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MODELING THE EFFECTS OF IMMUNIZATIONS TIMING ON CHILD HEALTH OUTCOMES IN INDIA

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SUMMARY

Timely vaccinations of children in developing countries are important for reducing morbidity and mortality, which are Millennium Development Goals. However, a majority of children do not possess vaccination cards compiling information on timing. We investigated the benefits of vaccination cards for the uptake of immunizations against diphtheria, pertussis and tetanus (DPT), polio, tuberculosis (BCG), and measles using data on over 200,000 Indian children from the District Level Health and Facility Survey 3. Methodological issues such as whether parents of children with higher morbidity levels may have them vaccinated were investigated. The results from the models for DPT, polio, measles, and BCG vaccinations showed significant beneficial effects of maternal education, household possessions, and access to health care facilities. Moreover, models for children's ages at the time of vaccination showed significant interactions between maternal education and access to and availability of health care facilities. Finally, models for child morbidity due to diarrhea, cough, and fever showed that timely vaccinations against DPT, access to piped water, and cooking with electricity or natural gas were associated with lower morbidity. Overall, issuing paper or electronic vaccination cards to children is likely to enhance timely uptake of various immunizations thereby reducing child morbidity.

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1. INTRODUCTION

In the *Millennium Declaration*, the United Nations member states and international organizations agreed to attain eight developmental goals (United Nations, 2009). Reducing maternal and child mortality and improving child health via immunization programs were rightly among the top priorities. While many less developed countries are likely to fall short in meeting the targets, analyses of demographic data can provide insights into the synergisms between diverse factors affecting child health for the formulation of cost-effective policies. For example, resources expended on postnatal care such as vaccinating children against diphtheria, pertussis and tetanus (DPT), polio, tuberculosis (i.e., BCG), and measles enhance their immunity systems and reduce morbidity (Scrimshaw *et al*., 1959). Lower morbidity, in turn, reduces nutrient loss and is likely to promote physical growth (Bhargava *et al*., 2011). At low-income levels, children's physical and cognitive developments are intertwined so that immunization programs are likely to have long-term benefits for economic development (Bhargava *et al*., 2001).

While children in countries such as India are often vaccinated in public health care facilities free of charge, availability of vaccines and staff may be inadequate especially in rural areas thereby hindering utilization. For

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example, the nationally representative District Level Health and Facility Survey-3 (DLHS-3) showed that 66% and 63% of children, respectively, received full three doses of polio and DPT vaccinations (International Institute for Population Sciences, 2010). Moreover, vaccination cards recording the vaccination dates were seen by enumerators for only 38% of the children. Thus, ensuring timely vaccination coverage in remote areas of India, especially against polio and DPT that require multiple doses, remains a challenge.

Further, the timing of vaccinations is known to be important from biomedical studies; early vaccination against pertussis produced higher antibody response among Italian infants (Belloni *et al*., 2003). Timely vaccinations help shrink the period during which children are exposed to preventable diseases. Moreover, there are often positive externalities from vaccinating children against diseases such as measles for reducing diarrhea prevalence (Kapoor and Raddaiah, 1991). In rural areas of less developed countries, it is often difficult to fully vaccinate children due to logistical problems especially for vaccinations requiring multiple doses. For example, data from demographic surveys in 45 less developed countries showed that full coverage against DPT ranged from 40% for Mauritania in 2000 to 96% in Kyrgyz in 1997 (Clark and Sanderson, 2009). Moreover, issues of timeliness of childhood vaccinations in the Commonwealth of Independent States and Uganda were discussed, respectively, by Akmatov *et al*. (2008) and Babirye *et al*. (2012). However, the effects of incomplete vaccination coverage on child health outcomes have not been previously investigated; data on children with vaccination cards in the DLHS-3 afford an investigation of the effects of timeliness of DPT vaccinations on morbidity. In view of low vaccination coverage in India, it is important to identify policies for increasing vaccination uptake via the use of popular technologies such as mobile phones (Section 7).

The analyses of data on vaccination uptake and timeliness present certain methodological difficulties. First, children from better off households may be more likely to possess cards recording the dates of vaccinations. However, there are differences in vaccination card issuance policies across Indian states so that the sample of children with cards will cover children from diverse socioeconomic backgrounds. For example, while approximately 90% of the children in DLHS-3 were vaccinated in public facilities or via public sponsored programs, many children vaccinated in private facilities did not possess vaccination cards. Moreover, the sample structure of children with and without vaccination cards can be viewed as a “choice-based sampling” or “case-control” design (Section 3.3). Although Hsieh *et al*. (1985) derived estimators for such samples, in practice mainly the coefficients of constant terms in the models are likely to be affected (Wang *et al*., 1997). Moreover, in the spirit of randomized controlled trials, likelihood ratio tests can be applied to test for differences in slope parameters for children in the two groups (Bhargava and Guthrie, 2002). Because vaccination cards are often issued at the time of first vaccinations, differences between children with and without cards are likely to be important for second and third doses of DPT and polio vaccinations.

Another methodological issue in the empirical modeling is that children not fully vaccinated may suffer from greater sickness levels. For such children, health care workers may recommend vaccinations so that the effects of vaccinations on morbidity might be confounded. Such issues have been considered in the “endogenous facility placement” literature (Becker, 1982) for child mortality, although they may be less applicable in countries such as India where there is a mix of public and private health care providers (Bhargava *et al*., 2005). By contrast, it is likely that children in urban areas have better access to health care and are more regularly vaccinated so that comparisons of the results for urban and rural children can yield useful insights. The primary objectives of this paper are to investigate the factors influencing uptake of child vaccinations in DLHS-3 and to analyze the effects of delayed vaccinations on child morbidity due to fever, cough, and diarrhea. The accuracy of maternal recalls of vaccinations was investigated by comparing the results for morbidity of children with and without vaccination cards.

The structure of this paper is as follows: The DLHS-3 data and constructed variables are described in Section 2. Certain indices were computed to reflect postnatal care available and received in public and/or private health care facilities. The analytical framework for specification of empirical models for children’s vaccinations is discussed in Section 3.1 and the models are outlined in Section 3.2. In Section 3.3, econometric and statistical methodological issues are discussed and the estimation and test procedures are outlined. The results from empirical models for children’s BCG, measles, DPT, and polio vaccinations are presented in Section 4; results for

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children's ages at the time of vaccinations are in Section 5. Section 6 presents the results for a morbidity index covering episodes of cough, fever, and diarrhea in the previous two weeks. Implications of the findings for public policies are discussed in Section 7.

2. THE DISTRICT LEVEL HEALTH AND FACILITY SURVEY-3 DATA FROM INDIA

The DLHS-3 was the largest ever stratified survey in 34 Indian states and territories covering 643,944 ever married women in age group 15–49 years with a response rate of 90% (International Institute of Population Sciences, 2010). Immunization and health data were available for 207,920 children on selecting the youngest child aged 0–60 months from the households. Vaccination cards were seen by enumerators for 38% of the children; dates of BCG, measles, polio, and DPT vaccinations were taken from the cards to calculate children's ages at the time of vaccinations. For children without vaccination cards, it was inquired if they received BCG and measles vaccinations and how many doses of polio and DPT vaccines were administered. For all children, it was inquired if they suffered from fever, cough, and diarrhea in the previous two weeks; it was also inquired if children received a medical checkup within 48 h of birth.

The DLHS-3 survey compiled several variables such as age of the mother, birth history, education, access to and utilization of health care services in public and private facilities, and household possessions. Several indices were created to capture the households' circumstances. The index of household possessions was based on 21 items: if the household had electricity, mattress, pressure cooker, chair, bed, sofa set, table, electric fan, clock, sewing machine, radio, black and white television, color television, refrigerator, mobile phone, other phone, bicycle, washing machine, scooter, car, and computer. The (0–1) responses were summed and this index ranged from 0 to 21. Cronbach (1984) alpha for the index was 0.86 showing high reliability. The source of drinking water, type of toilet, fuel used for cooking, and numbers of rooms in the house were inquired.

The index for maternal knowledge about diarrhea was based on five items regarding what actions to take if the child gets diarrhea: give oral rehydration solution, give salt and sugar solution, give plenty of fluids, continue normal food, and continue breastfeeding. The 0–1 responses were summed and this index ranged from 0 to 5. Another index for maternal knowledge of pneumonia was based on seven items for recognizing children's symptoms: difficulty in breathing, not able to breathe or breastfeed, excessively drowsy, pain in chest and productive cough, wheezing or whistling sounds, rapid breathing, and runny nose; this index ranged from 0 to 7. The index of children's morbidity was based on three symptoms inquired, namely, if the child had diarrhea, fever, and cough in the previous fortnight. The affirmative responses were summed to produce an index of child morbidity (Rand Corporation, 1983, Bhargava, 1994) that ranged from 0 to 3. Such indices capture the intensity of sicknesses although sickness durations were not recorded in DLHS-3.

Further, two indices were created for access to health facilities via roads and for availability of health facilities in the village. The health facilities connected by road index was based on five items inquiring if the village was connected to a Primary Health Center (PHC), Block PHC, Sub-center, Community Health Center (CHC), and a District Hospital; this index ranged from 0 to 5. The health facilities available index was based on 10 items on availability in the village of a Sub-center, Integrated Child Development Scheme, PHC, Block PHC, CHC, District/Government hospital, Government dispensary, Private clinic, Private hospital/nursing home, and Ayurvedic hospital. This index was an indicator of public and private health care facilities and ranged from 0 to 10; health facilities indices were set to their respective maximum values for urban households.

The sample means and standard deviations of selected variables from DLHS-3 data for children without and with vaccination cards are reported in Table I. The differences in means were statistically significant ($p < 0.05$) for all variables in the two groups and the results provide several insights. The mean ages of children were 22.3 and 19.9 months, respectively, in the groups without and with vaccination cards. Mean maternal education was significantly lower in the group without vaccination cards; higher percentages of children with cards were residing in urban areas. Piped water was available to 27% and 32% households, respectively, in the two groups; use of electricity or natural gas was higher among households in the vaccination card group. The sample mean

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Table I. Sample means and standard deviations of variable in the District Level Health Survey-3

	No vaccination cards		Vaccination cards	
	Mean	SD	Mean	SD
Children's age, months	22.25	14.26	17.86	12.49
Maternal education, 1–4	2.04	1.17	2.51	1.19
Girl (1 = yes, 0 = no), %	46.7	–	46.0	–
Urban (1 = yes, 0 = no), %	17.0	–	21.0	–
Piped water (1 = yes, 0 = no), %	26.9	–	32.3	–
Cook with electricity or gas (1 = yes, 0 = no), %	12.0	–	19.5	–
Number of rooms, 1–10	2.81	1.83	3.22	1.96
Household possession index, (0–21)	6.10	4.11	7.49	4.48
Health facilities connected by road index, 0–5	3.77	1.89	3.90	1.78
Health facilities available index, 0–10	3.23	3.41	3.82	3.64
Measles vaccination (1 = yes, 0 = no), %	58.0	–	99.9	–
BCG vaccination (1 = yes, 0 = no), %	83.0	–	99.9	–
Number of DPT vaccinations, *n*	1.46	1.34	2.27	1.03
Number of polio vaccinations, *n*	1.62	1.34	2.45	1.01
Cough in the last 2 weeks (1 = yes, 0 = no), %	19.0	–	24.0	–
Fever in the last 2 weeks (1 = yes, 0 = no), %	19.6	–	23.4	–
Diarrhea in the last 2 weeks (1 = yes, 0 = no), %	12.0	–	13.0	–
Morbidity index last 2 weeks, 0–3	0.51	0.86	0.61	0.90
Birth order, *n*	2.90	1.97	2.31	1.57
Check up within 48 h of birth (1 = yes, 0 = no), %	38.6	–	53.4	–
Knowledge diarrhea index, 0–5	1.29	1.04	1.45	1.05
Knowledge pneumonia index, 0–7	2.72	1.39	2.70	1.46
Vaccination card seen (1 = yes, 0 = no), %	38.0	–	100.	–
Age at BCG vaccination, months	–		4.20	5.50
Age at measles vaccination, months	–		12.85	5.99
Age at DPT1 vaccination, months	–		5.23	5.52
Age at DPT2 vaccination, months	–		6.69	5.68
Age at DPT3 vaccination, months	–		8.14	5.85
Age at polio 1 vaccination, months	–		5.26	5.572
Age at polio 2 vaccination, months	–		6.67	5.69
Age at polio 3 vaccination, months	–		8.13	5.84
Average age DPT 1–3 vaccinations, months	–		6.47	4.90

There were 128,388 children without vaccination cards and 79,532 children with cards; different number of observations was used to compute means; differences between the means of variables in the card and non-card groups were all significant at 5%.

of household possessions index was significantly higher in the group with vaccination cards. Similarly, sample means of the health facilities connected by road index were 3.77 and 3.90, respectively, for the two groups; sample mean of the health facilities available index was significantly higher for the group with vaccination cards.

For children without vaccination cards, the mothers reported that 58% received BCG vaccinations and 69% received measles vaccinations. By contrast, these percentages were 99.99 for children with vaccination cards indicating that the cards were typically issued at the time of first vaccinations. The mean numbers of polio and DPT vaccinations were, respectively, 1.62 and 1.46 for the children without cards; the corresponding means were 2.45 and 2.27 for children with vaccination cards. Interestingly, the morbidity index based on episodes of cough, fever, and diarrhea for children without vaccination cards was 0.51, whereas it was significantly *higher* (0.61) for children with vaccination cards. These findings suggest that morbidity was likely to be underreported for children without vaccination cards who typically belonged to poorer and less educated households.

For children with vaccination cards, mean ages at the time of BCG and measles vaccinations were 4.2 and 12.9 months, respectively. The mean ages at the time of first polio and DPT vaccinations were 5.26 and 5.23 months, respectively; these immunizations generally took place simultaneously. Finally, due to incomplete coverage of DPT vaccinations, the average age of children at the time of DPT1, DPT2, and DPT3 vaccinations was calculated to be 6.5 months; the corresponding average age for polio vaccinations was also 6.5 months. In the empirical analyses in Section 6, average age at the three DPT vaccinations or age at first DPT vaccinations were employed.

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3. MODELING THE PROXIMATE DETERMINANTS OF BCG, MEASLES, DPT, AND POLIO VACCINATIONS

3.1. Some conceptual aspects

While the role of immunization programs for improving child survival and health in less developed countries is widely recognized (United Nations, 2009), vaccination uptake is hampered by poor access especially in rural areas. Moreover, cold chain and other equipment are necessary for preserving vaccines, and many rural areas in countries such as India lack even electricity. Hence, governments often vaccinate children via special campaigns. Despite such efforts, it may be difficult for uneducated parents to appreciate the benefits of full vaccination coverage so that literacy campaigns are also necessary. From a logistical standpoint, timely administering of BCG and measles vaccinations is easier than for the three doses of polio and DPT vaccinations.

Further, vaccination cards have the advantage that dates of vaccinations are recorded so that children's ages at the time of vaccination can be calculated. While it may be difficult for mothers in remote areas to maintain paper vaccination cards, card issuance is likely to enhance vaccination uptake and improve data quality. Even in remote areas where non-governmental organizations provide basic health care services, cards can facilitate timely vaccinations. From a methodological standpoint, there are likely to be differences in quality of information especially on polio and DPT vaccinations for children with and without cards. Such issues can be investigated by analyzing the effects of vaccinations on children's morbidity patterns. For example, controlling for socioeconomic and demographic factors, one would expect children receiving all three doses of DPT vaccinations in a timely manner to exhibit lower morbidity levels.

Another set of issues influencing the empirical models are potential feedbacks effects such as parents getting the children vaccinated if they face morbidity spells. The previous economics literature has considered such effects for child mortality, although mortality is an extreme event and government is not the exclusive provider of health care in most developing countries (Bhargava *et al*., 2005). By contrast, this phenomenon may be apparent for multiple doses of DPT vaccinations that can lower morbidity due to cough and fever. Such issues can be investigated using data on children's ages at the time of vaccinations. For example, if parents had their children vaccinated against DPT due to higher morbidity, then the age at DPT vaccinations will be correlated with errors affecting the morbidity model, that is, age would be an endogenous variable. By contrast, if there are no feedback effects, then exogeneity hypothesis for age at vaccination may be accepted in the model for child morbidity. Exogeneity tests are useful for uncovering such aspects and are briefly described in Section 3.3.

3.2. The empirical models

The binary model for BCG (and measles) vaccinations can be written as follows:

$$\begin{aligned}(\text{BCG vaccination})_i = a_0 &+ a_1(\text{Dummy variable for vaccination card})_i + a_2(\text{Dummy variable for girl})_i \\ &+ a_3(\text{Maternal education})_i + a_4(\text{Child's age})_i + a_5(\text{Birth order})_i + a_6\left[(\text{Birth order})_i\right]^2 \\ &+ a_7(\text{Household possessions index})_i + a_8\left[(\text{Household possessions index})_i\right]^2 \\ &+ a_9(\text{Checkup within 48 } h)_i + a_{10}(\text{Knowledge diarrhea index})_i \\ &+ a_{11}(\text{Health facilities connected by road index})_i + a_{12}(\text{Health facilities available index})_i \\ &+ a_{13}[(\text{Health facilities connected by road index}) * (\text{Maternal education})]_i \\ &+ a_{14}[(\text{Health facilities available index}) * (\text{Maternal education})]_i + u_{1i} \quad (i = 1, \ldots, N)\end{aligned} \tag{1}$$

The explanatory variables in model (1) were described in Section 2. The dummy variable for whether the child had a vaccination card allowed the means in the two groups to differ. Model (1) was postulated to be nonlinear in birth order and household possessions index variables; an indicator variable for children belonging to "scheduled castes" was also included in some of the models. The variable for if the child had a medical

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checkup within 48 h after birth was likely to reflect the influence of previous health care utilization on vaccination uptake. Interactions between maternal education and health facilities connected by road and that with facilities available reflected the phenomenon that effects of lower maternal education can be offset to some degree by access to and availability of health care services. Dummy variables for 27 major Indian states were included in the models although the coefficients were suppressed. Note that as is often the case in large demographic surveys, missing observations on explanatory variables decreased the sample sizes available for estimation by up to 40%. Sample means for the subset of data used for estimating the comprehensive models were close to the corresponding means reported in Table I for the full sample. Multiple imputations (Rubin, 1987) were conducted for certain models to assess the effects of missing observations on robustness of the estimated parameters. As discussed in Section 3.3, mainly the estimated coefficients of the constant term in the models are likely to be affected in such situations.

Further, in the models for polio and DPT vaccinations, dependent variables ranged from 0 to 3 and ordinal regression models were estimated. Models were also estimated for children's ages at the time of vaccinations using the information from vaccination cards. To reduce the numbers of missing observations on one or more doses of DPT vaccinations, average age at the time of vaccinations was modeled. Because the children received different numbers of DPT vaccinations, this variable was replaced by age at first DPT vaccination to assess the robustness of the results. The model for children's morbidity index is given by

$$\begin{aligned}(\text{Morbidity index})_i = b_0 &+ b_1(\text{Dummy variable for girl})_i + b_2(\text{Child's age})_i + b_3(\text{Maternal education})_i \\ &+ b_4\left[(\text{Maternal education})_i\right]^2 + b_5(\text{Birth order})_i + b_6(\text{Knowledge diarrhea index})_i \\ &+ b_7(\text{Household possessions index})_i + b_8(\text{Average age at DPT vaccinations})_i \\ &+ b_9(\text{Piped water})_i + b_{10}(\text{Cook with electricity or gas})_i + b_{11}(\text{Number of rooms})_i \\ &+ b_{12}\left[(\text{Number of rooms})_i\right]^2 + u_{2i}(i = 1, \ldots, N)\end{aligned} \tag{2}$$

The environmental variables such as access to piped water and cooking with electricity or natural gas were likely to lower children's morbidity. Also, number of rooms was included in (2) in a nonlinear fashion; having a separate kitchen can reduce exposure to indoor pollution. For children possessing vaccination cards, average age at DPT vaccinations was likely to be positively associated with morbidity levels; this variable was replaced by age at first DPT vaccination for robustness checks. Finally, the model for morbidity index (2) was also estimated for the pooled sample of children with and without vaccination cards with age at DPT vaccinations replaced by numbers of DPT vaccinations. Comparisons of the results from the models for morbidity estimated using data from vaccination cards and number of DPT vaccinations reported by mothers will shed light on the accuracy of the reported variables.

3.3. Statistical and econometric issues

The binary models (1) for BCG and measles vaccinations were estimated by maximum likelihood using algorithms in software packages (e.g., Stata, 2012). The dependent variables in the models for polio and DPT vaccinations ranged from 0 to 3; hence, the ordinal regression models were estimated by maximum likelihood (McCullagh, 1980). At a conceptual level, the data covering two groups of children with and without vaccination cards can be viewed as having a "choice-based sampling" or "case-control" structure (e.g., Mantel and Haenszel, 1959). In particular, "prospective" data on multiple doses of vaccinations such as against polio and DPT can be extracted for children with vaccination cards; for children without vaccination cards, vaccination data are essentially "retrospective" in nature. Hsieh *et al*. (1985) derived the conditional maximum likelihood and full information maximum likelihood estimators for such samples noting that the conditional

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maximum likelihood estimator was a special case. Wang *et al*. (1997) showed that the two estimators differed mainly for the constant terms in the model and that the two sets of maximum likelihood estimators were equivalent in large samples.

There are four aspects of the DLHS-3 data that merit special treatment from a methodological standpoint. First, there was differential information available for the two groups since children's ages at the time of vaccination can be calculated only for the card group. Moreover, it was likely that children's polio and DPT vaccination records were more accurately compiled in vaccination cards than the maternal recalls of the numbers of vaccinations. This issue will be investigated by comparing the results from models for child morbidity using explanatory variables extracted from vaccination cards and those based on maternal recalls.

Second, because the overall constant term is affected by the choice-based sample design, it was feasible to test constancy of slope parameters across the two groups using likelihood ratio tests (Bhargava and Guthrie, 2002). Because most vaccination cards were issued at the time of BCG or first polio and DPT vaccinations, differences between the groups were likely to be important for second and third doses of polio and DPT vaccinations. The pooled model (1) can be estimated with a dummy variable for vaccination card group, and separately for children with and without vaccination cards. In view of 13 parameters in (1) and 27 dummy variables for Indian states, the likelihood ratio statistic was distributed in large samples as a χ^2 variable with 40 degrees of freedom.

Third, propensity scores were employed (Rosenbaum and Rubin, 1983; Stata, 2012) to compare groups of children with and without vaccination cards for measles vaccinations that were administered around the age of 1 year. The comparison for vaccinations against measles can provide insights since vaccination cards were typically issued at the time of first vaccinations against DPT and polio, that is, it would not be appropriate to compare vaccinations against polio and DPT via propensity scores for subgroups of children with and without vaccination cards. The application of propensity scores can reduce apparent "biases" in simple comparisons between groups with and without vaccination cards and provide insights into robustness of the estimated coefficients (Section 4).

The final set of methodological issues addressed were the endogeneity of explanatory variables (Sargan, 1958) such as children's age at the time of DPT vaccinations in the model for morbidity. For example, educated mothers are more likely to ensure that their children are vaccinated against DPT in a timely fashion. By contrast, due to poor access and/or knowledge, parents in rural areas may wait to have their children fully vaccinated unless the children start experiencing high morbidity levels. Such factors would induce correlation between the errors affecting the morbidity model and ages at the time of DPT vaccination for rural children. While there is often a paucity of instrumental variables that are highly correlated with endogenous variables in cross-sectional data (Bhargava, 1994), indices such as for maternal knowledge are likely to be determined at earlier stages and are more likely to be strongly correlated with endogenous variables than the responses to individual items. Exogeneity hypotheses for children's ages at the time of DPT vaccinations were tested via χ^2 statistics that are asymptotically equivalent to Lagrange multiplier tests (Rao, 1948) and are available in software packages (e.g., Stata, 2012).

4. RESULTS FROM MODELS FOR BCG, MEASLES, POLIO, AND DPT VACCINATIONS USING THE DLHS-3 DATA

Table II present the results from models for BCG, measles, DPT, and polio vaccinations. Binary logistic models were estimated by maximum likelihood for BCG and measles vaccinations, whereas ordinal regressions were estimated by maximum likelihood for DPT and polio vaccinations. The models included 27 dummy variables for the major Indian states although their coefficients were suppressed; "marginal effects" are also reported for the binary models. First, children possessing vaccinations cards were significantly ($p < 0.05$) more likely to be vaccinated. The likelihood ratio statistic for testing null hypothesis that parameters were the same in the two groups was 29.4 for BCG vaccinations and it accepted the hypothesis at 5% level; the null hypothesis was

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Table II. Estimated parameters from binary logistic and ordinal regression models for children's BCG, measles, DPT, and polio vaccinations using DLHS-3 data

	BCG, 0–1[a]			Measles, 0–1[a]			DPT, 0–3[b]		Polio, 0–3[b]	
Explanatory variables	Coefficient	SE	ME[c]	Coefficient	SE	ME[c]	Coefficient	SE	Coefficient	SE
Constant	2.233	0.210	–	−1.090	0.097	–	0.259	0.049	−0.039	0.052
Dummy variable vaccination card (1 = yes)	8.389*	0.707	0.497*	6.907*	0.219	0.823*	1.087*	0.011	1.245*	0.012
Dummy variable for girl (1 = yes)	−0.117*	0.022	−0.008*	−0.070*	0.017	−0.008*	−0.049*	0.010	−0.033*	0.010
Child's age, months	0.023*	0.001	0.001*	0.077*	0.001	0.009*	0.032*	0.001	0.030*	0.001
Maternal education, 1–4	0.320*	0.028	0.019*	0.219*	0.019	0.026*	0.179*	0.011	0.134*	0.011
Birth order, *n*	−0.082*	0.017	−0.004*	−0.011	0.014	−0.001	−0.036*	0.009	−0.031*	0.009
(Birth order)^2	−0.001	0.002	0.000	−0.009*	0.002	−0.001*	−0.003*	0.001	−0.003*	0.001
Knowledge diarrhea index, 0–5	0.175*	0.013	0.011*	0.192*	0.009	0.023*	0.117*	0.005	0.072*	0.005
Household possessions index, 0–21	0.050*	0.011	0.003*	0.052*	0.008	0.006*	0.059*	0.005	0.051*	0.005
(Household possessions index)^2	0.001	0.001	0.000	−0.001	0.001	0.000	−0.002*	0.001	−0.001*	0.0002
Check up within 48 h birth (1 = yes)	0.401*	0.026	0.024*	0.165*	0.019	0.020*	0.212*	0.011	0.188*	0.012
Health facilities connected by road index, 0–5	0.014	0.012	0.012	0.016	0.010	0.002	0.036*	0.006	0.023*	0.006
Health facilities available index, 0–10	−0.038*	0.007	−0.002*	0.002	0.006	0.000	−0.007*	0.004	−0.006	0.004
(Maternal education) * (health facilities connected by road index)	−0.009	0.006	−0.001	−0.002	0.004	0.000	−0.008*	0.003	−0.003	0.003
(Maternal education) * (health facilities available index)	0.011*	0.003	0.001*	−0.004*	0.002	−0.001*	0.0001	0.001	0.0001	0.001
χ^2 (40) test parameter constancy in groups with/ without vaccination cards	29.38	–		66.21*	–		8265.72*	–	4284.82*	–
R^2	0.409*	–		0.528*	–		0.220*	–	0.216*	

There were 114,467 children in the sample and 27 dummy variables were included for the major Indian states.
[a]Binary logistic models were estimated by maximum likelihood.
[b]Ordinal regression models were estimated by maximum likelihood.
[c]Marginal effects
*$p < 0.05$.

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rejected for measles vaccination where the test statistic was 66.2. Moreover, likelihood ratio statistics for DPT and polio vaccinations were 8265.7 and 4284.8, respectively. These large criteria suggested that there were systematic differences between the groups with and without vaccination cards in the uptake of three doses of DPT and polio vaccinations.

Second, the dummy variable for girls was estimated with negative and significant coefficients in all four models showing lower vaccination rates for girls (Mathew, 2012). A dummy variable for scheduled caste was also included in these models and it reached statistical significance in the model for BCG vaccinations although the results were very similar. Moreover, birth order was estimated with significant negative coefficients in the models for BCG, DPT, and polio vaccinations, and its squared was also estimated with negative and significant coefficients for measles, DPT, and polio vaccinations. Thus, households with large numbers of children were less likely to have their children vaccinated and the situation was worse for children born at high birth orders. Increased access to health care and family planning services is likely to be beneficial for vaccination uptake especially for girls.

Third, maternal education and knowledge diarrhea index were significant predictors in all four models. Moreover, interactions between maternal education and health facilities connected by road were significant in the model for DPT vaccinations, whereas interactions between maternal education and health facilities available index were significant in the models for BCG and measles vaccinations. Similar results were obtained using the marginal effects in the models for BCG and measles vaccinations. Also, coefficients of the dummy variable for whether the child had a medical checkup within 48 h of birth were significant in all four models. These results indicate the importance of timely utilization of health care services for children's vaccination uptake.

Fourth, household possessions index was estimated with positive and significant coefficients in all four models and its squared was estimated with negative and significant coefficients in the models for DPT and polio vaccinations. Better-off households were more likely to have their children vaccinated, although the effects declined with possessions index levels for the DPT and polio vaccinations. Fifth, the R^2 was statistically significant for all models; in view of the large heterogeneity across households, fit of the models seemed reasonable. Finally, the results from propensity scores for measles vaccinations estimated 0.38 as the group difference between children with and without vaccination cards (with standard error 0.009) for several subsamples of children in the data. These results were comparable to the marginal effect of the coefficient of indicator variable for vaccination card group in the measles vaccinations model in Table II, once nonlinearities in the explanatory variables were accounted for. Overall, the results from logistic regressions and propensity scores indicated significantly higher chances of measles vaccinations for children in the vaccination card group.

5. RESULTS FOR CHILDREN'S AGES AT BCG, MEASLES, POLIO, AND DPT VACCINATIONS IN THE CARD GROUP

The results for children's ages at the time of BCG, measles, DPT, and polio vaccinations are reported in Table III using ordinary least squares (OLS) and the information from vaccination cards. The main findings were as follows: First, the dummy variable for girls was estimated with positive coefficients that were significant in the models for DPT and polio vaccinations. Thus, girls were at a disadvantage in receiving timely vaccinations.

Second, the coefficients of maternal education were negative and significant in all four models; the coefficients of knowledge about diarrhea were also negative and significant in all models except for measles where the negative coefficient was not significant at 5% level. Thus, better educated mothers and those with greater knowledge of diarrhea were significantly more likely to have their children vaccinated at earlier ages. There were nonlinearities apparent with respect to birth order. For example, in the model for measles vaccinations, age at the time of vaccinations increased with birth order after crossing the threshold level of three children. Thus, large numbers of children born to women were significantly associated with delays in the age at which younger siblings were vaccinated, presumably reflecting the time constraints on mothers with large numbers of children.

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Table III. Estimated parameters from regression models for children's ages at BCG, measles, DPT, and polio vaccinations using DLHS-3 data

	Age BCG, months[a]		Age measles, months[a]		Average age DPT 1–3, months[a]		Average age polio 1–3, months[a]	
Explanatory variables:	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
Constant	4.450	0.206	13.339	0.292	6.678	0.178	6.639	0.180
Dummy variable for girl (1 = yes)	0.075	0.045	0.103	0.065	0.125*	0.039	0.112*	0.040
Maternal education, 1–4	−0.141*	0.052	−0.166*	0.076	−0.118*	0.045	−0.117*	0.046
Birth order, *n*	−0.068	0.044	−0.167*	0.067	−0.092*	0.038	−0.083*	0.039
(Birth order)^2	0.016*	0.006	0.026*	0.009	0.020*	0.005	0.019*	0.005
Knowledge diarrhea index, 0–5	−0.102*	0.023	−0.040	0.033	−0.069*	0.020	−0.064*	0.020
Household possessions index, 0–21	−0.060*	0.021	−0.119*	0.030	−0.067*	0.018	−0.058*	0.018
(Household possessions index)^2	0.001	0.001	0.004*	0.002	0.001	0.001	0.001	0.001
Check up within 48 h birth (1 = yes)	−0.245*	0.052	−0.121*	0.076	−0.123*	0.045	−0.121*	0.046
Health facilities connected by road index,0–5	−0.047	0.031	−0.018	0.048	0.040	0.027	0.031	0.028
Health facilities available index, 0–10	0.001	0.018	0.025	0.028	−0.033*	0.016	−0.027	0.016
(Maternal education) * (health facilities connected by road index)	−0.141*	0.052	0.011	0.018	−0.022*	0.010	−0.015	0.011
(Maternal education) * (health facilities available index)	0.006	0.012	−0.006	0.009	0.011*	0.005	0.008	0.005
R^2	0.045*	–	0.025*	–	0.056*	–	0.051*	

There were 56,804 children in the sample with vaccination cards and 27 dummy variables were included for the major Indian states.
[a]Models were estimated by ordinary least squares.
*$p < 0.05$.

Third, the household possessions index was significantly negatively associated with children's ages at the time of BCG, measles, DPT, and polio vaccinations; the squared terms were estimated with a positive and significant coefficient in the model for measles. Moreover, the dummy variable for if the child had a medical checkup within 48 h of birth was estimated with negative and significant coefficients in all four models. Interactions between maternal education and health facilities were significant in the models for BCG and DPT vaccinations; interaction between maternal education and health facilities available was significant in the model for DPT vaccinations. Thus, greater access to and availability of health care services were associated with timely vaccination patterns.

Finally, although the data on the three DPT and polio vaccinations were more precise for children with cards, the R^2 was lower in these models than for binary and ordinal models in Table II. Such problems were partly due to heterogeneity across the households in DLHS-3 and also because age at the time of vaccination was a continuous variable with higher variation.

6. RESULTS FOR CHILDREN'S MORBIDITY USING THE POOLED SAMPLE AND THE DATA FROM VACCINATION CARDS

The first column in Table IV presents the results for children's morbidity index for the pooled sample of children with and without vaccination cards. The ordinal regression model was estimated by maximum likelihood and the number of DPT vaccinations was included as an explanatory variable. This variable was replaced by the average age at the time of the DPT vaccinations in the models that were estimated for children with vaccination cards in columns 2–4. First, note that coefficients of dummy variable for children with vaccination cards were not significant in morbidity models and this variable was dropped from the models. Second, focusing on the results from ordinal regressions for the pooled sample, morbidity levels declined with children's ages. Moreover, in contrast with the results in Tables II and III for vaccinations uptake, morbidity

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Table IV. Estimated parameters from regression models for children's morbidity from the pooled sample and for children with vaccination cards

Explanatory variables	Morbidity index, 0–3 pooled sample[a]		Morbidity index, 0–3 vaccination cards[a]		Morbidity index, 0–3 vaccination cards[b]		Morbidity index, 0–3 vaccination cards[c]	
	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
Constant	0.670	0.033	0.481	0.059	0.666	0.027	−0.260	0.580
Age, months	−0.008*	0.001	−0.008*	0.001	−0.003*	0.001	−0.198	0.130
Dummy variable for girl (1 = yes)	−0.049*	0.011	−0.055*	0.017	−0.024*	0.008	−0.032*	0.014
Maternal education, 1–4	0.354*	0.028	0.406*	0.043	0.158*	0.020	0.202*	0.041
(Maternal education)^2	−0.062*	0.006	−0.074*	0.009	−0.030*	0.004	−0.034*	0.007
Birth order, *n*	0.017*	0.003	0.006	0.006	0.003	0.002	−0.001	0.006
Number DPT vaccinations, 0–3	0.045*	0.004	–		–		–	
Average age DPT 1–3 vaccinations, months	–		0.016*	0.002	0.008*	0.001	0.282	0.178
Knowledge diarrhea index, 0–5	−0.069*	0.005	−0.038*	0.008	−0.016*	0.004	−0.019*	0.006
Household possessions index, 0–21	−0.016*	0.002	−0.015*	0.003	−0.007*	0.001	0.001	0.005
Piped water, 1 = yes	−0.238*	0.012	−0.199*	0.019	−0.077*	0.009	0.025	0.055
Cook with electricity or gas, 1 = yes	−0.069*	0.018	−0.081*	0.026	−0.035*	0.011	−0.059*	0.020
Number of rooms, 1–10	−0.021*	0.003	−0.087*	0.015	−0.044*	0.007	−0.056*	0.012
(Number of rooms)^2	−0.062*	0.006	0.008*	0.002	0.004*	0.001	0.005*	0.001
χ^2 (1) test for exogeneity	–		–		–		3.82	
χ^2 (2) test for misspecification of over-identifying restrictions	–		–		–	–	1.49	
R^2	0.014*	–	0.017*	–	0.015*	–	0.015*	

There were 156,858 children in the pooled sample and 53,238 children with vaccination cards.
[a]Model estimated using ordinal regression.
[b]Model estimated by ordinary least squares.
[c]Model estimated by instrumental variables treating average age DPT 1–3 as an endogenous variable and using knowledge of pneumonia index, health facilities connected by road index, and health facilities available index as instruments.
*$p < 0.05$.

levels of girls were significantly lower than for boys. While it is possible that female morbidity may have been underreported, greater resilience to disease shown by girls born at low birth orders was a factor underlying their higher survival chances in Uttar Pradesh (Bhargava, 2003).

Third, there were nonlinearities apparent with respect to maternal education and both coefficients were significant in the model. Also, higher birth order predicted significantly higher morbidity levels. Greater maternal knowledge of diarrhea and higher values of household possessions index were significantly associated with lower child morbidity. Fourth, households' environmental variables were significant predictors of morbidity; having access to piped water (Jalan and Ravallion, 2003) and cooking with electricity or natural gas were significantly associated with lower morbidity. Nonlinearities with respect to the numbers of rooms in the house implied lower morbidity levels although at a declining rate.

Fifth, coefficient of the number of DPT vaccinations was estimated with a *positive* sign that was significant in the model estimated using the pooled sample of children with and without vaccination cards. The positive sign was surprising and may have been due to misreporting of morbidity variables and/or DPT doses. Also, factors such as parents having their children vaccinated at later ages due to higher morbidity can confound the results. Further, results from the ordinal model in column 2 for children with vaccination cards showed that the average age at DPT vaccinations was *positively* associated with children's morbidity, that is, children who were vaccinated at older ages were more likely to be sick. This was also the case when average age at DPT was replaced by children's ages at the first DPT vaccination. Because there were no other noticeable differences in the results in columns 1 and 2, and data on DPT vaccinations were likely to be more accurately compiled for children with vaccination cards, the results for children with cards seemed plausible, that is, children who were vaccinated at older ages were likely to experience higher morbidity levels.

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To further investigate the potentially confounding effects of age at the time of DPT vaccinations and morbidity levels while tackling endogeneity of the age variable, the model for morbidity was estimated by OLS and the results are in column 3. The results from ordinal regression and OLS in columns 2 and 3, respectively, were very similar. Coefficient of the variable average age at DPT vaccinations estimated by OLS was 0.008; when this variable was replaced by the age at first DPT vaccination, the estimate was 0.006, which was quite close. Next, in column 4, the model for morbidity was estimated using instrumental variables treating the average age at DPT vaccinations as an endogenous variable. The health facilities connected by road index, health facilities available index, and knowledge of pneumonia index were used as instrumental variables in the estimation. The standard errors of the estimated parameters in column 4 were larger than the corresponding standard errors in column 3. While the coefficient of average age at DPT vaccinations increased from 0.008 to 0.282 in column 4, its standard error was large (0.178); hence, the coefficient was not significant at 5% level. Lagrange multiplier test statistic for exogeneity of average age at DPT vaccinations was 3.82 and it accepted the exogeneity null hypothesis at 5% level. Moreover, χ^2 test for validity of over-identifying restrictions was 1.49 and it also accepted the null hypothesis. Thus, the hypothesis that there were feedbacks from higher morbidity levels to children being vaccinated against DPT was not supported by the pooled sample for rural and urban children.

Further, as noted in Section 3.3, feedback effects from high morbidity to greater uptake of DPT vaccinations may be more important for rural households. The morbidity model was re-estimated using data on children from rural households with vaccination cards. The sample criterion for Lagrange multiplier test statistic increased to 4.57 and exogeneity null hypothesis was rejected at the 5% level. Moreover, the test criterion for over-identifying restrictions was 12.95 and it also rejected the null hypothesis. While the predictive power of the instrumental variables was low, χ^2 statistics for rural children indicated the presence of feedback effects from higher morbidity to greater uptake of the DPT vaccinations, that is, parents in rural areas may have responded to higher morbidity levels by having their children vaccinated. These issues are further discussed in the conclusion.

Finally, the effects of missing observations on robustness of the estimated parameters were investigated using multiple imputations for the morbidity index model for children with vaccination cards estimated by OLS (Stata, 2012). The choice of the model and subsample seemed reasonable since numerical optimization

Table V. Estimated parameters from multiple imputation regression models for children's morbidity from the sample for children with vaccination cards

	Morbidity index, 0–3 vaccination cards[a]		Morbidity index, 0–3 vaccination cards[a]		Morbidity index, 0–3 vaccination cards[a]	
Explanatory variables	Coefficient	SE	Coefficient	SE	Coefficient	SE
Constant	0.629	0.023	0.630	0.023	0.630	0.023
Age, months	−0.002*	0.001	−0.002*	0.001	−0.002*	0.001
Dummy variable for girl (1 = yes)	−0.022*	0.007	−0.022*	0.007	−0.022*	0.007
Maternal education, 1–4	0.139*	0.017	0.139*	0.017	0.139*	0.017
(Maternal education)^2	−0.026*	0.003	−0.026*	0.003	−0.026*	0.003
Birth order, *n*	0.004	0.002	0.004	0.002	0.004	0.002
Average age DPT 1–3 vaccinations, months	0.008*	0.001	0.008*	0.001	0.008*	0.001
Knowledge diarrhea index, 0–5	−0.020*	0.004	−0.020*	0.004	−0.019*	0.004
Household possessions index, 0–21	−0.004*	0.001	−0.004*	0.001	−0.004*	0.001
Piped water, 1 = yes	−0.070*	0.007	−0.070*	0.007	−0.070*	0.007
Cook with electricity or gas, 1 = yes	−0.045*	0.010	−0.045*	0.010	−0.045*	0.010
Number of rooms, 1–10	−0.043*	0.006	−0.043*	0.006	−0.043*	0.006
(Number of rooms)^2	0.004*	0.001	0.004*	0.001	0.004*	0.001
Number of imputations	5	–	10	–	20	–

There were 74,580 children with vaccination cards and 53,238 children with complete data.
[a]Model estimated by ordinary least squares *m* times using complete samples with imputations and the reported estimates were pooled.
*$p < 0.05$.

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schemes necessary for estimating binary and ordinal models were likely to require more intensive computational methods. Also, the data for children with vaccination cards were less susceptible to measurement errors. In the multiple imputations, missing observations on birth order, knowledge diarrhea index, and morbidity index were predicted using ordered logistic regressions; "predictive mean matching" was used for the average age at DPT1-3 variable.

The three columns in Table V report the results for children's morbidity index by pooling the results from 5, 10, and 20 imputations, respectively. The results in the three columns of Table V were extremely close and were very similar to those reported in the third column of Table IV, which dropped missing observations in the estimation. The main difference was in the estimated coefficient of the constant term that fell from 0.666 in Table IV to 0.630 in Table V, although this difference was not statistically significant. Differences in the estimated coefficients in Tables IV and V were generally in the third places of decimal. More importantly, coefficients that were statistically significant in Table IV remained significant in the results from multiple imputations in Table V. Overall, while dropping children with missing observations reduced the sample sizes for children's morbidity model in Table IV, multiple imputations produced very similar results presumably due to the large degrees of freedom available for the estimation.

7. CONCLUSION

This paper analyzed the effects of demographic, socioeconomic, and health care variables on the uptake of BCG, measles, DPT, and polio vaccinations by Indian children using data from the DLHS-3. The effects of DPT vaccinations on children's morbidity due to cough, fever, and diarrhea were also analyzed. A novel aspect of the analyses was to distinguish between children with and without vaccination cards and to analyze the proximate determinants of children's ages at the time of vaccinations. Methodological issues such as higher morbidity levels encouraging parents to have their children vaccinated were addressed and the analyses provided several insights.

First, the results showed the importance of maternal education and knowledge about diarrhea for the uptake of vaccinations. Moreover, children born at high birth order and girls were significantly less likely to be vaccinated; easier access to and greater availability of health care facilities predicted higher vaccination uptake. Thus, higher utilization of health care and family planning services is likely to increase vaccination uptake by Indian children. This is important in rural areas where, for example, only 63% of children received three doses of polio vaccinations. While India is currently experiencing rapid economic growth, the benefits are not permeating at the same speed to uneducated and rural households, and it is important for policy makers to expand public health care programs.

Second, the results from the models for children's ages at the time of vaccinations reaffirmed the importance of maternal education, household possessions index, health care utilization, and children's birth order for timely vaccinations. Because the age data were extracted from children's vaccination cards, these variables were likely to have smaller measurement errors than maternal recalls. Third, importance of measurement aspects was evident in the models for morbidity where number of DPT vaccinations for the pooled sample of children with and without cards showed that children with greater number of DPT vaccinations suffered from higher morbidity. By contrast, when average age at DPT vaccinations (or age at first DPT vaccination) was used as an explanatory variable, the coefficient was positive and significant indicating that delays in DPT vaccinations were likely to increase morbidity. Thus, greater resources should be spent for issuing vaccination cards to children for ensuring timely vaccinations. In view of increased use of mobile phones among the poor in India, the authors are currently devising an "electronic vaccination card" system for increasing vaccination uptake. The use of "smart phone" technology in public health clinics can also enhance vaccine delivery via better utilization of the available stocks.

Fourth, the methodological aspects addressed in the analyses afforded useful insights. The choice-based sampling structure of the data for children with and without vaccination cards underscored the need for testing the null hypothesis that model parameters were constant across the two groups. The null was strongly rejected

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for the multiple doses of DPT and polio vaccinations. In the absence of paper or electronic vaccination cards for children, it may be unrealistic to expect uneducated parents to have their children fully vaccinated against polio and DPT. Despite the resources expended on polio vaccination campaigns, the mean number of polio vaccination for children with and without vaccination cards were 2.45 and 1.62, respectively. In fact, less than 30% of children had vaccination cards in the "backward" states of Madhya Pradesh, Rajasthan, and Uttar Pradesh, so that greater utilization of paper or electronic vaccination cards is likely to facilitate the uptake of timely vaccinations.

Fifth, modeling the ages at time of vaccinations shed light on behavioral aspects in that some parents might delay child vaccinations if they did not see a pressing need for them. The feedback effects from higher morbidity to uptake of vaccinations vitiate exogeneity assumptions for variables such as age at DPT vaccinations. Whereas the exogeneity null hypothesis was accepted for the pooled sample, the null was rejected for rural children; this phenomenon was likely to be important for rural households with poor access to health care. Such issues have not been previously considered and can obscure the associations between vaccination uptake and child morbidity.

Finally, the goals of United Nations (2009) of lowering child mortality are more likely to be attained if policy makers incorporate the ground realities in less developed countries. In India, there is an effort to increase the uptake of antenatal care and encourage women to deliver babies in medical facilities (National Rural Health Mission, 2008). Approximately two thirds of infant (under 1 year) mortality occurs within the 30-day period after birth (neonatal mortality) and a third between 1 and 12 months (postnatal mortality). While tetanus vaccination for mothers and supervised deliveries will lower neonatal mortality, timely vaccinations for children in the 1–12 month group are critical for reducing postnatal mortality. Moreover, debilitating effects of polio virus can be prevented by administering all three doses in a timely fashion. Efficacy of health policies in India will be enhanced by issuing paper or electronic vaccination cards for all children; greater resources expended on immunization programs will reduce child morbidity and mortality and are likely to promote physical growth. Improved child health, in turn, is critical for economic development.

CONFLICT OF INTEREST

The authors had no conflicts of interest in conducting these analyses.

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