variable on the individual and cluster-level controls and district (columns 1–3) or state (columns 4–6) fixed effects; these regressions do not include the fixed effects for the child's age in months used in the vaccination specifications, because the dependent variables are the child's age or depend on it, and they are estimated without calendar-month-of-interview fixed effects. Their first-stage F -statistics therefore differ slightly from those of Table 2. Columns (1) and (4) report the OLS coefficient on local 3G coverage; columns (2) and (5) the reduced-form coefficient on the Terrain Ruggedness Index (per 10 units); columns (3) and (6) the 2SLS coefficient on 3G coverage instrumented by the index. Panel D asks whether 3G coverage or ruggedness predicts the child's age in months within the samples of children who have reached the recommended age of the doses due at 16–24 months (16–35 months), of the first dose of measles-containing vaccine (9–35 months) and of the doses due at 14 weeks (4–35 months). In Panels A and B the unit of observation is the interviewed woman with her most recent birth, if alive, as in the one-child-per-woman sample: Panel A uses the women whose most recent birth is alive and under 60 months, Panel B those whose most recent birth is under 36 months, the range covered by the vaccination module; like the analytical sample, both are restricted to clusters inside the extent of the coverage map and to observations with complete controls. Panel C uses the analytical sample, in which every living child under 36 months of an interviewed woman is an observation. "Mean, uncovered clusters" is the weighted mean of the dependent variable among the observations in clusters without 3G coverage. First-stage partial F on the instrument: 67 (district FE) and 54 (state FE) in Panel A; 58 and 51 in Panel B; 57 and 50 in Panel C; in Panel D, 53, 57, 57 (district FE) and 44, 51, 51 (state FE) for the three samples, in the order shown. Weighted by DHS survey weights; standard errors clustered at the DHS cluster level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C First stage and effects by age of the child

First-stage estimates by subgroup

Table C1: First-stage estimates by subgroup

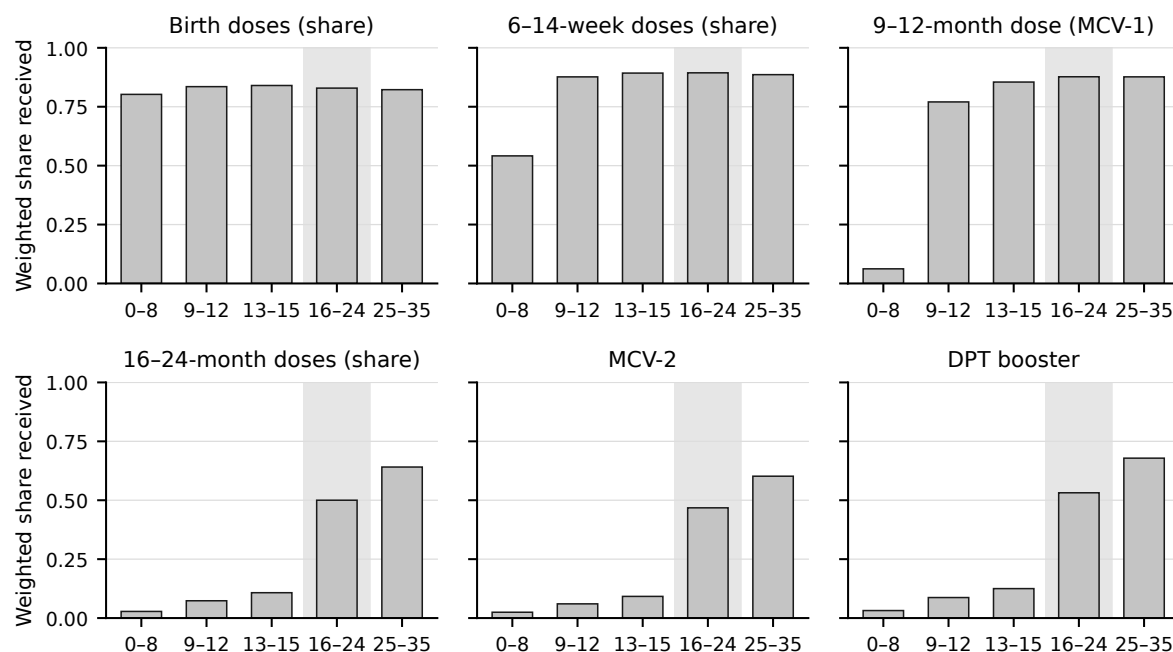
Subgroup	<i>N</i>	Mean 3G	District FE (benchmark)			State FE		
			(1) TRI	SE	<i>F</i>	(2) TRI	SE	<i>F</i>
Full sample	113,249	0.291	−0.028***	(0.004)	56.1	−0.022***	(0.003)	56.8
Urban clusters	23,374	0.598	−0.010	(0.011)	0.8	−0.014	(0.010)	2.1
Rural clusters	89,875	0.181	−0.033***	(0.003)	97.2	−0.027***	(0.003)	94.6
Rural, nightlights low tercile	29,857	0.081	−0.028***	(0.004)	47.1	−0.022***	(0.003)	39.9
Rural, nightlights mid tercile	29,657	0.155	−0.029***	(0.007)	17.6	−0.027***	(0.004)	41.1
Rural, nightlights high tercile	30,361	0.285	−0.032***	(0.010)	11.0	−0.019**	(0.008)	5.9
Mother's schooling < 8 years	43,903	0.220	−0.022***	(0.004)	25.3	−0.016***	(0.003)	22.5
Mother's schooling ≥ 8 years	69,346	0.334	−0.031***	(0.004)	47.9	−0.026***	(0.004)	49.3
Wealth quintiles 1–2	52,951	0.141	−0.024***	(0.003)	48.1	−0.018***	(0.003)	41.8
Wealth quintiles 3–5	60,298	0.413	−0.028***	(0.005)	30.0	−0.024***	(0.004)	30.6

Notes. Each row reports two separate weighted OLS regressions of local 3G coverage on the Terrain Ruggedness Index (per 10 units) within the subgroup, with mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, fixed effects for the child's exact age in completed months and for the calendar month of interview, and district (benchmark) or state fixed effects, estimated within the subgroup, on the analytical sample of living children under 36 months. Nighttime-light terciles are computed across rural clusters. "Mean 3G" is the weighted mean of local 3G coverage in the subgroup. Estimates are weighted with normalized DHS survey weights; standard errors clustered at the DHS cluster level. *F* is the square of the cluster-robust *t*-statistic on the instrument. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Age profile of vaccination and additional age-cohort estimates

This subsection reports the vaccination rates by age that underlie the age bins of Section 5.3 (Figure C1 and Tables C2 and C3), the reduced form by two-month age bin (Table C4), the tests of equality of the effects across age groups (Table C5), the age-bin estimates for the indicators of having received all the doses of a stage (Table C6) and for the one-child-per-woman sample (Table C7), and the comparison between receipt by 24 months and receipt by the interview among children aged 25–35 months (Table C8).

A. Weighted receipt by age bin



B. 2SLS estimates by age bin, with 95% confidence intervals

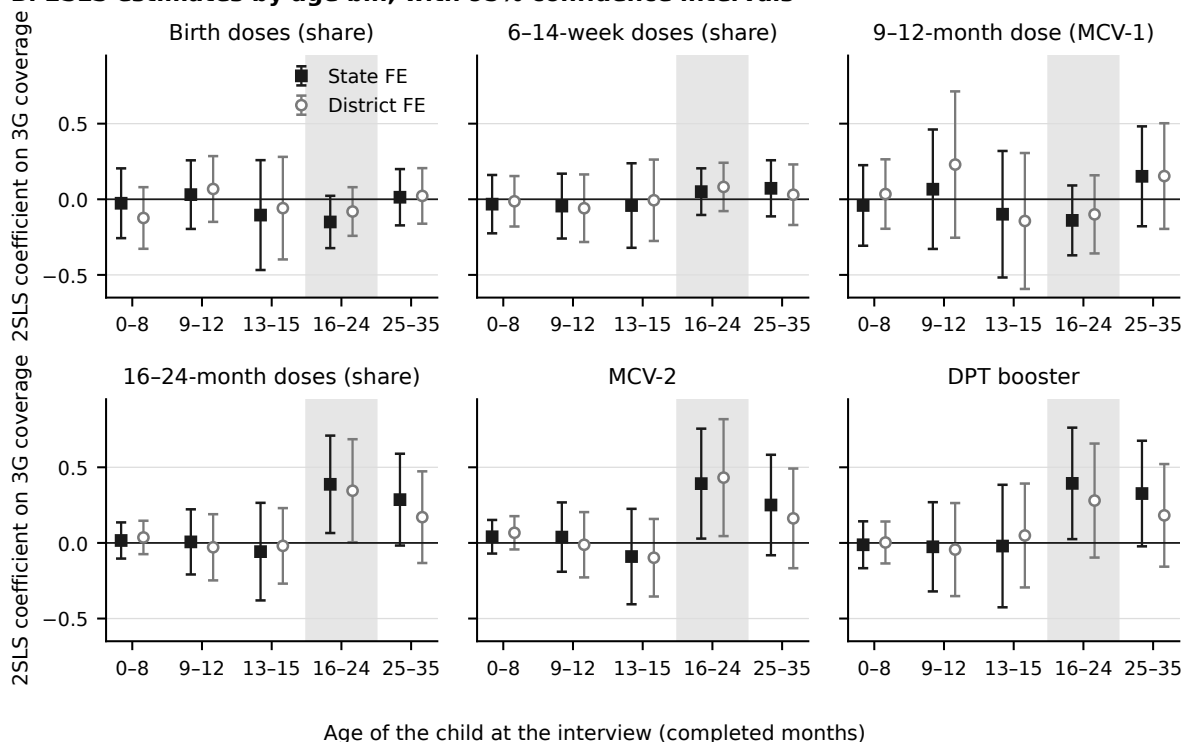


Figure C1: Vaccination rates and effects of 3G coverage by age of the child: all outcomes
Notes. Age of the child at the interview in completed months. Panel A: weighted share of the doses received by the interview in each age bin (Table C2). Panel B: 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, estimated separately in each age bin with state fixed effects (squares) or district fixed effects (circles), with 95 percent confidence intervals based on standard errors clustered at the DHS cluster level (Table 4). The shaded area marks the 16–24-month window in which MCV-2 and the DPT booster become due.

Table C2: Vaccination rates by age of the child

Outcome	Age of the child at the interview (completed months)				
	(1) 0–8	(2) 9–12	(3) 13–15	(4) 16–24	(5) 25–35
Birth doses, share received	0.802	0.835	0.840	0.829	0.822
6–14-week doses, share received	0.541	0.877	0.893	0.894	0.886
9–12-month dose (MCV-1)	0.062	0.770	0.855	0.877	0.877
16–24-month doses, share received	0.028	0.073	0.108	0.500	0.641
MCV-2	0.025	0.060	0.092	0.468	0.602
DPT booster	0.032	0.087	0.125	0.532	0.679
Birth doses, all received	0.618	0.675	0.680	0.662	0.655
6–14-week doses, all received	0.352	0.760	0.786	0.789	0.771
9–12-month dose (MCV-1)	0.062	0.770	0.855	0.877	0.877
16–24-month doses, all received	0.017	0.034	0.055	0.408	0.529
Children	29,238	12,578	9,664	27,371	34,398
Children in uncovered clusters	21,808	9,363	7,038	20,184	25,164

Notes. NFHS-5 (2019–21). Weighted means (normalized DHS survey weights) of each outcome among the children of the bin with a non-missing outcome, in the analytical sample of all living children under 36 months (the base sample before outcome-specific missing values; the regressions of Table 4 use, for each outcome, the children with a non-missing outcome); the last two rows report the number of children in the bin and the number living in clusters without 3G coverage. The four stages of the schedule follow India’s immunization schedule: birth (BCG, OPV-0, hepatitis B birth dose), 6–14 weeks (DPT-1 to DPT-3, OPV-1 to OPV-3), 9–12 months (MCV-1), 16–24 months (MCV-2, DPT booster); “share received” is the share of the stage’s doses received by the interview and “all received” an indicator for all doses of the stage received; for the single-dose 9–12-month stage the two coincide. Because receipt is measured by the interview, the rates are cumulative in age; the profile pools covered and uncovered clusters and shows when the doses of each stage are received in the data.

Table C3: Vaccination rates by month of age

Age (months)	<i>N</i>	(1) BCG	(2) DPT-1	(3) DPT-3	(4) MCV-1	(5) MCV-2	(6) DPT booster
0	3,055	0.816	0.030	0.011	0.010	0.009	0.011
1	3,320	0.896	0.199	0.018	0.014	0.010	0.016
2	3,439	0.927	0.668	0.035	0.030	0.017	0.027
3	3,439	0.947	0.827	0.151	0.039	0.020	0.032
4	3,520	0.954	0.868	0.458	0.067	0.026	0.030
5	3,187	0.957	0.902	0.637	0.113	0.033	0.036
6	3,327	0.951	0.907	0.714	0.130	0.033	0.047
7	3,040	0.953	0.927	0.772	0.174	0.034	0.041
8	2,911	0.961	0.930	0.806	0.276	0.041	0.047
9	3,084	0.958	0.934	0.833	0.608	0.042	0.060
10	3,009	0.958	0.938	0.851	0.788	0.054	0.080
11	3,114	0.954	0.925	0.850	0.795	0.062	0.089
12	3,371	0.954	0.928	0.860	0.830	0.082	0.117
13	3,370	0.957	0.942	0.873	0.854	0.081	0.114
14	3,217	0.955	0.934	0.862	0.849	0.084	0.123
15	3,077	0.962	0.944	0.882	0.861	0.112	0.139
16	3,294	0.940	0.924	0.862	0.858	0.202	0.224
17	3,088	0.958	0.941	0.873	0.873	0.336	0.381
18	3,173	0.953	0.939	0.888	0.877	0.446	0.491
19	2,924	0.943	0.927	0.882	0.868	0.501	0.567
20	2,913	0.961	0.940	0.893	0.887	0.523	0.611
21	2,836	0.955	0.932	0.893	0.883	0.541	0.621
22	3,012	0.954	0.928	0.884	0.876	0.531	0.623
23	2,956	0.951	0.942	0.891	0.879	0.553	0.620
24	3,175	0.956	0.937	0.888	0.893	0.589	0.661
25	3,382	0.947	0.928	0.876	0.876	0.575	0.667
26	3,161	0.945	0.938	0.889	0.888	0.603	0.673
27	3,288	0.945	0.928	0.885	0.883	0.598	0.687
28	3,300	0.943	0.921	0.879	0.866	0.583	0.662
29	3,319	0.945	0.930	0.886	0.884	0.610	0.677
30	3,197	0.942	0.930	0.881	0.874	0.592	0.680
31	3,022	0.959	0.937	0.890	0.880	0.617	0.679
32	2,990	0.937	0.916	0.882	0.870	0.595	0.687
33	2,830	0.943	0.924	0.875	0.864	0.614	0.678
34	2,979	0.952	0.937	0.898	0.894	0.625	0.685
35	2,930	0.942	0.916	0.884	0.864	0.615	0.692

Notes. NFHS-5 (2019–21). Weighted share (normalized DHS survey weights) of children who had received each dose by the interview, by age of the child at the interview in completed months, in the analytical sample of all living children under 36 months (*N* is the number of children of each age; the total, 113,249, is the analytical sample before outcome-specific missing values, whereas the regressions of Table 4 use, for each outcome, the children with a non-missing outcome). Spacing separates the age bins of Table 4 (0–8, 9–12, 13–15, 16–24, 25–35 months), chosen from this profile: MCV-1 rises sharply at 9 months and is still rising at 12; MCV-2 and the DPT booster rise sharply from 16 months and more slowly after about 20 months.

Table C4: Reduced form by two-month age bin: terrain ruggedness and receipt of the 16–24-month doses

Age (months)	16–24-month doses, share			MCV-2			DPT booster		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	District FE	State FE	<i>N</i>	District FE	State FE	<i>N</i>	District FE	State FE	<i>N</i>
0–1	–0.000 (0.002)	+0.000 (0.001)	6,356	–0.001 (0.001)	–0.001 (0.001)	6,360	+0.001 (0.002)	+0.001 (0.002)	6,359
2–3	+0.001 (0.002)	+0.000 (0.002)	6,844	+0.000 (0.002)	–0.001 (0.002)	6,847	+0.002 (0.004)	+0.001 (0.003)	6,848
4–5	–0.004 (0.003)	–0.000 (0.003)	6,660	–0.005 (0.004)	–0.001 (0.003)	6,672	–0.003 (0.004)	+0.001 (0.003)	6,664
6–7	–0.003 (0.003)	–0.002 (0.003)	6,324	–0.002 (0.003)	–0.001 (0.003)	6,337	–0.005 (0.004)	–0.002 (0.003)	6,332
8–9	+0.004 (0.003)	+0.001 (0.002)	5,946	+0.003 (0.003)	+0.000 (0.002)	5,958	+0.004 (0.005)	+0.002 (0.004)	5,955
10–11	+0.002 (0.005)	+0.000 (0.004)	6,072	+0.002 (0.005)	+0.001 (0.004)	6,096	+0.003 (0.006)	+0.000 (0.005)	6,078
12–13	+0.001 (0.005)	+0.001 (0.005)	6,656	–0.002 (0.005)	–0.003 (0.005)	6,696	+0.004 (0.008)	+0.003 (0.006)	6,666
14–15	+0.001 (0.004)	+0.001 (0.004)	6,217	+0.005 (0.005)	+0.003 (0.004)	6,255	–0.003 (0.006)	–0.000 (0.005)	6,228
16–17	–0.005 (0.007)	–0.006 (0.007)	6,306	–0.002 (0.008)	–0.007 (0.007)	6,347	–0.009 (0.008)	–0.005 (0.008)	6,316
18–19	–0.003 (0.009)	–0.005 (0.008)	6,016	–0.009 (0.010)	–0.009 (0.009)	6,057	+0.002 (0.010)	–0.002 (0.009)	6,024
20–21	+0.000 (0.008)	–0.005 (0.007)	5,682	–0.002 (0.009)	–0.003 (0.009)	5,716	+0.002 (0.010)	–0.008 (0.008)	5,688
22–23	–0.023** (0.010)	–0.019** (0.008)	5,902	–0.025** (0.012)	–0.016* (0.009)	5,938	–0.024** (0.011)	–0.023*** (0.008)	5,910
24–25	–0.019** (0.008)	–0.008 (0.008)	6,448	–0.027*** (0.010)	–0.008 (0.009)	6,502	–0.010 (0.009)	–0.008 (0.008)	6,465
26–27	–0.015** (0.008)	–0.012** (0.006)	6,335	–0.017** (0.008)	–0.013* (0.007)	6,401	–0.014 (0.009)	–0.012* (0.007)	6,348
28–29	–0.005 (0.009)	–0.008 (0.007)	6,505	–0.007 (0.010)	–0.008 (0.008)	6,557	–0.002 (0.010)	–0.008 (0.007)	6,519
30–31	+0.007 (0.007)	+0.005 (0.007)	6,113	+0.013 (0.009)	+0.007 (0.008)	6,169	+0.000 (0.008)	+0.002 (0.008)	6,119
32–33	–0.009 (0.009)	–0.013* (0.008)	5,714	–0.003 (0.010)	–0.008 (0.008)	5,766	–0.015 (0.010)	–0.019** (0.009)	5,727
34–35	–0.003 (0.010)	–0.006 (0.007)	5,817	–0.002 (0.012)	–0.011 (0.009)	5,860	–0.001 (0.010)	–0.000 (0.008)	5,829

Notes. NFHS-5 (2019–21). Reduced-form estimates: coefficients on the Terrain Ruggedness Index (TRI, per 10 units) in regressions of the outcome on the instrument, in subsamples defined by the child’s age at the interview in two-month bins of completed months, for all living children under 36 months in the analytical sample. Standard errors clustered at the DHS cluster level in parentheses; *N* is the number of children with a non-missing outcome in the bin (identical for the two specifications). Each specification includes fixed effects for the child’s exact age in completed months and for the calendar month of interview within the bin, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and district or state fixed effects; estimates are weighted with normalized DHS survey weights. The 16–24-month stage comprises MCV-2 and the DPT booster; its outcome is the share of the two doses received by the interview. Spacing precedes the bin in which the 16–24-month window begins (16–17 months) and the bin that contains its last month (24–25 months). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C5: Effects by age group and tests of equality across age groups

Outcome	Coefficient, by age (months)			Difference	
	(1) 0–15	(2) 16–24	(3) 25–35	(2) – (1)	(3) – (2)
<i>Panel A: District fixed effects (benchmark)</i>					
16–24-month doses, share					
2SLS	+0.022 (0.054) [44]	+0.345** (0.174) [32]	+0.170 (0.155) [51]	+0.323* (0.181) { $p = 0.075$ }	–0.175 (0.223) { $p = 0.434$ }
Reduced form	–0.0006 (0.0015)	–0.0094** (0.0042)	–0.0051 (0.0046)	–0.0088** (0.0045) { $p = 0.049$ }	+0.0043 (0.0061) { $p = 0.480$ }
MCV-2					
2SLS	+0.032 (0.053) [44]	+0.432** (0.197) [33]	+0.162 (0.168) [51]	+0.400** (0.204) { $p = 0.050$ }	–0.269 (0.264) { $p = 0.307$ }
Reduced form	–0.0009 (0.0014)	–0.0118** (0.0048)	–0.0049 (0.0050)	–0.0110** (0.0051) { $p = 0.031$ }	+0.0070 (0.0073) { $p = 0.340$ }
DPT booster					
2SLS	+0.011 (0.070) [44]	+0.280 (0.192) [32]	+0.182 (0.173) [51]	+0.270 (0.203) { $p = 0.184$ }	–0.098 (0.237) { $p = 0.680$ }
Reduced form	–0.0003 (0.0019)	–0.0076 (0.0048)	–0.0055 (0.0051)	–0.0073 (0.0052) { $p = 0.154$ }	+0.0022 (0.0065) { $p = 0.740$ }
<i>Panel B: State fixed effects</i>					
16–24-month doses, share					
2SLS	+0.000 (0.060) [43]	+0.387** (0.164) [35]	+0.286* (0.155) [46]	+0.387** (0.173) { $p = 0.025$ }	–0.101 (0.204) { $p = 0.620$ }
Reduced form	–0.0000 (0.0013)	–0.0089*** (0.0034)	–0.0070* (0.0036)	–0.0089** (0.0036) { $p = 0.013$ }	+0.0019 (0.0046) { $p = 0.679$ }
MCV-2					
2SLS	+0.010 (0.058) [43]	+0.392** (0.185) [35]	+0.251 (0.169) [46]	+0.382** (0.194) { $p = 0.049$ }	–0.141 (0.241) { $p = 0.558$ }
Reduced form	–0.0002 (0.0012)	–0.0090** (0.0040)	–0.0061 (0.0040)	–0.0088** (0.0042) { $p = 0.036$ }	+0.0029 (0.0056) { $p = 0.600$ }
DPT booster					
2SLS	–0.012 (0.077) [42]	+0.394** (0.188) [34]	+0.326* (0.178) [46]	+0.405** (0.197) { $p = 0.039$ }	–0.067 (0.227) { $p = 0.767$ }
Reduced form	+0.0002 (0.0016)	–0.0090** (0.0039)	–0.0080* (0.0041)	–0.0093** (0.0041) { $p = 0.023$ }	+0.0010 (0.0051) { $p = 0.839$ }

Notes. Estimates for two age groups at a time from a fully interacted model: 3G coverage, the Terrain Ruggedness Index, the controls, the fixed effects for the child’s exact age in completed months and for the calendar month of interview and the district or state fixed effects are all specific to each age group, so the coefficients coincide with those of separate regressions by age group. “2SLS” rows report the effect of 3G coverage instrumented by the index, with the cluster-robust first-stage F -statistic of each group in brackets; “Reduced form” rows report the coefficient on the index (per 10 units). The last two columns report the differences between age groups, with standard errors that account for the correlation between the two coefficients within DHS clusters and the p -value of the test of equality in braces. Sample: all living children under 36 months in the analytical sample with a non-missing outcome. Controls as in Table 4; estimates weighted with normalized DHS survey weights; standard errors clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C6: Effects of 3G coverage by age of the child: all doses of the stage received

Outcome	Age of the child at the interview (completed months)				
	(1) 0–8	(2) 9–12	(3) 13–15	(4) 16–24	(5) 25–35
<i>Birth doses, all received</i>					
District FE	−0.356*	+0.211	−0.255	−0.207	+0.097
	(0.183) [32.2]	(0.222) [24.4]	(0.274) [22.4]	(0.156) [33.1]	(0.144) [52.6]
State FE	−0.231	+0.199	−0.400	−0.230	+0.037
	(0.204) [28.6]	(0.233) [21.6]	(0.289) [25.2]	(0.164) [34.5]	(0.151) [45.8]
Mean, 3G = 0	0.628	0.687	0.699	0.674	0.669
N	29,055	12,470	9,593	27,106	34,003
<i>6–14-week doses, all received</i>					
District FE	−0.016	−0.074	−0.115	+0.185	+0.027
	(0.129) [32.2]	(0.185) [24.1]	(0.204) [22.6]	(0.149) [33.6]	(0.151) [51.6]
State FE	−0.091	−0.119	−0.188	+0.149	+0.056
	(0.144) [28.7]	(0.195) [21.6]	(0.198) [25.6]	(0.142) [34.8]	(0.138) [45.2]
Mean, 3G = 0	0.354	0.768	0.796	0.798	0.786
N	29,169	12,553	9,641	27,290	34,286
<i>9–12-month dose (MCV-1)</i>					
District FE	+0.035	+0.230	−0.144	−0.100	+0.153
	(0.117) [26.0]	(0.247) [20.5]	(0.229) [13.4]	(0.132) [22.0]	(0.178) [45.6]
State FE	−0.041	+0.067	−0.099	−0.140	+0.152
	(0.136) [20.2]	(0.201) [23.4]	(0.213) [16.0]	(0.118) [27.2]	(0.169) [36.9]
Mean, 3G = 0	0.060	0.775	0.865	0.886	0.883
N	19,562	8,947	8,010	23,400	30,001
<i>16–24-month doses, all received</i>					
District FE	+0.048	−0.039	+0.039	+0.555**	+0.132
	(0.043) [32.7]	(0.086) [24.4]	(0.095) [23.5]	(0.220) [32.2]	(0.160) [50.8]
State FE	−0.003	−0.043	−0.062	+0.562***	+0.230
	(0.048) [28.8]	(0.088) [22.0]	(0.138) [24.9]	(0.203) [34.5]	(0.168) [45.9]
Mean, 3G = 0	0.018	0.035	0.056	0.421	0.540
N	29,069	12,459	9,547	27,026	33,812

Notes. NFHS-5 (2019–21). 2SLS estimates of the effect of local 3G coverage (point coverage at the DHS cluster coordinate), instrumented by the Terrain Ruggedness Index (TRI), in subsamples defined by the child’s age at the interview in completed months; the dependent variable is indicated in the row heading. Standard errors clustered at the DHS cluster level in parentheses; cluster-robust first-stage F -statistic of each subsample in brackets, next to the standard error; “Mean, 3G = 0” is the weighted mean of the outcome among children of the bin in uncovered clusters; N is the number of children with a non-missing outcome in the bin (identical for the two specifications). Each specification includes fixed effects for the child’s exact age in completed months and for the calendar month of interview within the bin, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and district or state fixed effects; estimates are weighted with normalized DHS survey weights. Sample: all living children under 36 months in the analytical sample. The four stages of the schedule follow India’s immunization schedule: birth (BCG, OPV-0, hepatitis B birth dose), 6–14 weeks (DPT-1 to DPT-3, OPV-1 to OPV-3), 9–12 months (MCV-1), 16–24 months (MCV-2, DPT booster); “all received” is an indicator for all doses of the stage received by the interview, which for the single-dose 9–12-month stage coincides with receipt of MCV-1. Table C2 reports the weighted vaccination rates of the same outcomes in each bin. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C7: Effects of 3G coverage by age of the child: one child per woman

Outcome	Age of the child at the interview (completed months)				
	(1) 0–8	(2) 9–12	(3) 13–15	(4) 16–24	(5) 25–35
<i>Birth doses, share received</i>					
District FE	−0.112 (0.103) [32.4]	+0.063 (0.111) [24.1]	−0.049 (0.173) [22.4]	−0.054 (0.084) [32.3]	+0.019 (0.093) [53.1]
State FE	−0.002 (0.117) [28.8]	+0.026 (0.116) [21.4]	−0.122 (0.186) [25.8]	−0.125 (0.090) [32.1]	+0.029 (0.089) [45.2]
Mean, 3G = 0	0.806	0.838	0.848	0.838	0.832
<i>N</i>	28,803	12,322	9,358	24,594	25,489
<i>6–14-week doses, share received</i>					
District FE	−0.010 (0.085) [32.3]	−0.062 (0.115) [23.8]	−0.011 (0.138) [22.5]	+0.102 (0.085) [33.1]	+0.010 (0.089) [52.1]
State FE	−0.014 (0.098) [28.9]	−0.050 (0.110) [21.4]	−0.055 (0.142) [26.2]	+0.080 (0.082) [32.6]	+0.070 (0.085) [44.3]
Mean, 3G = 0	0.543	0.881	0.900	0.903	0.899
<i>N</i>	28,915	12,405	9,404	24,751	25,699
<i>9–12-month dose (MCV-1)</i>					
District FE	+0.031 (0.114) [26.5]	+0.220 (0.248) [20.2]	−0.145 (0.226) [13.9]	−0.063 (0.134) [21.9]	+0.021 (0.138) [42.7]
State FE	−0.034 (0.132) [21.5]	+0.053 (0.203) [23.2]	−0.132 (0.211) [16.6]	−0.072 (0.119) [26.4]	+0.008 (0.131) [34.2]
Mean, 3G = 0	0.060	0.775	0.864	0.888	0.891
<i>N</i>	19,391	8,838	7,810	21,193	22,431
<i>16–24-month doses, share received</i>					
District FE	+0.033 (0.056) [32.9]	−0.043 (0.111) [24.1]	−0.038 (0.125) [23.5]	+0.369** (0.180) [31.6]	+0.179 (0.148) [51.2]
State FE	+0.015 (0.061) [29.0]	+0.009 (0.111) [21.8]	−0.082 (0.164) [25.5]	+0.424** (0.174) [32.3]	+0.313** (0.157) [45.0]
Mean, 3G = 0	0.028	0.072	0.108	0.509	0.655
<i>N</i>	28,816	12,311	9,313	24,519	25,376
<i>MCV-2</i>					
District FE	+0.058 (0.053) [32.7]	−0.027 (0.109) [23.9]	−0.118 (0.128) [23.7]	+0.459** (0.203) [32.3]	+0.237 (0.172) [51.4]
State FE	+0.038 (0.056) [29.2]	+0.035 (0.117) [21.5]	−0.099 (0.160) [26.6]	+0.415** (0.195) [32.6]	+0.337* (0.182) [44.6]
Mean, 3G = 0	0.025	0.063	0.091	0.479	0.619
<i>N</i>	28,856	12,361	9,367	24,672	25,576
<i>DPT booster</i>					
District FE	+0.005 (0.071) [33.0]	−0.056 (0.158) [24.0]	+0.032 (0.175) [23.2]	+0.301 (0.199) [31.6]	+0.147 (0.161) [51.7]
State FE	−0.010 (0.079) [29.1]	−0.017 (0.152) [21.7]	−0.060 (0.206) [25.0]	+0.444** (0.200) [32.1]	+0.308* (0.171) [45.4]
Mean, 3G = 0	0.031	0.081	0.125	0.537	0.690
<i>N</i>	28,839	12,328	9,328	24,553	25,426

Notes. NFHS-5 (2019–21). 2SLS estimates of the effect of local 3G coverage (point coverage at the DHS cluster coordinate), instrumented by the Terrain Ruggedness Index (TRI), in subsamples defined by the child’s age at the interview in completed months; the dependent variable is indicated in the row heading. Standard errors clustered at the DHS cluster level in parentheses; cluster-robust first-stage *F*-statistic of each subsample in brackets, next to the standard error; “Mean, 3G = 0” is the weighted mean of the outcome among children of the bin in uncovered clusters; *N* is the number of children with a non-missing outcome in the bin (identical for the two specifications). Each specification includes fixed effects for the child’s exact age in completed months and for the calendar month of interview within the bin, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and district or state fixed effects; estimates are weighted with normalized DHS survey weights. Sample: the most recent birth of each woman, if alive and under 36 months (one child per woman). The four stages of the schedule follow India’s immunization schedule: birth (BCG, OPV-0, hepatitis B birth dose), 6–14 weeks (DPT-1 to DPT-3, OPV-1 to OPV-3), 9–12 months (MCV-1), 16–24 months (MCV-2, DPT booster); “share received” is the share of the stage’s doses received by the interview; for the single-dose 9–12-month stage it coincides with receipt of MCV-1. Table C2 reports the weighted vaccination rates of the same outcomes in each bin. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C8: On time or at all? 3G coverage and receipt of the 16–24-month doses by 24 months and by the interview

Outcome	2SLS		Reduced form		(5) Mean, 3G = 0	(6) N
	(1) District FE	(2) State FE	(3) District FE	(4) State FE		
<i>MCV-2</i>						
Ever received	+0.162 (0.168) [51.5]	+0.251 (0.169) [46.0]	−0.005 (0.005)	−0.006 (0.004)	0.609	34,106
By 24 months, dated doses	+0.219 (0.180) [41.2]	+0.300* (0.178) [39.4]	−0.006 (0.005)	−0.007* (0.004)	0.534	30,365
By 24 months, lower bound	+0.247 (0.151) [51.5]	+0.275* (0.156) [46.0]	−0.007 (0.005)	−0.007* (0.004)	0.472	34,106
By 24 months, upper bound	+0.177 (0.167) [51.5]	+0.237 (0.169) [46.0]	−0.005 (0.005)	−0.006 (0.004)	0.588	34,106
After 24 months, dated doses	−0.019 (0.038) [41.2]	+0.011 (0.037) [39.4]	+0.001 (0.001)	−0.000 (0.001)	0.023	30,365
<i>DPT booster</i>						
Ever received	+0.182 (0.173) [50.9]	+0.326* (0.178) [46.1]	−0.005 (0.005)	−0.008* (0.004)	0.682	33,881
By 24 months, dated doses	+0.171 (0.195) [40.8]	+0.317 (0.198) [37.7]	−0.005 (0.005)	−0.007* (0.004)	0.609	29,642
By 24 months, lower bound	+0.193 (0.166) [50.9]	+0.245 (0.167) [46.1]	−0.006 (0.005)	−0.006 (0.004)	0.529	33,881
By 24 months, upper bound	+0.168 (0.175) [50.9]	+0.289 (0.178) [46.1]	−0.005 (0.005)	−0.007* (0.004)	0.660	33,881
After 24 months, dated doses	+0.013 (0.036) [40.8]	+0.044 (0.039) [37.7]	−0.000 (0.001)	−0.001 (0.001)	0.026	29,642
<i>Within-child gap, MCV-1 → MCV-2</i>						
Ever	+0.039 (0.145) [45.6]	+0.099 (0.155) [36.9]	−0.001 (0.004)	−0.002 (0.003)	−0.196	30,001
By 24 months, lower bound	+0.125 (0.174) [45.6]	+0.140 (0.180) [36.9]	−0.004 (0.005)	−0.003 (0.004)	−0.351	30,001
<i>Within-child gap, DPT-3 → DPT booster</i>						
Ever	+0.189 (0.143) [50.7]	+0.321** (0.154) [45.9]	−0.006 (0.004)	−0.008** (0.004)	−0.213	33,860
By 24 months, lower bound	+0.203 (0.143) [50.7]	+0.245* (0.148) [45.9]	−0.006 (0.004)	−0.006* (0.004)	−0.365	33,860

Notes. NFHS-5 (2019–21). Sample: living children aged 25–35 months at the interview, all of whom are past the end of the 16–24-month window (inside the raster extent, with complete controls). “Ever received” is receipt by the interview. “By 24 months” uses the dose date recorded on the vaccination card (month precision) and the child’s date of birth; 82 percent of the received doses have a usable card date, for both MCV-2 and the DPT booster. The undated received doses are treated in three ways: in the “dated doses” coding they are set to missing, so that the sample comprises dated recipients and non-recipients; in the lower bound they are counted as not received by 24 months; in the upper bound as received by 24 months. “After 24 months” is receipt with a card date after 24 months of age (dated-doses sample). Gaps are the indicator for the later dose minus the indicator for the earlier dose of the same child (lower-bound coding for the later dose by 24 months). Columns (1)–(2): 2SLS coefficients on binary local 3G coverage (point coverage at the DHS cluster coordinate) instrumented by the Terrain Ruggedness Index (TRI), with standard errors in parentheses and, next to them, the cluster-robust first-stage F -statistic in brackets; columns (3)–(4): reduced-form coefficients on TRI per 10 units; column (5): weighted mean of the outcome among children in clusters without 3G coverage. All specifications include fixed effects for the child’s exact age in completed months and for the calendar month of interview, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, and district or state fixed effects; estimates are weighted with normalized DHS survey weights and standard errors are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

D Threats to identification: additional diagnostics

This appendix reports the diagnostics that underlie Section 5.5. Table D1 relates terrain ruggedness to the level and growth of nighttime lights before the diffusion of mobile broadband. Table D2 reports, for each dose pair, the interaction between ruggedness and exposure to floods and extreme rainfall in the reduced form of the within-child completion outcome. Table D3 relates ruggedness to the access and outreach conditions recorded in NFHS-5. Table D4 compares the reduced-form relationship between ruggedness and vaccination in NFHS-4 (2015–16) and NFHS-5 (2019–21), for each dose on age-appropriate samples and for the within-child completion pairs of the first year of life. Table D5 reports the completion estimates for the return visit around 9 months, from BCG to MCV-1, under the specifications of Table 6. Table D6 reports a diagnostic based on Mission Indradhanush, the national catch-up immunization campaign launched in 2015, which targeted children under two years of age in selected districts: it asks whether the ruggedness gradient in routine vaccination observed in NFHS-4 was attenuated among the children whose districts were reached by the campaign while they were of catch-up age. The interaction between ruggedness and campaign exposure is statistically indistinguishable from zero across these outcomes and shows no systematic attenuation of the ruggedness gradient, providing no indication that differential campaign timing explains the change in the first-year gradient. The exercise is a diagnostic and not an evaluation of the programme, whose geographic targeting was explicitly non-random and prioritized areas with low vaccination coverage and related risk factors. Finally, Table D7 reports the level estimates of the effect of 3G coverage with and without motorized travel time to the nearest health facility among the controls, which complement the completion estimates in row 5 of Table 6.

Table D1: Terrain ruggedness and pre-3G local development

Dependent variable	District FE		State FE		(5) <i>N</i>
	(1) Coef.	(2) Std.	(3) Coef.	(4) Std.	
Light intensity, 2000–02	−0.1242*** (0.0109)	−0.239	−0.1440*** (0.0133)	−0.277	24,553
Change, 2000–02 to 2005–07, given the 2000–02 level	−0.0154*** (0.0031)	−0.137	−0.0167*** (0.0029)	−0.149	24,553

Notes. Unweighted OLS regressions of each dependent variable on the Terrain Ruggedness Index (TRI, per 10 units), with one observation per DHS cluster and district or state fixed effects. Nighttime lights are the harmonized DMSP-OLS series of Li et al. (2020), averaged within a 2-km buffer around urban clusters and a 5-km buffer around rural clusters and transformed as $\log(1 + x)$; the change is between the transformed averages of 2000–02 and 2005–07, conditional on the 2000–02 level. Columns (2) and (4) report the effect of one standard deviation of TRI in standard deviations of the dependent variable. Standard errors, in parentheses, are clustered at the district level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D2: Terrain ruggedness, access shocks and within-child completion

Dose pair	Window (months)	District FE		State FE		(5) Share exposed
		(1) TRI	(2) TRI $\times$ shock	(3) TRI	(4) TRI $\times$ shock	
<i>Panel A: Flood recorded in the district</i>						
DPT-1 $\rightarrow$ DPT-3	1–4	+0.0001 (0.0014)	−0.0018 (0.0017)	−0.0000 (0.0013)	−0.0008 (0.0017)	0.20
OPV-1 $\rightarrow$ OPV-3	1–4	−0.0020 (0.0020)	+0.0018 (0.0020)	−0.0009 (0.0017)	+0.0025 (0.0020)	0.20
BCG $\rightarrow$ MCV-1	9–12	−0.0009 (0.0017)	+0.0012 (0.0019)	−0.0006 (0.0014)	+0.0006 (0.0017)	0.22
MCV-1 $\rightarrow$ MCV-2	16–24	−0.0079** (0.0038)	+0.0023 (0.0036)	−0.0094*** (0.0033)	+0.0037 (0.0032)	0.31
DPT-3 $\rightarrow$ DPT booster	16–24	−0.0066* (0.0036)	+0.0023 (0.0036)	−0.0102*** (0.0031)	+0.0035 (0.0031)	0.31
<i>Panel B: Month of extreme rainfall at the cluster</i>						
DPT-1 $\rightarrow$ DPT-3	1–4	−0.0002 (0.0015)	−0.0003 (0.0014)	−0.0001 (0.0013)	−0.0004 (0.0014)	0.12
OPV-1 $\rightarrow$ OPV-3	1–4	−0.0017 (0.0021)	+0.0011 (0.0019)	−0.0005 (0.0017)	+0.0015 (0.0020)	0.12
BCG $\rightarrow$ MCV-1	9–12	−0.0008 (0.0017)	+0.0016 (0.0023)	−0.0007 (0.0014)	+0.0021 (0.0028)	0.13
MCV-1 $\rightarrow$ MCV-2	16–24	−0.0052 (0.0036)	−0.0063 (0.0042)	−0.0061** (0.0031)	−0.0056 (0.0039)	0.23
DPT-3 $\rightarrow$ DPT booster	16–24	−0.0090** (0.0036)	+0.0120*** (0.0039)	−0.0118*** (0.0030)	+0.0112*** (0.0036)	0.23

Notes. Reduced-form regressions of the within-child completion outcome of each dose pair (later minus earlier vaccination) on TRI (per 10 units), the shock indicator, their interaction, the controls and birth-quarter fixed effects, which absorb common birth-cohort and season-of-birth variation in exposure to the shocks, with district or state fixed effects. The shock is measured in the window in which the later vaccination falls due (ages in the column “Window”; column (5) reports the share of children exposed to the shock in that window); floods from the India Flood Inventory (Saharia et al., 2021; events recorded in the child’s district), extreme rainfall from CHIRPS (Funk et al., 2015; a month above the cluster’s 1981–2010 95th percentile for that calendar month and at least 200 mm). Samples as in Table 5. All specifications include fixed effects for the child’s exact age in completed months and for the calendar month of interview, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city. Estimates are weighted with normalized DHS survey weights. Standard errors, in parentheses, are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D3: Terrain ruggedness and access and outreach conditions

Dependent variable	(1) Mean	(2) District FE	(3) State FE	(4) N
Mother met an ANM/LHV in the last three months	0.458	+0.0055*	+0.0012	113,249
		(0.0031)	(0.0027)	
ANM/LHV visited the home in the last three months	0.252	+0.0009	−0.0012	113,189
		(0.0025)	(0.0021)	
Mother met an ASHA or Anganwadi worker in the last three months	0.627	−0.0027	−0.0044	113,249
		(0.0032)	(0.0028)	
ASHA or Anganwadi worker visited the home in the last three months	0.450	−0.0075**	−0.0069***	113,148
		(0.0032)	(0.0027)	
Child received most vaccinations at a community-based vaccination site rather than at a health facility	0.681	−0.0033	−0.0032	108,634
		(0.0030)	(0.0026)	
Mother received the Mother and Child Protection card after registering the pregnancy	0.960	+0.0001	−0.0003	99,146
		(0.0010)	(0.0009)	
Child received any immunization through the Anganwadi centre in the last 12 months	0.835	+0.0041*	+0.0010	86,759
		(0.0024)	(0.0021)	
log(1 + x) of travel time to the nearest health facility (minutes)	2.133	+0.1140***	+0.0614***	113,185
		(0.0104)	(0.0087)	

Notes. Reduced-form regressions of each variable on TRI (per 10 units) with the controls and district or state fixed effects, estimated on children under 36 months; column (1) reports the weighted mean of each variable in the estimation sample. Meetings with frontline health workers and their home visits refer to the mother's reports for the three months before the interview (the question on ASHA and Anganwadi workers also covers other community health workers); the community-based vaccination sites are sub-centres or ANM sessions, Anganwadi centres, government mobile clinics, camps and pulse polio booths. The question on the Mother and Child Protection card is asked to mothers who registered the pregnancy, and the question on immunization through the Anganwadi centre is asked about children who received any benefit from the centre in the last 12 months, which explains the smaller samples. Travel time is the motorized travel time of Weiss et al. (2020) at the cluster location. All specifications include fixed effects for the calendar month of interview, mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city. Estimates are weighted with normalized DHS survey weights; standard errors, in parentheses, are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D4: Terrain ruggedness and vaccination in NFHS-4 (2015–16) and NFHS-5 (2019–21)

Outcome	Due	NFHS-4 (2015–16)		NFHS-5 (2019–21)	
		(1) District FE	(2) State FE	(3) District FE	(4) State FE
<i>Panel A: Receipt of each dose (children who have reached its minimum eligible age)</i>					
BCG	birth	−0.0019 (0.0018)	−0.0023* (0.0014)	−0.0002 (0.0012)	+0.0002 (0.0010)
OPV-0	birth	−0.0037 (0.0022)	−0.0060*** (0.0018)	+0.0012 (0.0016)	+0.0005 (0.0015)
DPT-1	6 wks	−0.0007 (0.0022)	−0.0032* (0.0017)	+0.0008 (0.0016)	+0.0010 (0.0014)
OPV-1	6 wks	−0.0010 (0.0021)	−0.0033** (0.0015)	−0.0007 (0.0018)	−0.0013 (0.0014)
DPT-2	10 wks	−0.0047** (0.0024)	−0.0066*** (0.0019)	−0.0001 (0.0018)	+0.0001 (0.0016)
OPV-2	10 wks	−0.0056** (0.0025)	−0.0079*** (0.0018)	−0.0018 (0.0023)	−0.0020 (0.0017)
DPT-3	14 wks	−0.0021 (0.0027)	−0.0046** (0.0020)	+0.0001 (0.0020)	+0.0011 (0.0016)
OPV-3	14 wks	−0.0028 (0.0032)	−0.0078*** (0.0025)	−0.0025 (0.0025)	−0.0014 (0.0021)
MCV-1	9 mo	−0.0044* (0.0025)	−0.0054*** (0.0020)	−0.0014 (0.0029)	−0.0004 (0.0022)
MCV-2	16 mo	—	—	−0.0074** (0.0035)	−0.0073** (0.0029)
DPT booster	16 mo	—	—	−0.0053 (0.0038)	−0.0083*** (0.0031)
<i>Panel B: Within-child completion (children aged 12–35 months)</i>					
DPT-1 → DPT-3	14 wks	−0.0007 (0.0022)	−0.0014 (0.0017)	−0.0003 (0.0014)	−0.0002 (0.0012)
OPV-1 → OPV-3	14 wks	−0.0001 (0.0030)	−0.0038 (0.0024)	−0.0016 (0.0020)	−0.0002 (0.0016)
BCG → MCV-1	9 mo	−0.0033* (0.0018)	−0.0042*** (0.0015)	−0.0006 (0.0017)	−0.0004 (0.0014)

Notes. Reduced-form regressions of each outcome on TRI (per 10 units) with the controls and district or state fixed effects, estimated separately in each survey round on living children under 36 months in clusters inside the extent of the 3G coverage map, with terrain ruggedness constructed in the same way in both rounds (123,853 children in NFHS-4 and 113,171 in NFHS-5 for BCG). MCV-2 and the DPT booster are not recorded in NFHS-4. In NFHS-4, the cluster-level controls are taken from the DHS geospatial covariates released with that round. All specifications include fixed effects for the child's exact age in completed months and, in NFHS-5, for the calendar month of interview, mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city. Estimates are weighted with normalized DHS survey weights; standard errors, in parentheses, are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D5: Completion of the return around 9 months, from BCG to MCV-1, and threats to identification

Specification	District FE		State FE		
	(1) 2SLS	(2) F	(3) 2SLS	(4) F	(5) N
(1) Baseline	+0.022 (0.064)	44.7	+0.020 (0.063)	48.2	64,159
(2) Pre-3G nightlights (DMSP)	+0.026 (0.082)	35.6	+0.017 (0.067)	48.5	64,159
(3) Flood and extreme-rainfall exposure	+0.023 (0.064)	44.7	+0.020 (0.063)	48.2	64,159
(4) Clean windows: no extreme rainfall	+0.050 (0.067)	45.2	+0.064 (0.067)	46.0	55,590
(5) Travel time to health facility	+0.038 (0.112)	18.6	+0.034 (0.091)	27.9	64,129
(6) Meetings and home visits by health workers	+0.028 (0.064)	44.7	+0.020 (0.062)	48.3	64,076

Notes. 2SLS estimates of equation (4) for the pair from BCG to MCV-1 (children aged 12–35 months) under the specifications of Table 6, with the shock and clean-window definitions applied to the 9–12-month window; columns (2) and (4) report the cluster-robust first-stage F -statistics. Controls, weights and clustering as in Table 6. $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

Table D6: Terrain ruggedness and exposure to Mission Indradhanush catch-up rounds, NFHS-4 (2015–16)

Dose	District and cohort FE		+ TRI $\times$ cohort, TRI $\times$ age FE	(4) Children exposed	(5) Districts with variation	(6) <i>N</i>
	(1) TRI	(2) TRI $\times$ exposed	(3) TRI $\times$ exposed			
DPT-3	−0.0033 (0.0032)	+0.0029 (0.0031)	+0.0028 (0.0038)	34,013	223	100,424
OPV-3	−0.0032 (0.0036)	+0.0010 (0.0036)	+0.0011 (0.0046)	34,070	223	100,688
MCV-1	−0.0052* (0.0027)	+0.0009 (0.0034)	−0.0019 (0.0040)	26,314	222	82,305
All eight basic doses	−0.0051 (0.0038)	+0.0002 (0.0039)	−0.0029 (0.0045)	26,205	222	81,938

Notes. Reduced-form regressions of receipt of each dose on TRI (per 10 units), an indicator of exposure to Mission Indradhanush and their interaction, estimated on NFHS-4 children who were at least three months beyond the scheduled age of the dose at the time of the interview, so that all children in the sample had a reasonable opportunity to receive it. A child is exposed if at least one round of the campaign took place in the child’s district before the interview while the child was between the scheduled age of the dose and 23 months. The eight basic doses are BCG, DPT-1 to DPT-3, OPV-1 to OPV-3 and MCV-1. District lists and starting months of the first phase (April 2015), the second phase (October 2015) and the third phase in Uttar Pradesh (April 2016), the only phases that precede the NFHS-4 interviews, are taken from the operational guidelines of the Ministry of Health and Family Welfare and from replies to parliamentary questions; each phase comprised four monthly rounds. Columns (1)–(2) include district and birth-quarter fixed effects; column (3) adds interactions of TRI with birth-quarter and age-band fixed effects, so that the interaction is identified only from differences in the timing of the campaign across districts. Column (5) reports the number of districts with both exposed and unexposed children. All specifications include fixed effects for the child’s exact age in completed months and for the calendar month of interview, mother’s age and its square, years of schooling, wealth quintile, an indicator for urban clusters, and cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city. Estimates are weighted with normalized DHS survey weights; standard errors, in parentheses, are clustered at the DHS cluster level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D7: Adding motorized travel time to the nearest health facility

Outcome	Sample ages	District FE (benchmark)		State FE		Mean, 3G = 0	N
		(1) Baseline	(2) + travel time	(3) Baseline	(4) + travel time		
<i>Panel A: Association between terrain ruggedness and travel time</i>							
log(1 + travel time)	0–35	+0.114*** (0.010)		+0.061*** (0.009)			113,185
<i>Panel B: 2SLS effect of 3G coverage on each outcome</i>							
Birth doses, share	0–35	−0.037 (0.056) [56.2]	−0.041 (0.090) [25.6]	−0.044 (0.061) [56.6]	−0.045 (0.086) [32.9]	0.826	112,163
Primary series, share	4–35	+0.021 (0.062) [56.6]	+0.061 (0.100) [26.3]	+0.015 (0.061) [57.1]	+0.034 (0.085) [34.2]	0.879	99,664
MCV-1	9–35	+0.053 (0.112) [44.6]	+0.121 (0.190) [17.6]	+0.015 (0.102) [48.2]	+0.042 (0.146) [26.8]	0.868	70,321
16–24-month doses, share	16–35	+0.219* (0.121) [50.6]	+0.357* (0.192) [25.6]	+0.325*** (0.123) [50.8]	+0.446*** (0.169) [33.5]	0.584	60,806
MCV-2	16–35	+0.260** (0.127) [51.5]	+0.414** (0.202) [26.1]	+0.305** (0.130) [51.2]	+0.417** (0.177) [33.8]	0.551	61,281
DPT booster	16–35	+0.188 (0.139) [50.7]	+0.312 (0.218) [25.5]	+0.352** (0.144) [50.8]	+0.484** (0.199) [33.4]	0.617	60,913

Notes. Sample: children in the analytical sample whose cluster has a value of the travel-time raster (113,185 children); within each row, the baseline and the specification with the added control are estimated on the same observations. Panel A reports a weighted regression of $\log(1 + x)$ of motorized travel time in minutes to the nearest health facility (Malaria Atlas Project 2020 raster, sampled at the released cluster coordinate) on the Terrain Ruggedness Index (per 10 units), with the baseline controls, fixed effects for the child's exact age in completed months and for the calendar month of interview and district or state fixed effects. Panel B reports 2SLS estimates of the effect of local 3G coverage, instrumented by the index, without (baseline) and with this variable added to the controls. The stage outcomes are the shares of the stage's doses received, estimated among children old enough for every dose of the stage (birth doses: BCG, OPV-0, HepB-0; primary series: DPT-1 to DPT-3 and OPV-1 to OPV-3; 16–24-month doses: MCV-2 and DPT booster); MCV-1, MCV-2 and the DPT booster are estimated among children who have reached their minimum age. All specifications include the controls of Table 3 and fixed effects for the child's exact age in completed months and for the calendar month of interview; estimates are weighted with normalized DHS survey weights; "Mean, 3G = 0" is the weighted mean of the outcome in uncovered clusters. Standard errors clustered at the DHS cluster level in parentheses; cluster-robust first-stage F in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

E Heterogeneous effects by household wealth

Table E1: Heterogeneity by household wealth

	District FE (benchmark)			State FE			Mean, 3G = 0 (<i>N</i>)	
	(1) Q1–2	(2) Q3–5	(3) Diff.	(4) Q1–2	(5) Q3–5	(6) Diff.	Q1–2	Q3–5
<i>Panel A: Doses due at 16–24 months</i>								
Share of the two doses received	+0.643*** (0.223) [35.8]	−0.094 (0.135) [28.0]	+0.737*** (0.254) {0.004}	+0.863*** (0.246) [36.7]	+0.015 (0.131) [27.9]	+0.848*** (0.272) {0.002}	0.557 28,565	0.617 32,273
Both doses received	+0.748*** (0.247) [35.8]	−0.087 (0.167) [28.0]	+0.834*** (0.291) {0.004}	+1.012*** (0.273) [36.7]	+0.013 (0.161) [27.9]	+0.999*** (0.309) {0.001}	0.463 28,565	0.514 32,273
MCV-2	+0.471** (0.217) [35.7]	+0.082 (0.164) [28.9]	+0.390 (0.271) {0.151}	+0.707*** (0.241) [35.9]	+0.099 (0.155) [28.9]	+0.608** (0.283) {0.032}	0.526 28,833	0.581 32,480
DPT booster	+0.838*** (0.270) [36.3]	−0.262* (0.145) [28.0]	+1.101*** (0.298) {< 0.001}	+1.057*** (0.300) [36.7]	−0.072 (0.139) [27.9]	+1.129*** (0.323) {< 0.001}	0.587 28,622	0.652 32,323
<i>Panel B: Within-child completion</i>								
16–24-month stage	+0.614*** (0.209) [32.9]	−0.030 (0.131) [25.6]	+0.644*** (0.235) {0.006}	+0.753*** (0.207) [35.8]	+0.104 (0.131) [25.8]	+0.648*** (0.236) {0.006}	−0.274 53,788	−0.261 60,523
Primary series	+0.076 (0.084) [41.5]	+0.006 (0.062) [32.2]	+0.070 (0.100) {0.481}	+0.026 (0.091) [45.0]	+0.016 (0.058) [31.3]	+0.009 (0.100) {0.925}	−0.087 69,865	−0.058 79,480
<i>Panel C: Doses due in the first year of life</i>								
Birth doses, share received	−0.043 (0.103) [47.8]	−0.079 (0.068) [30.1]	+0.036 (0.121) {0.766}	−0.061 (0.138) [41.6]	−0.036 (0.064) [30.4]	−0.025 (0.148) {0.866}	0.801 52,389	0.856 59,838
Primary series, share received	+0.095 (0.104) [47.3]	−0.045 (0.066) [31.5]	+0.140 (0.121) {0.248}	+0.014 (0.138) [44.9]	+0.020 (0.064) [31.1]	−0.006 (0.150) {0.968}	0.856 46,505	0.906 53,215

Notes. The sample is split by the household’s DHS wealth quintile: bottom two quintiles (52,951 children) or top three (60,298). The pattern is the same when households are classified, and the wealth control is measured, with an asset index that excludes mobile phones, landlines, internet access and computers (Section 6): with district fixed effects, the effect on the share of the doses due at 16–24 months is 0.614 in the bottom two quintiles, significant at the 1 percent level, and small and statistically insignificant in the top three; the difference is significant at the 5 percent level. Columns (1), (2), (4) and (5): 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, estimated separately in each group, with standard errors clustered at the DHS cluster level in parentheses and the group’s cluster-robust first-stage *F* in brackets. Columns (3) and (6): difference between the two group coefficients (column 1 minus column 2; column 4 minus column 5) from a fully interacted stacked 2SLS model, in which treatment, instrument, controls, fixed effects for the child’s exact age in completed months and for the calendar month of interview and district or state fixed effects are all group-specific, so that the group coefficients coincide with the separate estimates; standard error clustered at the DHS cluster level in parentheses and stars from that test; in braces, the *p*-value of that test. Levels are estimated among the children who have reached the minimum age of every dose of the stage (16–35 months for the doses due at 16–24 months, 4–35 months for the primary series and 0–35 months for the birth doses). Panel B reports the common coefficient of the stacked within-child differences of the stage’s dose pairs (MCV-1 → MCV-2 and DPT-3 → DPT booster, children aged 16–35 months; DPT-1 → DPT-3 and OPV-1 → OPV-3, children aged 12–35 months), with pair-specific controls and fixed effects; its *N* counts child-pair observations and its mean is the mean within-child difference. All specifications include the controls of Table 3 and fixed effects for the child’s exact age in completed months and for the calendar month of interview; estimates are weighted with normalized DHS survey weights. The last two columns report the weighted mean of the outcome in uncovered clusters and the number of observations in each group. Because these are linear 2SLS coefficients, subgroup estimates are not constrained to the unit interval. **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

F Heterogeneous effects by reported symptoms

Table F1 splits the sample by the share of the other sampled children under 36 months in the same DHS cluster who had diarrhoea (NFHS-5 item h11) or fever (h22) in the two weeks before the interview. Because the median of both shares is zero, the comparison is between children for whom at least one other sampled child in the cluster had the symptom and

the remaining children. These are syndromic proxies for the local disease environment and do not measure the diseases prevented by the doses we study. For the doses due at 16–24 months, the estimates are positive in both groups of every split, and none of the differences between groups is significant at the 5 percent level. With district fixed effects, the estimates are larger among children for whom another sampled child in the cluster had fever, with differences significant at the 10 percent level for the share of the doses received and for the DPT booster; these differences disappear with state fixed effects, and the ordering of the groups is not stable across outcomes and specifications.

Table F1: Heterogeneity by reported symptoms among other children in the cluster

	District FE (benchmark)			State FE			Mean, 3G = 0 (N)	
	(1) High	(2) Low	(3) Diff.	(4) High	(5) Low	(6) Diff.	High	Low
Diarrhoea								
<i>Panel A: Doses due at 16–24 months</i>								
Share of the two doses received	+0.373 (0.229) [22.8]	+0.122 (0.139) [39.2]	+0.251 (0.267) {0.348}	+0.342 (0.229) [22.2]	+0.339** (0.151) [33.3]	+0.003 (0.273) {0.991}	0.567 18,860	0.593 40,532
Both doses received	+0.490* (0.262) [22.8]	+0.165 (0.162) [39.2]	+0.325 (0.308) {0.292}	+0.334 (0.257) [22.2]	+0.392** (0.176) [33.3]	−0.059 (0.310) {0.850}	0.467 18,860	0.496 40,532
MCV-2	+0.400* (0.220) [23.9]	+0.131 (0.157) [39.7]	+0.269 (0.275) {0.327}	+0.263 (0.217) [22.7]	+0.315* (0.168) [33.5]	−0.052 (0.277) {0.851}	0.530 19,074	0.562 40,783
DPT booster	+0.338 (0.284) [22.8]	+0.128 (0.150) [39.2]	+0.210 (0.317) {0.508}	+0.419 (0.299) [22.2]	+0.375** (0.165) [33.3]	+0.044 (0.337) {0.897}	0.605 18,894	0.622 40,604
<i>Panel B: Doses due in the first year of life</i>								
Birth doses, share received	−0.143 (0.130) [18.4]	+0.012 (0.063) [45.7]	−0.156 (0.145) {0.284}	−0.084 (0.119) [20.3]	+0.023 (0.073) [38.9]	−0.107 (0.139) {0.441}	0.806 34,947	0.836 74,749
Primary series, share received	+0.098 (0.145) [19.5]	−0.005 (0.059) [44.7]	+0.103 (0.156) {0.509}	+0.033 (0.144) [20.0]	+0.045 (0.065) [38.7]	−0.011 (0.158) {0.942}	0.863 31,097	0.886 66,318
Fever								
<i>Panel A: Doses due at 16–24 months</i>								
Share of the two doses received	+0.522** (0.237) [20.2]	+0.050 (0.126) [45.3]	+0.472* (0.269) {0.079}	+0.321* (0.189) [26.5]	+0.324** (0.154) [31.8]	−0.003 (0.241) {0.990}	0.567 25,032	0.598 34,362
Both doses received	+0.551** (0.266) [20.2]	+0.126 (0.154) [45.3]	+0.425 (0.306) {0.165}	+0.294 (0.206) [26.5]	+0.433** (0.186) [31.8]	−0.139 (0.273) {0.611}	0.466 25,032	0.504 34,362
MCV-2	+0.502** (0.243) [20.6]	+0.097 (0.143) [45.6]	+0.405 (0.283) {0.152}	+0.201 (0.188) [26.8]	+0.381** (0.177) [31.6]	−0.179 (0.260) {0.490}	0.527 25,300	0.571 34,559
DPT booster	+0.538** (0.274) [20.2]	+0.026 (0.140) [45.5]	+0.513* (0.307) {0.096}	+0.436* (0.238) [26.2]	+0.289* (0.166) [32.0]	+0.147 (0.287) {0.609}	0.607 25,079	0.624 34,421
<i>Panel B: Doses due in the first year of life</i>								
Birth doses, share received	+0.031 (0.097) [23.8]	−0.122** (0.061) [47.0]	+0.154 (0.114) {0.176}	−0.005 (0.103) [27.9]	−0.066 (0.070) [34.4]	+0.061 (0.123) {0.620}	0.807 46,362	0.841 63,335
Primary series, share received	+0.091 (0.108) [23.2]	−0.060 (0.060) [46.9]	+0.150 (0.123) {0.220}	+0.025 (0.106) [27.9]	+0.014 (0.065) [34.2]	+0.010 (0.122) {0.933}	0.868 41,292	0.887 56,124

Notes. Each child is classified by the leave-one-out share of the other sampled children under 36 months in the same DHS cluster who had diarrhoea (NFHS-5 item h11) or fever (h22) in the two weeks before the interview. Because the median of both shares is zero, “High” means that at least one other sampled child in the cluster had the symptom. Children with no other sampled child under 36 months in the cluster, for whom the leave-one-out share is undefined, are excluded. Columns (1), (2), (4) and (5): 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, estimated separately in each group, with standard errors clustered at the DHS cluster level in parentheses and the group’s cluster-robust first-stage F in brackets. Columns (3) and (6): difference between the two group coefficients (column 1 minus column 2; column 4 minus column 5) from a fully interacted stacked 2SLS model, in which treatment, instrument, controls, fixed effects for the child’s exact age in completed months and for the calendar month of interview and district or state fixed effects are all group-specific, so that the group coefficients coincide with the separate estimates; standard error clustered at the DHS cluster level in parentheses and stars from that test; in braces, the p -value of that test. Levels are estimated among the children who have reached the minimum age of every dose of the stage (16–35 months for the doses due at 16–24 months, 4–35 months for the primary series and 0–35 months for the birth doses). All specifications include the controls of Table 3 and fixed effects for the child’s exact age in completed months and for the calendar month of interview; estimates are weighted with normalized DHS survey weights. The last two columns report the weighted mean of the outcome in uncovered clusters and the number of observations in each group. Because these are linear 2SLS coefficients, subgroup estimates are not constrained to the unit interval. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

G Further sensitivity and robustness checks

Table G1: Alternative measures of local 3G coverage: district fixed effects

Outcome	(1) Point coverage	(2) Area share, DHS buffer	(3) Population share, DHS buffer	(4) Any covered pixel, DHS buffer	(5) Area share, 10 km
<i>Panel A: Doses due at 16–24 months</i>					
16–24-month stage (completion)	+0.230** (0.113) [46.7]	+0.426** (0.213) [27.9]	+0.465* (0.248) [18.4]	+0.500 (0.312) [8.6]	+0.777* (0.422) [17.6]
16–24 months: share of doses re- ceived	+0.218* (0.121) [50.5]	+0.413* (0.234) [28.7]	+0.463 (0.282) [17.8]	+0.505 (0.348) [7.8]	+0.728* (0.435) [19.5]
MCV-2	+0.258** (0.127) [51.3]	+0.494** (0.250) [28.6]	+0.553* (0.300) [17.8]	+0.600 (0.369) [7.9]	+0.875* (0.474) [19.3]
DPT booster	+0.188 (0.139) [50.6]	+0.355 (0.267) [28.7]	+0.399 (0.316) [17.8]	+0.433 (0.376) [7.9]	+0.627 (0.485) [19.5]
<i>Panel B: Earlier stages of the schedule</i>					
Primary series (completion)	+0.032 (0.050) [59.6]	+0.061 (0.096) [32.7]	+0.067 (0.107) [21.0]	+0.073 (0.117) [9.0]	+0.107 (0.171) [22.7]
Birth: share of doses received	−0.037 (0.056) [56.0]	−0.069 (0.106) [30.9]	−0.078 (0.117) [20.9]	−0.089 (0.137) [9.0]	−0.132 (0.201) [20.5]
6–14 weeks: share of doses received	+0.021 (0.062) [56.4]	+0.041 (0.119) [30.0]	+0.046 (0.136) [19.9]	+0.052 (0.153) [8.7]	+0.076 (0.221) [20.8]
9–12 months: MCV-1	+0.055 (0.112) [44.5]	+0.098 (0.200) [28.0]	+0.102 (0.211) [21.3]	+0.106 (0.221) [11.0]	+0.191 (0.391) [16.5]
Mean of the coverage measure	0.29	0.27	0.30	0.49	0.22

Notes. 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, under five definitions of coverage (Section 3.3): (1) coverage of the raster pixel containing the released cluster coordinate (baseline); (2) share of the area and (3) share of the population covered within the standard DHS displacement radius (2 km for urban and 5 km for rural clusters), with population from WorldPop 2018; (4) indicator for at least one covered pixel within the same buffer; (5) share of the area covered within 10 km. Standard errors, clustered at the DHS cluster level, in parentheses; cluster-robust first-stage F -statistics in brackets. Completion outcomes are the common coefficients of Table 5, Panel B; the other outcomes are levels on age-appropriate samples, with the stages of the schedule defined in Section 3.2. All specifications include district fixed effects, fixed effects for the child’s exact age in completed months and for the calendar month of interview (pair-specific in the completion models) and the controls of Table 5, and are weighted with normalized DHS survey weights. Coefficients on the binary measures (1) and (4) and on the shares (2), (3) and (5) refer to different changes in coverage and are not comparable in magnitude. Conventional significance stars are not reported for column (4) because its first stage is weak; inference for that column is based on cluster-robust Anderson–Rubin 95 percent confidence sets, which are $[+0.06, +2.02]$ for the 16–24-month completion coefficient, $[+0.05, +2.43]$ for MCV-2 and $[-0.01, +2.26]$ for the share of 16–24-month doses received (computed on a grid from -5 to $+5$). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table G2: Alternative measures of local 3G coverage: state fixed effects

Outcome	(1) Point coverage	(2) Area share, DHS buffer	(3) Population share, DHS buffer	(4) Any covered pixel, DHS buffer	(5) Area share, 10 km
<i>Panel A: Doses due at 16–24 months</i>					
16–24-month stage (completion)	+0.362*** (0.116) [47.9]	+0.553*** (0.180) [35.8]	+0.644*** (0.231) [21.6]	+0.807 (0.391) [7.6]	+0.737*** (0.245) [35.6]
16–24 months: share of doses re- ceived	+0.327*** (0.123) [50.7]	+0.515*** (0.200) [35.7]	+0.612** (0.262) [20.6]	+0.785 (0.432) [6.8]	+0.670** (0.265) [36.8]
MCV-2	+0.308** (0.130) [51.1]	+0.489** (0.209) [35.5]	+0.583** (0.268) [20.4]	+0.749 (0.427) [6.7]	+0.637** (0.278) [36.6]
DPT booster	+0.353** (0.145) [50.7]	+0.556** (0.236) [35.8]	+0.660** (0.308) [20.7]	+0.841 (0.491) [6.9]	+0.723** (0.311) [36.8]
<i>Panel B: Earlier stages of the schedule</i>					
Primary series (completion)	+0.008 (0.051) [59.1]	+0.012 (0.079) [42.3]	+0.014 (0.094) [24.3]	+0.019 (0.123) [7.6]	+0.016 (0.104) [41.9]
Birth: share of doses received	−0.043 (0.061) [56.6]	−0.066 (0.093) [44.4]	−0.079 (0.111) [25.1]	−0.112 (0.160) [7.2]	−0.092 (0.130) [41.3]
6–14 weeks: share of doses received	+0.016 (0.061) [57.0]	+0.024 (0.094) [43.5]	+0.029 (0.114) [24.9]	+0.040 (0.156) [7.5]	+0.033 (0.130) [41.6]
9–12 months: MCV-1	+0.016 (0.102) [48.2]	+0.023 (0.146) [40.9]	+0.026 (0.166) [26.7]	+0.033 (0.204) [10.1]	+0.033 (0.205) [37.9]
Mean of the coverage measure	0.29	0.27	0.30	0.49	0.22

Notes. 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index, under five definitions of coverage (Section 3.3): (1) coverage of the raster pixel containing the released cluster coordinate (baseline); (2) share of the area and (3) share of the population covered within the standard DHS displacement radius (2 km for urban and 5 km for rural clusters), with population from WorldPop 2018; (4) indicator for at least one covered pixel within the same buffer; (5) share of the area covered within 10 km. Standard errors, clustered at the DHS cluster level, in parentheses; cluster-robust first-stage F -statistics in brackets. Completion outcomes are the common coefficients of Table 5, Panel B; the other outcomes are levels on age-appropriate samples, with the stages of the schedule defined in Section 3.2. All specifications include state fixed effects, fixed effects for the child's exact age in completed months and for the calendar month of interview (pair-specific in the completion models) and the controls of Table 5, and are weighted with normalized DHS survey weights. Coefficients on the binary measures (1) and (4) and on the shares (2), (3) and (5) refer to different changes in coverage and are not comparable in magnitude. Conventional significance stars are not reported for column (4) because its first stage is weak; inference for that column is based on cluster-robust Anderson–Rubin 95 percent confidence sets, which are [+0.30, +3.13] for the 16–24-month completion coefficient, [+0.15, +3.51] for MCV-2 and [+0.22, +3.68] for the share of 16–24-month doses received (computed on a grid from −5 to +5). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table G3: OLS estimates under alternative measures of local 3G coverage

Outcome	(1) Point coverage	(2) Area share, DHS buffer	(3) Population share, DHS buffer	(4) Area share, 10 km
<i>Panel A: District fixed effects (benchmark)</i>				
Birth doses: share received	−0.005 (0.005)	−0.005 (0.009)	−0.005 (0.008)	+0.012 (0.014)
Primary series: share received	−0.014*** (0.005)	−0.016* (0.009)	−0.017** (0.008)	+0.006 (0.015)
MCV-1	−0.005 (0.007)	−0.005 (0.013)	−0.003 (0.012)	+0.024 (0.021)
16–24-month doses: share received	−0.006 (0.008)	−0.002 (0.015)	−0.009 (0.014)	+0.023 (0.023)
MCV-2	−0.003 (0.009)	−0.003 (0.017)	−0.009 (0.015)	+0.020 (0.027)
DPT booster	−0.007 (0.009)	+0.002 (0.017)	−0.006 (0.015)	+0.028 (0.026)
<i>Panel B: State fixed effects</i>				
Birth doses: share received	−0.007 (0.005)	−0.010 (0.009)	−0.007 (0.008)	−0.006 (0.012)
Primary series: share received	−0.009* (0.005)	−0.005 (0.010)	−0.004 (0.008)	+0.012 (0.013)
MCV-1	−0.004 (0.008)	−0.002 (0.016)	+0.001 (0.013)	+0.010 (0.022)
16–24-month doses: share received	−0.002 (0.008)	+0.004 (0.015)	+0.001 (0.013)	+0.015 (0.020)
MCV-2	+0.005 (0.009)	+0.012 (0.016)	+0.009 (0.015)	+0.022 (0.021)
DPT booster	−0.008 (0.009)	−0.005 (0.016)	−0.006 (0.015)	+0.007 (0.022)

Notes. OLS estimates of the effect of local 3G coverage on the stage-level shares and on MCV-1, MCV-2 and the DPT booster of Table 3, on the same age-appropriate samples, under four definitions of coverage (Section 3.3): (1) coverage of the raster pixel containing the released cluster coordinate (baseline); (2) share of the area and (3) share of the population covered within the standard DHS displacement radius (2 km for urban and 5 km for rural clusters); (4) share of the area covered within 10 km. The corresponding 2SLS estimates are reported in Tables G1 and G2. All specifications include fixed effects for the child's exact age in completed months and for the calendar month of interview, the controls of Table 3 and district or state fixed effects, and are weighted with normalized DHS survey weights. Standard errors, clustered at the DHS cluster level, in parentheses.

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

Table G4: Japanese encephalitis vaccination: programme and other districts

	(1)	(2)
	JE-programme districts	Other districts
Districts	173	435
Share of districts	0.28	0.72
Children	34,759	78,490
Share of children (weighted)	0.36	0.64
Mean Terrain Ruggedness Index	2.76	5.77
Mean 3G coverage	0.22	0.33
First-stage F , district fixed effects	0.1	73.7
First-stage F , state fixed effects	1.2	71.0
JE-1 received (children aged 9–35 months)	0.70	0.19
JE-2 received (children aged 16–35 months)	0.55	0.14

Notes. Analytical sample (living children under 36 months). JE-programme districts are the NFHS-5 districts in which Japanese encephalitis vaccination is part of the routine immunization schedule. They are identified from the official lists of JE-endemic and JE-vaccination districts published by the Ministry of Health and Family Welfare and the National Vector Borne Disease Control Programme in 2011–2014, the most recent lists that name the districts, and checked against the Ministry’s counts, by state, of the districts with JE vaccination in routine immunization in September 2019. The two sources agree in all but nine states. Where the 2019 count covers all the districts of a state, all are classified as programme districts; where the named districts and the 2019 count differ and the documents do not identify the districts concerned, the classification follows the named lists, except that districts in states absent from the 2019 counts are classified as non-programme districts. The first-stage F is the cluster-robust F -statistic of the Terrain Ruggedness Index (per 10 units) in the regression of 3G coverage on the index, the individual and cluster-level controls, fixed effects for the child’s exact age in completed months and for the calendar month of interview and district or state fixed effects, estimated separately in each group of districts. Means are weighted with normalized DHS survey weights.

Table G5: Results under alternative codings of undated card entries for MCV-1

Outcome	Undated card entries for MCV-1 coded as		
	(1) Missing (baseline)	(2) Received	(3) Not received
<i>Panel A: District fixed effects (benchmark)</i>			
16–24-month stage (completion)	+0.230** (0.113) [46.7]	+0.218** (0.105) [50.9]	+0.192* (0.101) [50.9]
MCV-1 to MCV-2 (completion)	+0.271* (0.148) [40.4]	+0.237* (0.123) [51.3]	+0.184 (0.122) [51.3]
MCV-1 received	+0.055 (0.112) [44.5]	+0.040 (0.085) [56.7]	+0.085 (0.114) [56.7]
<i>Panel B: State fixed effects</i>			
16–24-month stage (completion)	+0.362*** (0.116) [47.9]	+0.336*** (0.111) [50.9]	+0.305*** (0.102) [50.9]
MCV-1 to MCV-2 (completion)	+0.354** (0.145) [42.6]	+0.305** (0.128) [51.1]	+0.242** (0.119) [51.1]
MCV-1 received	+0.016 (0.102) [48.2]	−0.004 (0.079) [57.4]	+0.076 (0.118) [57.4]
Mean of MCV-1 received	0.861	0.883	0.721

Notes. 2SLS estimates of the effect of 3G coverage, instrumented by the Terrain Ruggedness Index. For MCV-1, NFHS-5 includes a response category, specific to India, that is used only when the vaccination card was seen and that records no date for the dose (Section 3.2); it applies to 13,067 of the 84,011 children aged 9–35 months in the analytical sample. Column (1) treats these entries as missing, as in all other tables; columns (2) and (3) code them as received and as not received. The 16–24-month completion coefficient is the common coefficient of Table 5, Panel B, estimated on the dose pairs from MCV-1 to MCV-2 and from DPT-3 to the DPT booster among children aged 16–35 months; the MCV-1 to MCV-2 row reports the corresponding pair-specific estimate; MCV-1 received is estimated among children aged 9–35 months. All specifications include the controls of Table 5, fixed effects for the child’s exact age in completed months and for the calendar month of interview (pair-specific in the stacked model) and district or state fixed effects, and are weighted with normalized DHS survey weights. Standard errors, clustered at the DHS cluster level, in parentheses; cluster-robust first-stage F -statistics in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

H Household connectivity and basic mobile coverage: additional evidence

This appendix reports the additional evidence discussed in Section 6: the reduced-form relationship between terrain ruggedness and vaccination by the mother’s mobile phone ownership in the NFHS-5 state-module subsample (Table H1), and the estimates that account for basic

mobile (2G) coverage (Table H2).

Table H1: Ruggedness and vaccination by the mother's mobile phone ownership (state-module subsample)

	Reduced form (TRI)		Difference (owns – not)	Mean, 3G = 0		N	
	Owens	Does not		Owens	Does not	Owens	Does not
<i>District FE (benchmark)</i>							
16–24-month doses, share received	+0.0150 (0.0092)	–0.0048 (0.0113)	+0.0198 (0.0138) {0.150}	0.594	0.558	5,292	4,028
Both 16–24-month doses received	+0.0191* (0.0115)	–0.0111 (0.0133)	+0.0303* (0.0162) {0.062}	0.497	0.459	5,292	4,028
MCV-2	+0.0250** (0.0108)	+0.0055 (0.0131)	+0.0195 (0.0164) {0.236}	0.566	0.515	5,327	4,057
DPT booster	+0.0046 (0.0105)	–0.0157 (0.0134)	+0.0202 (0.0154) {0.188}	0.623	0.600	5,297	4,035
Birth doses, share received	–0.0009 (0.0040)	–0.0053 (0.0055)	+0.0044 (0.0067) {0.515}	0.837	0.820	9,704	7,422
Primary series, share received	–0.0030 (0.0039)	–0.0053 (0.0058)	+0.0023 (0.0068) {0.736}	0.889	0.878	8,632	6,548
<i>State FE</i>							
16–24-month doses, share received	–0.0012 (0.0074)	+0.0028 (0.0105)	–0.0039 (0.0120) {0.743}	0.594	0.558	5,292	4,028
Both 16–24-month doses received	+0.0015 (0.0093)	–0.0070 (0.0121)	+0.0084 (0.0140) {0.547}	0.497	0.459	5,292	4,028
MCV-2	+0.0054 (0.0087)	+0.0021 (0.0122)	+0.0033 (0.0145) {0.818}	0.566	0.515	5,327	4,057
DPT booster	–0.0080 (0.0085)	+0.0032 (0.0115)	–0.0113 (0.0128) {0.378}	0.623	0.600	5,297	4,035
Birth doses, share received	+0.0025 (0.0031)	–0.0031 (0.0051)	+0.0056 (0.0058) {0.335}	0.837	0.820	9,704	7,422
Primary series, share received	–0.0013 (0.0030)	–0.0081* (0.0049)	+0.0068 (0.0056) {0.225}	0.889	0.878	8,632	6,548

Notes. The sample is restricted to the children of women in the households selected for the NFHS-5 state module (about 15 percent of households in every state), the only women asked whether they have a mobile phone that they themselves use, and is split by the answer. Each outcome is estimated among children who have reached the minimum age at which the doses become due (Section 4.3). The first two columns report the reduced-form coefficient of the outcome on the Terrain Ruggedness Index (per 10 units), estimated separately in each group. The third column reports the difference between the two coefficients (owners minus non-owners), from a pooled model in which the ruggedness coefficient, the controls, the fixed effects for the child's exact age in completed months and for the calendar month of interview and the district or state fixed effects are all group-specific, with its p -value in braces. Group-specific 2SLS estimates are not reported because the first stage within each group is weak (cluster-robust F between 3 and 17). The last four columns report the weighted mean of the outcome among children in uncovered clusters and number of children in each group. All specifications include mother's age and its square, years of schooling, wealth quintile, an indicator for urban clusters, cluster-level controls for elevation, nighttime lights, temperature, precipitation and travel time to the nearest city, fixed effects for the child's exact age in completed months and for the calendar month of interview, and district or state fixed effects, and are weighted with normalized DHS survey weights. Standard errors, clustered at the DHS cluster level, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table H2: 3G coverage, basic mobile coverage and the doses due at 16–24 months

		2G coverage as a control		Within clusters with 2G coverage	
Outcome	(1) Benchmark	(2) 2G, 2018 release	(3) 2G, 2014 release	(4) 2G, 2018 release	(5) 2G, 2014 release
<i>Panel A: District FE (benchmark)</i>					
16–24-month doses, share	+0.218* (0.121) [50.5] N 60,838; 0.584	+0.223* (0.125) [48.6]	+0.202 (0.133) [44.7]	+0.240 (0.170) [32.7] N 48,078; 0.581	+0.073 (0.179) [20.6] N 50,187; 0.584
16–24-month doses, both received	+0.274** (0.140) [50.5] N 60,838; 0.486	+0.277* (0.144) [48.6]	+0.244 (0.153) [44.7]	+0.267 (0.193) [32.7] N 48,078; 0.480	+0.103 (0.212) [20.6] N 50,187; 0.484
MCV-2	+0.258** (0.127) [51.3] N 61,313; 0.551	+0.261** (0.132) [49.4]	+0.242* (0.141) [45.5]	+0.326* (0.177) [33.5] N 48,489; 0.545	+0.151 (0.213) [21.2] N 50,611; 0.549
DPT booster	+0.188 (0.139) [50.6] N 60,945; 0.617	+0.194 (0.144) [48.6]	+0.175 (0.152) [44.7]	+0.164 (0.196) [32.7] N 48,168; 0.615	+0.004 (0.188) [20.5] N 50,276; 0.617
Birth doses, share	−0.037 (0.056) [56.0] N 112,227; 0.826	−0.036 (0.057) [53.6]	−0.041 (0.061) [49.4]	−0.059 (0.072) [40.2] N 88,526; 0.821	−0.078 (0.081) [23.6] N 92,471; 0.820
Primary series, share	+0.021 (0.062) [56.4] N 99,720; 0.879	+0.026 (0.064) [54.0]	+0.026 (0.068) [49.4]	+0.088 (0.088) [40.3] N 79,017; 0.877	−0.007 (0.085) [24.8] N 82,424; 0.876
Completion, 16–24-month stage	+0.230** (0.113) [46.7] N 114,311; −0.268	+0.237** (0.117) [44.6]	+0.210* (0.124) [41.3]	+0.221 (0.161) [28.2] N 90,296; −0.269	+0.163 (0.188) [16.8] N 94,234; −0.266
Completion, primary series	+0.032 (0.050) [59.6] N 149,345; −0.074	+0.023 (0.051) [57.5]	+0.038 (0.055) [53.0]	+0.089 (0.070) [44.0] N 118,353; −0.076	+0.167* (0.098) [25.4] N 123,438; −0.077
<i>Panel B: State FE</i>					
16–24-month doses, share	+0.327*** (0.123) [50.7] N 60,838; 0.584	+0.348*** (0.130) [47.3]	+0.329** (0.135) [44.8]	+0.309** (0.152) [35.9] N 48,078; 0.581	+0.280* (0.161) [25.6] N 50,187; 0.584
16–24-month doses, both received	+0.371*** (0.141) [50.7] N 60,838; 0.486	+0.394*** (0.150) [47.3]	+0.357** (0.154) [44.8]	+0.313* (0.173) [35.9] N 48,078; 0.480	+0.288 (0.187) [25.6] N 50,187; 0.484
MCV-2	+0.308** (0.130) [51.1] N 61,313; 0.551	+0.329** (0.138) [47.7]	+0.308** (0.143) [45.1]	+0.322** (0.158) [36.8] N 48,489; 0.545	+0.268 (0.182) [26.3] N 50,611; 0.549
DPT booster	+0.353** (0.145) [50.7] N 60,945; 0.617	+0.374** (0.153) [47.3]	+0.360** (0.158) [44.7]	+0.302* (0.182) [35.9] N 48,168; 0.615	+0.293* (0.176) [25.5] N 50,276; 0.617
Birth doses, share	−0.043 (0.061) [56.6] N 112,227; 0.826	−0.037 (0.064) [52.0]	−0.029 (0.067) [49.5]	−0.101 (0.074) [43.0] N 88,526; 0.821	−0.102 (0.076) [28.4] N 92,471; 0.820
Primary series, share	+0.016 (0.061) [57.0] N 99,720; 0.879	+0.018 (0.064) [52.6]	+0.028 (0.067) [49.6]	+0.027 (0.079) [44.7] N 79,017; 0.877	−0.039 (0.074) [29.8] N 82,424; 0.876
Completion, 16–24-month stage	+0.362*** (0.116) [47.9] N 114,311; −0.268	+0.386*** (0.124) [44.3]	+0.353*** (0.126) [42.0]	+0.384** (0.152) [32.6] N 90,296; −0.269	+0.440** (0.175) [22.8] N 94,234; −0.266
Completion, primary series	+0.008 (0.051) [59.1] N 149,345; −0.074	+0.003 (0.053) [54.9]	+0.017 (0.056) [51.9]	+0.027 (0.063) [45.8] N 118,353; −0.076	+0.094 (0.077) [29.5] N 123,438; −0.077

Notes. 2SLS estimates of the effect of local 3G coverage, instrumented by the Terrain Ruggedness Index (per 10 units), with standard errors clustered at the DHS cluster level in parentheses and the cluster-robust first-stage F in brackets. Basic mobile (2G) coverage is measured like 3G coverage: an indicator equal to one if the raster pixel containing the released cluster coordinate is covered in the 2G layer of the Mobile Coverage Explorer, in the 2018 release (the same release as the 3G layer) and in the 2014 release. In the analytical sample, 15 percent of children live in clusters with no mobile coverage in 2018, 56 percent in clusters with 2G but not 3G coverage and 29 percent in clusters with 3G coverage (almost all of which also have 2G coverage). Column (1) is the benchmark specification (Tables 3 and 5). Columns (2) and (3) add the 2G indicator to the controls (pair-specific in the completion models). Columns (4) and (5) restrict the sample to clusters with 2G coverage in the 2018 and 2014 releases before estimation. Because 2G coverage is itself strongly related to terrain (the cluster-robust F -statistic on ruggedness in a regression of the 2G indicator is 64 for 2018 and 122 for 2014 with district fixed effects), these estimates address the role of basic mobile service without decomposing the effects of the two technologies. Within the 2G-covered clusters, the first-stage F -statistic in the sample of all children aged 0–35 months is 40.2 (2018) and 23.6 (2014) with district fixed effects, and 43.0 and 28.4 with state fixed effects. Level outcomes are estimated among children who have reached the minimum age of every dose of the stage, as in Table 3. The completion rows report the common coefficient of the stacked within-child differences of the stage’s dose pairs, as in Table 5, Panel B; their N counts child-pair observations and their mean is the mean within-child difference. Below each estimate in columns (1), (4) and (5): the number of observations and the weighted mean of the outcome among children in clusters without 3G coverage. All specifications include the controls of Table 3 and fixed effects for the child’s exact age in completed months and for the calendar month of interview; estimates are weighted with normalized DHS survey weights. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.