Multilevel analysis of predictors of multiple indicators of childhood vaccination in Nigeria

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ABSTRACT

Background

Substantial inequalities exist in childhood vaccination coverage levels. To increase vaccine uptake, factors that predict vaccination coverage in children should be identified and addressed.

Methods

Using data from the 2018 Nigeria Demographic and Health Survey and geospatial data sets, we fitted Bayesian multilevel binomial and multinomial logistic regression models to analyse independent predictors of three vaccination outcomes: receipt of the first dose of Pentavalent vaccine (containing diphtheria-tetanus-pertussis, *Hemophilus influenzae* type B and Hepatitis B vaccines) (PENTA1) (n=6059) and receipt of the third dose having received the first (PENTA3/1) (n=3937) in children aged 12-23 months, and receipt of measles vaccine (MV) (n=11839) among children aged 12-35 months.

Results

Factors associated with vaccination were broadly similar for documented versus recall evidence of vaccination. Based on any evidence of vaccination, we found that health card/document ownership, receipt of vitamin A and maternal educational level were significantly associated with each outcome. Although the coverage of each vaccine dose was higher in urban than rural areas, urban residence was not significant in multivariable analyses that included travel time. Indicators relating to socio-economic status, as well as ethnic group, skilled birth attendance, lower travel time to the nearest health facility and problems seeking health care were significantly associated with both PENTA1 and MV. Maternal religion was related to PENTA1 and PENTA3/1 and maternal age related to MV and PENTA3/1; other significant variables were associated with one outcome each. Substantial residual community level variances in different strata were observed in the fitted models for each outcome.

Conclusion

Our analysis has highlighted socio-demographic and health care access factors that affect not only beginning but completing the vaccination series in Nigeria. Other factors not measured by the DHS such as health service quality and community attitudes should also be investigated and addressed to tackle inequities in coverage.

Keywords

Vaccination coverage; Vaccination determinants; Bayesian multilevel modelling; Demographic and Health Surveys; diphtheria-pertussis-tetanus vaccine; measles vaccine

Introduction

Childhood vaccination is one of the core strategies for achieving goal 3 of the Sustainable Development Goals (SDGs) of reducing under-five mortality to less than 25/1000 live births by 2030 [1]. Immunization Agenda 2030 (IA2030) [2] has the goal of all persons fully benefiting from vaccines to improve overall health and general well-being. IA2030 preconizes extension of immunization services to regularly reach "zero-dose" (those who receive no vaccines – often approximated by those who did not receive the first dose of pentavalent vaccine (containing diphtheria-tetanus-pertussis, *Hemophilus influenzae* type B and Hepatitis B vaccines) – PENTA1) and under-immunized children and to advance and sustain high coverage for all vaccines across the life course.

The global challenge of getting vaccines to all children is highlighted in the case of Nigeria. Notably, in 2019 Nigeria had the highest estimated number of infants who did not receive PENTA1 and the highest number of those who did not receive MV through routine services [3].

To increase vaccine uptake and implement optimal intervention strategies to address childhood vaccination inequalities in Nigeria, factors (both enablers and barriers) that predict vaccination coverage in children should be identified and addressed in a timely manner. Several studies, especially those conducted in sub-Saharan Africa have identified different individual, household, and community level factors to be associated with childhood vaccination. These include maternal education and age, household wealth, mother's attendance for antenatal care, skilled birth attendance, rural/urban residence, knowledge of immunization, shorter distance from vaccination site, level of partner's support, trust in

vaccines and immunization programs, lifestyle, number of children, occupation, lack of time or language barriers, and reminders to parent's [4-15].

In this study, we develop both binomial and multinomial multilevel statistical frameworks to identify factors that predict select indicators of childhood vaccination in Nigeria to help policymakers and program managers make informed decisions aimed at improving the survival and health of children[12, 13, 16, 17]. In particular, we investigate potential differences in factors that predict vaccination according to the strength of evidence of vaccination (documented versus recall evidence of vaccination), and examine whether factors affecting whether children start the vaccination series differ from those related to completing it, having begun.

We examine the role of geospatial environmental and climatic (geospatial) factors as well as individual, household and additional community level attributes in predicting vaccination coverage using multilevel modelling approaches which acknowledge the nested structure of the data, i.e., child, household, community and stratum levels. Although geospatial covariates have been extensively used for predicting vaccination coverage and other health outcomes in children [18-20] , there is insufficient evidence on how geospatial factors combine to influence vaccination at the individual child level, especially when adjusting for other covariate effects [19, 21, 22]. This is one of the objectives we aim to address in this work.

Materials and methods

Data

The study used data from the nationally representative cross-sectional 2018 Nigeria Demographic and Health Survey (NDHS) which was implemented by the National Population Commission (NPC) with technical assistance provided by Inner City Fund (ICF) International through The Measure DHS Program [23]. Data collection was conducted from 14 August to 29 December 2018 with pre-test conducted from 30 April to 20 May 2018. The survey utilised a stratified two-stage sampling approach. In the first stage, 1389 enumeration areas (EAs) or clusters were selected as the primary sampling units. At the second stage, 40427 households were selected. Stratification was achieved by separating each administrative level 1 area (i.e., the 36 states and the Federal Capital Territory) into urban and rural areas, and samples were selected independently within each stratum. Detailed information on the description of the methods employed in the study is available elsewhere [23].

Outcome variables

The primary outcome variables/indicators in this study are receipt of PENTA1 vaccine (n=6059) and receipt of PENTA3 having received PENTA1 (PENTA3/1 - the converse of dropout, n=3937) among children aged 12-23 months, and receipt of MV (n=11839) among children aged 12-35 months. For each of the three indicators, we assessed the binomial outcome: any evidence of vaccination versus no evidence of vaccination. For each of PENTA1 and MV, we additionally assessed the multinomial outcome: no evidence of vaccination, card invalid/history evidence of vaccination and card valid vaccination, to assess potential variation in associations that could be caused by misclassifying vaccination status when a verbal history of vaccination is accepted [24] (Supplementary Table S1). Valid and invalid vaccine doses were defined according to WHO guidance [25].

Explanatory variables

Demographic and Health Survey (DHS) covariates

The study considered covariates at the child-, household- and community-levels. The selection of these covariates was informed by literature on the predictors of vaccination coverage or of child health outcomes in general, expert opinion, and availability in the 2018 NDHS or other sources, as detailed in Table S1 [6, 11, 17, 21, 26-35]. The study however excluded some pre-selected DHS covariates due to missingness or multicollinearity (see supplementary materials). These variables include preceding birth interval, antenatal and postnatal care, maternal receipt of tetanus toxoid vaccination (these variables had >15% missing cases for MV and were excluded from the analyses to make the results comparable across all the three indicators), maternal decision-making (whether mother decides health care, visits, and purchases) - and region of residence. Also, among similar covariates (e.g., mother's occupation and employment status), one was selected for inclusion in our model based on the literature and expert opinion.

Geospatial covariates

The geospatial covariates retained in this study include travel time to health facility, enhanced vegetation Index (EVI) and livestock density index. Tertiles of the distribution of these covariate were used to allow similar number of observations for each tertile. We present further description about these covariates and their relevance in the supplementary Fig S1 and Table S2 [18-22, 29, 36, 37]. Other geospatial covariates considered included distance to conflict locations, maximum number of conflicts, night light intensity, annual aridity index, maximum temperature, annual precipitation/rainfall, proximity to national borders, water, protected areas, and slope [18-20] were excluded from final models due to multicollinearity (as was EVI) or non-significance after adjusting for DHS variables.

Data analysis

Estimation of measures of association (fixed effects)

Cross-tabulations and single-level logistic regression analysis

We tabulated each outcome against each of the selected covariates separately to explore relationships and used Chi-squared tests to determine the significance of the associations. We then fitted frequentist single level simple logistic regression models to obtain the corresponding crude odds ratios (cORs) and associated 95% confidence intervals (CI). These results were later compared with results from the multiple multilevel analyses to determine changes in statistical significance and direction of effects.

Multiple multilevel binomial regression analysis (any evidence of vaccination) and interaction effects

We fitted Bayesian multilevel [38, 39] binomial regression models to estimate adjusted odds ratios (aORs) and corresponding 95% credible intervals, accounting for the hierarchical structure of the data (child/household, community, and stratum levels) and, intrinsically, the survey design (clustering and stratification) through the last two hierarchies (Fig S2). A detailed description of the model is included in the Supplementary Information (SI).

We investigated whether child/household covariate effects could be modified by the geospatial covariates by introducing interaction terms between both sets of covariates. To incorporate the interaction terms, we first fitted the main effects model using both DHS and geospatial covariates and then introduced the interactions between selected DHS and geospatial covariates sequentially, retaining only those that were significant in the final model.

Multiple multilevel multinomial regression analysis (vaccination according to source of evidence)

The study also employed a Bayesian multinomial multivariable multilevel modelling approach to estimate the adjusted relative risk (aRR) and associated 95% credible intervals for covariates significantly associated with PENTA1 and MV using the multinomial outcomes defined previously. No interaction terms were considered for the multinomial analyses due to model complexities and non-convergence challenges.

Measures of variation (random effects analysis)

We computed summary measures [30, 40] of the amount of residual variation attributable to the hierarchies in the binomial models. These included the variance partitioning coefficient (VPC) which measures residual variation between clusters/communities in different strata; the median odds ratio (MOR) which quantifies residual community level variation in the likelihood of vaccination on the odds ratio scale, and the percent change in variance (PCV) which measures change in residual variation due to the inclusion of covariates in the models [41-45].

Also, although prediction was not the main goal, we evaluated the discriminatory or predictive power of the fitted models using the area under the receiver operating characteristic (AUROC) curve (see supplementary materials for details).

All analyses were implemented in Stata version 16 [46], MLwiN version 3.05 [47], and the R programming language version 4.0.3 [48]. Additionally, we used the runmlwin [49] program to run the MLwiN multilevel modelling software from within Stata. We utilized MCMC algorithms with a burn-in length of 1000, a monitoring chain length of 60000, and thinning of 20. Convergence of the MCMC chains was assessed via visual inspection of the trace and autocorrelation plots of the parameters.

Ethical approval and consent to participate

Ethical approval was obtained from the Nigeria National Health Research Ethics Committee and the ICF Institutional Review Board for the main NDHS [23], and from the Ethics and Research Governance, University of Southampton, United Kingdom. Written informed consent was obtained from all study respondents. However, the data were analysed anonymously in the present study. All methods were performed in accordance with the relevant guidelines and regulations.

Results

Outcome indicators of vaccination coverage in Nigeria

Among 6059 children aged 12-23 months, 3937 (65%) had any evidence of receiving PENTA1 and 3041 PENTA3 vaccination hence PENTA3/1 was 77%. Among the 2039 children with documented evidence of PENTA1 vaccination at or after 6 weeks of age, 1769(86.7%) had documented receipt of PENTA3 vaccine, while PENTA3/1 was lower (67.8%) among the children with only a verbal history of vaccination. Among 11839 children aged 12-35 months, 2111 (18%) had documented receipt of a valid dose of MV (at or after age 9 months); 4522 (38%) had either invalid documented doses or a verbal history of vaccination, and 5206 (44%) had no evidence of MCV receipt (Tables S3, S6, S8, S10, S12).

Cross-tabulation results

As expected, the receipt of PENTA1, PENTA3/1 and MV was higher among children with a health card/document (or a home-based record - HBR) than those without. Multiple other individual and family factors related to socio-economic and demographic status, access to communications technology, use of other services and length of stay in household were significantly associated with at least one of the outcome indicators using Chi-squared tests.

Of geospatial/community variables, rural/urban residence, livestock density index, travel time to nearest health facility, and vegetation index were associated with all three indicators (supplementary Tables S3, S6 and S8).

Multiple multilevel binomial analyses results

Figs 1- 3 show the adjusted odds ratios and their corresponding 95% credible intervals for receipt of PENTA1, PENTA3/1 and MV vaccination, based on any evidence of vaccination - definitions and reference categories are described in the supplementary Table S1 and detailed results shown in Tables S4, S5, S7 and S9. Note that Fig1 shows the results for both the main effects and the interaction terms for PENTA1.

Factors associated with vaccination were broadly similar for documented versus recall evidence of vaccination and included individual and community (geospatial) attributes. Although coverage of each vaccine-dose was higher in urban than rural areas, urban status was not significant in multivariable analyses. Based on any evidence of vaccination, we found that HBR, receipt of vitamin A and higher maternal educational level were significantly positively associated with each outcome. Indicators relating to socio-economic status, as well as ethnic group, skilled birth attendance, lower travel time to a clinic and reported problems seeking health care were significantly associated with both PENTA1 and MV. Maternal religion was related to PENTA1 and PENTA1/3 and maternal age related to MV and PENTA3/1; other variables were significantly associated with one outcome each.

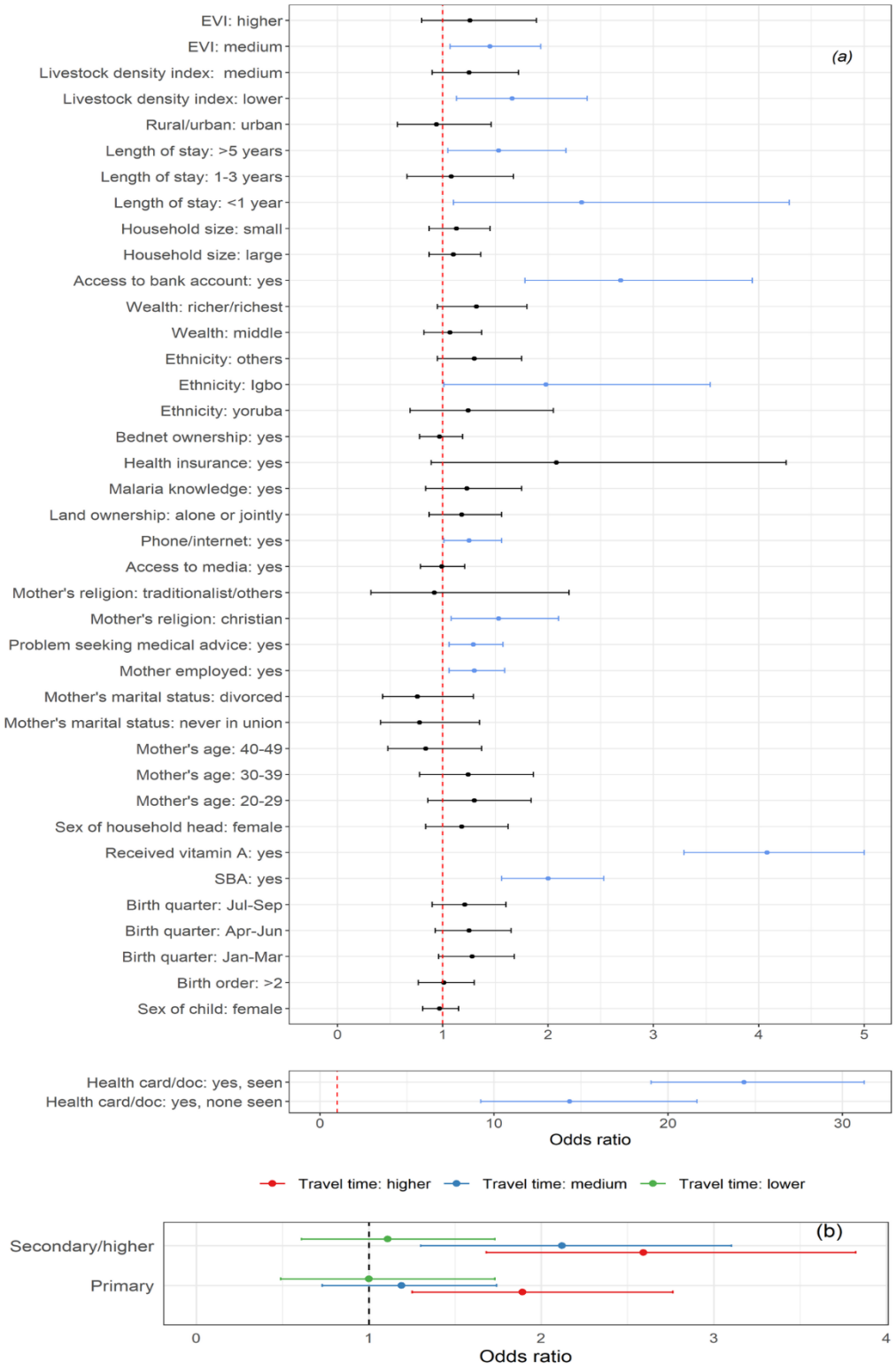

Fig 1. (a) Plots of adjusted odds ratios and corresponding 95% credible intervals based on the Bayesian multilevel binomial analysis for PENTA1. The vertical dotted lines mark the odds ratio of 1 and the blue lines mark significant covariates. (b) Interaction effects between maternal education and travel time to the nearest health facility for PENTA1. The vertical dotted line marks the odds ratio of 1.

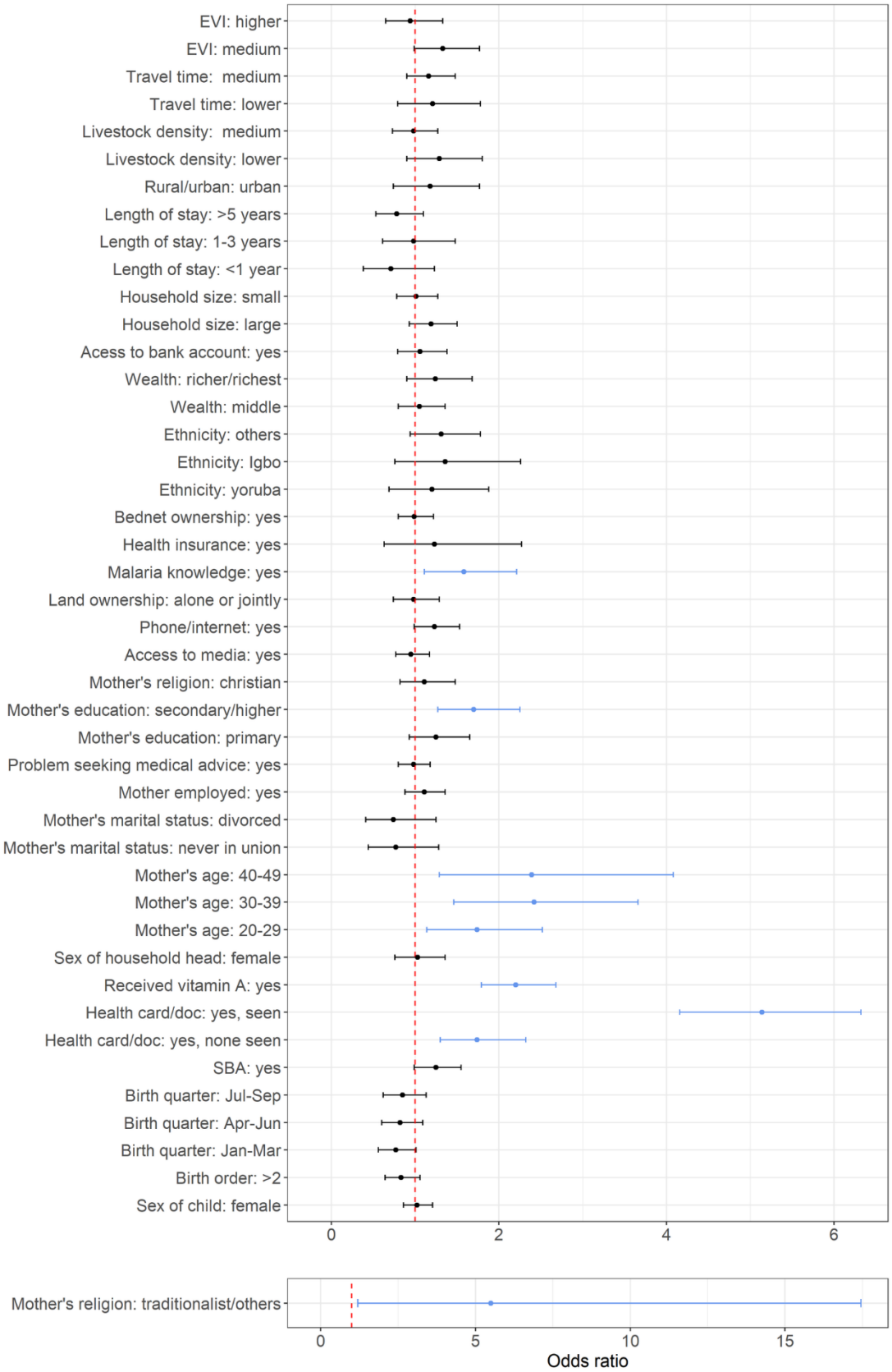

Fig 2. Plots of adjusted odds ratios and corresponding 95% credible interval based on Bayesian multilevel binomial analysis for PENTA3/1 (completion of the PENTA series among those who received PENTA1). The vertical dotted line marks the odds ratio of 1 and the blue lines mark significant covariates.

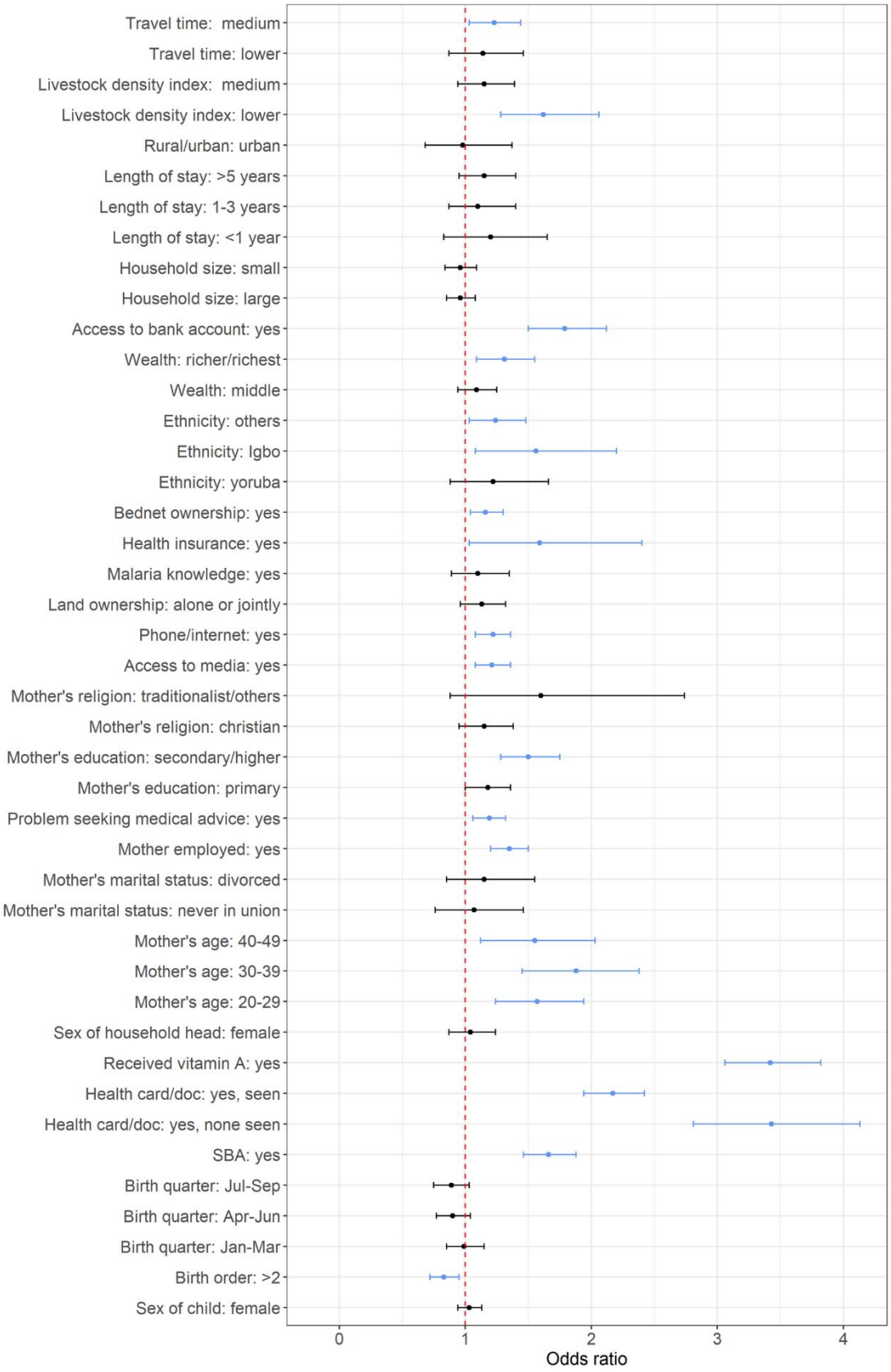

Fig 3. Plots of adjusted odds ratios and corresponding 95% credible interval based on Bayesian multilevel binomial analysis for MV vaccination coverage. The vertical dotted line marks the odds ratio of 1 and the blue lines mark significant covariates.

There were few differences in determinants of receipt of PENTA1 compared to MV (Fig 1 and Figs 3 and 4).

Being Christian (aOR=1.53, 95% Cr.I: 1.08, 2.10, compared with families practising Islam), having a length of stay of < 1 year (aOR=2.32, 95% Cr.I: 1.10, 4.29) or > 5 years (aOR=1.53, 95% Cr.I: 1.05, 2.17), and residence in communities with lower livestock density index (aOR=1.66, 95% Cr.I: 1.13, 2.37, reference higher livestock index) or those with medium vegetation index (aOR=1.45, 95% Cr.I: 1.07, 1.93, reference lower vegetation index) were associated with higher odds of receipt of PENTA1 but not MV. Significant interaction between maternal education and travel time to the nearest health facility was found in the model for PENTA1 vaccination (Fig 1(b), Tables S4 and S5). The effect of education was greatest among those with higher travel times and was not significant among the lowest travel times, while the effect of longer travel times was only significant among those whose mothers had no education (Table S5).

Birth order, wealth, health insurance, bednet ownership and access to traditional media were significantly associated with MV receipt but not the other outcomes. Interestingly, reporting a problem seeking health care was positively associated with receipt of both PENTA1 and MV. Among those who received PENTA1, receipt of PENTA3 was associated with mother's age, education, and knowledge of malaria, HBR possession and receipt of vitamin A (Fig 2, Table S7).

Finally, we summarized significant covariates in Fig 4 for easy reference.

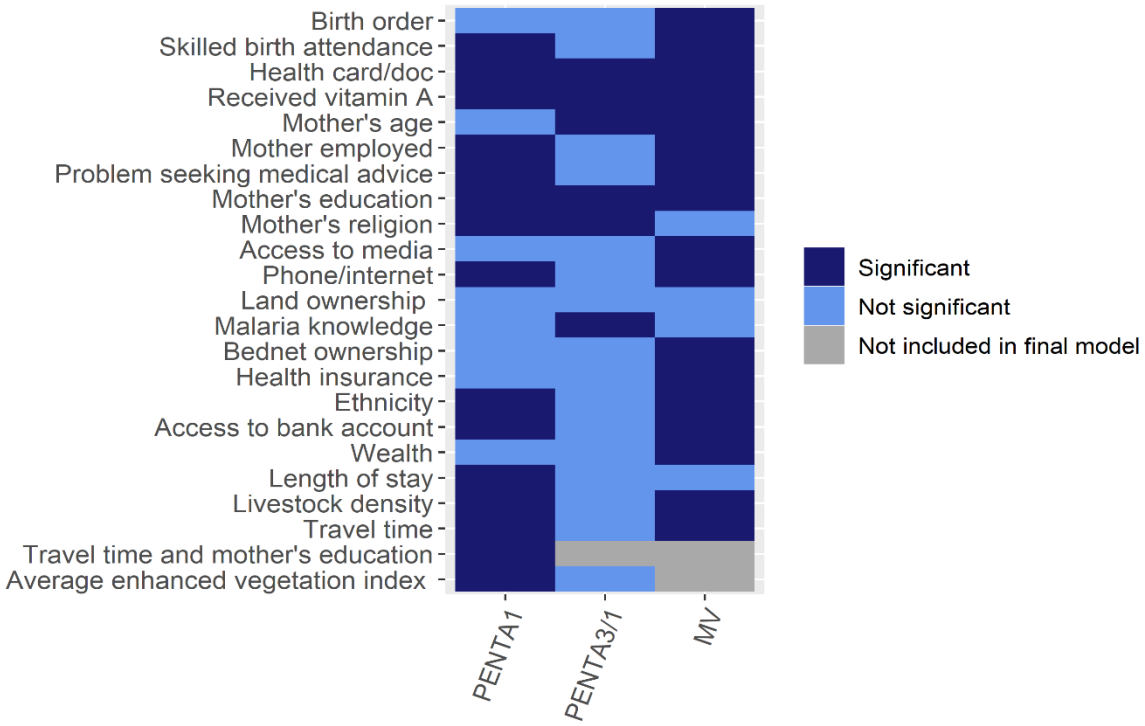

Fig 4. Summary of factors predictive of PENTA1, PENTA3/1 and MV vaccinations including the interaction term for PENTA1.

Substantial residual community level variances in different strata were observed in the fitted model for each outcome (Tables S4, S7 and S9). Specifically, 26%, 15%, and 19% of variation in PENTA1, PENTA3/1 and MV, respectively, could be attributable to communities in different strata. The median odds ratios of 2.7, 2.1, and 2.3 respectively for PENTA1, PENTA3/1 and MV, which are at least two times higher than the reference value (MOR=1), are an indication of substantial community level variation in the likelihood of receiving PENTA1, PENTA3/1 and MV vaccinations. Also, the estimated PCV values demonstrate that the covariates included in our models led to 67%, 61%, and 57% reduction in residual variation at both the community and stratum levels in the fitted models for PENTA1, PENTA3/1 and MV respectively. Lastly, the discriminatory or predictive power of the fitted models for correctly predicting the likelihood of PENTA1, PENTA3/1, and MV vaccinations based on the AUROC curve were 91.3%, 77.1% and 80.2% respectively as displayed in the supplementary Fig S3.

Multiple multilevel multinomial analyses results

Overall, there were few differences in the direction and magnitude of associations between the independent variables and the outcomes classified according to source of evidence of vaccination ("card valid" or "card invalid/history") – Fig 5, and supplementary Fig S4, supplementary Tables 10-13. A few differences were found, however. For example, for PENTA1, lower travel time significantly increased the odds of card valid vaccination but not card invalid/history vaccination and the effect of receipt of vitamin A was highest for card valid vaccination. For MV, areas with lower travel time (compared to higher travel time) and middle wealth status (compared to poorer/poorest) had significantly higher likelihood of card valid vaccination (relative to no evidence of vaccination) but not card invalid/history vaccination. Receipt of vitamin A was significantly associated with MV vaccination irrespective of source of evidence, but the effect was greater for card valid MV vaccination. Length of stay less than 1 year was associated with card invalid/history of vaccination but not card valid vaccination.

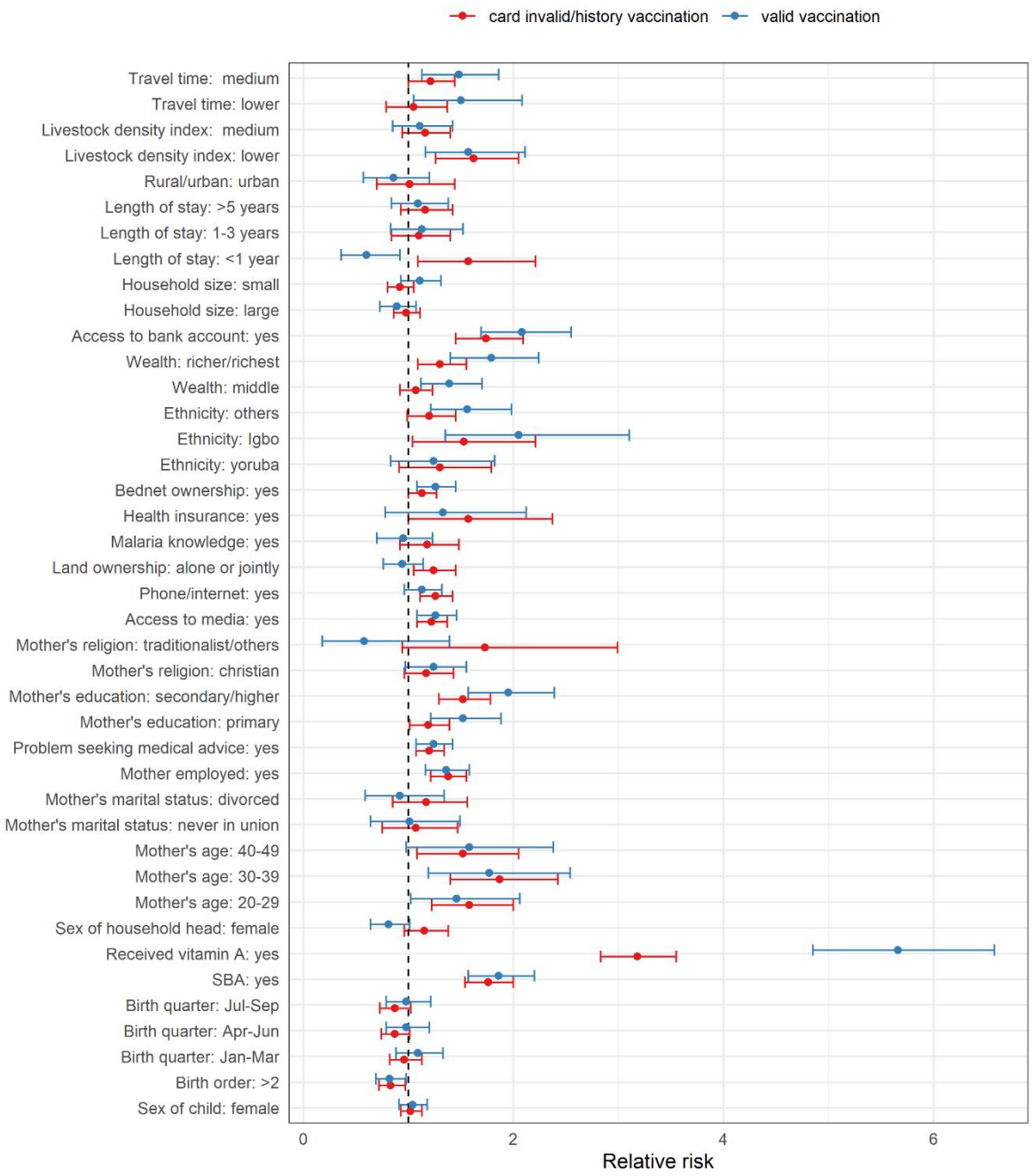

Fig 5. Plots of relative risks and corresponding 95% credible interval based on Bayesian multilevel multinomial analysis for MV vaccination coverage. The vertical dotted line marks the relative risk of 1.

Discussion

Our analyses of correlates of vaccination include several innovations. First, we examined separately factors associated with beginning (PENTA1) and completing (PENTA3/1 and MV) the vaccination series. Second, we included community-level geospatial factors as well as individual attributes. Third, we used multinomial analyses to examine potential

differences in findings when analyses were stratified by the strength of evidence of vaccination. Differences between associations of receipt of PENTA1 according to source of evidence may relate to misclassification of the outcome when a verbal history is accepted. The fact that we found few differences suggests that the mother's recall was reasonably accurate, as reported elsewhere [24, 50]. For MV, differences according to source of evidence may also relate to the vaccination strategy used. Children aged 12-35 months in Aug-Dec 2018 (when the DHS fieldwork was done) were mostly eligible for the November 2017 measles campaign in Nigeria. Doses recorded on the HBR represent only those received via routine immunization while a verbal history may include doses received during campaigns although we have previously found evidence that these are under-reported in Nigeria [20]. Overall, our analyses showed that for both PENTA1 and MV, factors that were predictive of card invalid/history vaccination were broadly similar to those that were predictive of card valid vaccination (i.e., the multinomial analysis), and to those found when considering any evidence of vaccination (i.e., the binomial analysis). There was a difference for travel time, where for both PENTA1 and MV, lower travel time to a health facility significantly increased the odds of card valid vaccination but not card invalid/history evidence of vaccination, indicating that proximity to a health facility has a marked influence on the timeliness and validity of vaccinations [4, 21, 51]. In what follows, we focus on the factors identified in the binomial analyses.

Ownership of a health card/document, receipt of Vitamin A - both of which are indicators of access to health services, and maternal education were positively associated with all three coverage indicators, the effect being modified by travel time for PENTA1, with mothers lacking education in remote areas being least likely to attend for vaccination. Skilled attendance at birth had significant positive associations with both PENTA1 and MV, further highlighting the importance of access to health services in improving vaccination coverage

and corroborating findings in previous studies [5, 10, 11, 15, 16, 28, 34, 35, 52-55]. Wealth-related indicators were associated with both PENTA1 and MV although some specific indicators differed, for example for PENTA1, maternal employment and having a bank account were important while for MV, wealth, health insurance, and bednet ownership were important. As is commonly found, economically empowered mothers make better health choices for their children [56, 57]. The association of PENTA1 with access to a mobile phone/internet may reflect both wealth and access to health information. Children born to Igbo mothers compared to Hausa/Fulani and those born to Christian mothers compared to Muslim mothers were more likely to receive PENTA1, which contributes to the geographical disparities in routine immunization (RI) coverage in the country [58, 59]. Associations of PENTA1 with livestock density and vegetation index may also reflect geographical disparities. Interestingly, the likelihood of PENTA1 receipt was higher among children born to mothers who reported a problem seeking medical advice/treatment, which we speculate to be a consequence of higher motivation and better health-seeking behaviour among these women. Thus, interventions seeking to improve vaccination coverage in remote areas should be designed especially with mother's educational level in mind [10, 11, 16].

While socio-economic factors helped predict PENTA1 receipt, among those who started the PENTA series, mother's education, knowledge of malaria, being at least ≥ 20 years old, possibly an indication of better knowledge of vaccination [16, 17, 28, 34, 52, 60, 61] and practising traditional/other religion (compared to Islam) were associated with increased likelihood of completion of the three-dose PENTA series (i.e. PENTA3/1), further highlighting the importance of maternal education and knowledge.

MV receipt was related both to socio-economic variables and access to media, birth order, health insurance, and bednet ownership. Children who had a birth order above two were less likely to receive MV, signalling that even though older mothers were more likely to have

their children vaccinated, this propensity could change with subsequent births [13, 14, 16, 58, 62, 63]. Health insurance and bednet ownership could reflect both wealth and a positive attitude to health care.

Finally, our analyses revealed substantial variation in the likelihood of vaccination at the community level, demonstrating the need for estimation of coverage and targeting of interventions at granular spatial scales [18, 19].

Study limitations

First, the study could not establish causal relationships due to the cross-sectional sampling design. Secondly, our study did not comprehensively assess all the factors that could affect vaccination coverage, particularly attitudes towards vaccination and supply-side factors such as vaccine and health worker availability and missed opportunities for vaccination [64] due to data limitations. Some important covariates such as antenatal care, postnatal care, and mother's receipt of tetanus toxoid injections before birth were excluded from the analysis because they had > 15% missing data for MV, but these would likely correlate with skilled birth attendance. Lastly, our analysis may have excluded important at-risk populations such as those living in conflict-affected areas and urban slums if the sampling frame used in the DHS did not fully capture these populations.

Conclusion

The study has identified several factors to be predictive of indicators of childhood vaccination coverage pointing to the need for an integrated approach to addressing inequities in vaccination coverage in Nigeria. This should include improvements in access to health facilities and services (e.g., skilled birth attendance), socioeconomic conditions of households, and improvements in maternal education through targeting uneducated and

teenage mothers with health literacy programmes including familiarization with the vaccination schedule and the importance of retention of home-based records. Also, better utilization of means of communication such as the traditional media and mobile phones/internet for disseminating vital health information is likely to yield improvements in coverage. Furthermore, community-focused interventions, and further research will be required to identify other supply- and demand-side factors as part of an overall strategy to improve childhood vaccination coverage in Nigeria. Also, the effects of the geospatial covariates are estimated for the entire country in our models. It will make sense to display maps of these if they were estimated for each region, for example. We will explore this detailed analysis in our future work.

Author contributions

CEU, FTC, AJT conceived and designed the study. OP, JMKA, WD-G, MKT, DAR and CEU contributed to data preparation. JMKA, CEU, DAR, FTC, WD-G performed the data analysis. JMKA, CEU, FTC wrote the first draft of the manuscript. All authors revised the manuscript and approved the final version of the manuscript.

Data availability statement

DHS data are publicly available from https://dhsprogram.com/data/available-datasets.cfm. Other data (i.e., geospatial covariates) are publicly available via the sources referenced in the methods section, and also presented in the Supplementary Information Table S2. The authors did not have any special access privileges that others would not have.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supporting Information

Multilevel analysis of predictors of multiple indicators of childhood vaccination in Nigeria

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Supporting Information

This supplementary information accompanies the main manuscript and contains Tables A–M, Figs A-D and additional texts referenced in the main manuscript.

Description and coding of outcome variables and covariate factors

Table A: Description and coding of outcome variables and covariate factors

Variable name and labels	Description and coding	Reference category
Outcome variables (binomial)		
Received PENTA1	No/don't know – 0, reported by mother/ vaccination date on card/ vaccination marked on card - 1	No/don't know – 0
Received PENTA3/1	Received PENTA1 but not PENTA3 – 0, Received both - 1	Received PENTA1 but not PENTA3 – 0
Received MV	No/don't know – 0, reported by mother/ vaccination date on card/ vaccination marked on card - 1	No/don't know – 0
Outcome variables (multinomial)		
Received PENTA1	No evidence of vaccination – 0, Card invalid/ history – 1, Card valid - 2	No evidence of vaccination – 0
Received MV	No evidence of vaccination – 0, Card invalid/ history – 1, Card valid - 2	No evidence of vaccination – 0
Predictor variables		
Sex of child	Male – 0, female – 1	Male – 0
Birth order	1-2 (1^{st} and 2^{nd} births) – 0, >2 - 1	1-2 – 0
Birth quarter	Jan-Mar – 0, Apr-Jun – 1, Jul-Sep – 2, Oct-Dec - 3	Oct-Dec - 3
Skilled birth attendance	No skilled attendant at birth – 0, Skilled attendant at birth - 1	No skilled attendant at birth – 0
Health card/document (or home-Based record -HBR)	Does not have health card/document – 0, yes, none seen – 1, yes, seen - 2	Does not have health card/document – 0
Received vitamin A	No/don't know – 0, Yes - 1	No/don't know – 0
Sex of household head	Male – 0, Female – 1	Male – 0

Mother's age group	15-19 – 0, 20-29 – 1, 30-39 – 2, 40-49 – 3	15-19 – 0
Marital status of mother	Never in union – 0, married – 1, Divorced – 2	married – 1
Mother employed in the past 12 months	No – 0, Yes (currently/in the past 1 year) – 1	No – 0
Mother had problem seeking medical advice or treatment	Did not have problem seeking medical advice or treatment – 0, Had problem seeking medical advice or treatment – 1	Did not have problem seeking medical advice or treatment – 0
Mother's education	No education – 0, Primary – 1, Secondary/higher – 2	No education – 0
Mother's religion	Islam – 0, Christian – 1, Traditionalist/others – 2	Islam – 0
Mother's media exposure	No – 0, Yes (radio/tv/newspaper at least once a week) – 1	No – 0
Mother's access to mobile phone/internet	No – 0, Yes – 1	No – 0
Mother's land ownership	Does not own land – 0, Owns land alone and/or jointly – 1	Does not own land – 0
Mother's knowledge of malaria	Has no knowledge – 0, Has knowledge – 1	Has no knowledge – 0
Mother had health insurance	No – 0, Yes – 1	No – 0
Household's bed net ownership	No – 0, Yes – 1	No – 0
Mother's ethnicity	Hausa/Fulani – 0, Yoruba – 1, Igbo – 2, Others (ekoi, ibibio, etc.) – 3	Hausa/Fulani – 0
Household wealth	Poorer/poorest – 0, Middle – 1, Richer/richest – 2	Poorer/poorest – 0
Access to bank account	No – 0, Yes – 1	No – 0
Household size	Large (>=9) – 0, Medium (5 to 8) – 1, Small (<=4) – 2	Medium (5 to 8) – 1
Length of stay in household	<1year/visitor – 0, 1-3years – 1, 4-5years – 2, >5years/always – 3	4-5years – 2
Rural/urban	Rural – 0, Urban – 1	Rural – 0
Livestock density index	Lower (0-21.4) – 0, Medium (21.5-73.2) – 1, Higher (73.3-5196.8) – 2	Higher (73.3-5196.8) – 2
Travel time to the nearest health facility (providing RI services)	Lower (0-3.9) – 0, Medium (4.0-12.5) – 1, Higher (12.6-532.8) – 2	Higher (12.6-532.8) – 2
Average enhanced vegetation index (2013-2018)	Lower (0.07-0.23) – 0, Medium (0.24-0.36) – 1, Higher (0.364-0.57) – 2	Lower (0.07-0.23)

Geospatial covariate description and processing steps

The geospatial covariates used in the analyses, as described in the main manuscript were travel time to the nearest health facility providing routine immunization (RI) services, livestock density and Enhanced Vegetation Index (EVI). These covariates were obtained from the sources mentioned in Table S2 and were processed as follows. Using ESRI ArcGIS v10.7, standardised gridded covariate layers were processed at 1km x 1 km for Nigeria from the raw data sets. For EVI, the data for the raster layers were taken from the 5-year period prior to the DHS survey, however, this was not possible for the other covariates. These layers were further processed to obtain the average EVI over the period. The livestock density index used in our work was obtained as the average of the individual livestock densities (i.e., cattle, chicken, goat, pig, and sheep) listed in Table B. Following these, covariate data values were extracted from each raster layer for each DHS cluster location using R. Prior to extraction, considerations for urban and rural clusters were made as in previous work [1] and buffers were created for data extraction to calculate a mean value at 2 km for urban areas and 5 km for rural areas. We present the surfaces of the resulting geospatial covariates and the extracted values at the cluster level in Fig A.

Table B: Description and sources of geospatial covariates used in our analyses.

1	Cattle density	No. of cattle per sq km	2010	Continuous	Gilbert, M. *et al.* (2018) Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010. Nature Scientific data, 5:180227. doi: 10.1038/sdata.2018.227
2	Chicken density	No. of chickens per sq km	2010	Continuous	Gilbert, M. *et al.* (2018) Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010. Nature Scientific data, 5:180227. doi: 10.1038/sdata.2018.227
3	Goat density	No. of goats per sq km	2010	Continuous	Gilbert, M. *et al.* (2018) Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010. Nature Scientific data, 5:180227. doi: 10.1038/sdata.2018.227
4	Pig density	No. Of pigs per sq km	2010	Continuous	Gilbert, M. *et al.* (2018) Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010. Nature Scientific data, 5:180227. doi: 10.1038/sdata.2018.227
5	Sheep density	No. Of sheep per sq km	2010	Continuous	Gilbert, M. *et al.* (2018) Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010. Nature Scientific data, 5:180227. doi: 10.1038/sdata.2018.227
6	Travel time to health facilities providing routine immunization (RI)	Minutes	2018	Continuous	[*Produced from locations of health facilities in Nigeria using the methodology in*] Weiss, D.J. *et al*. (2018). A global map of travel time to cities to access inequalities in accessibility in 2015. *Nature*.
7	Average Modis Enhanced Vegetation Index between 2013 and 2018	EVI (0 to 1)	2013-2018	Continuous	Didan, K. (2015). MOD13A3 MODIS/Terra vegetation Indices Monthly L3 Global 1km SIN Grid V006. NASA EOSDIS LP DAAC.

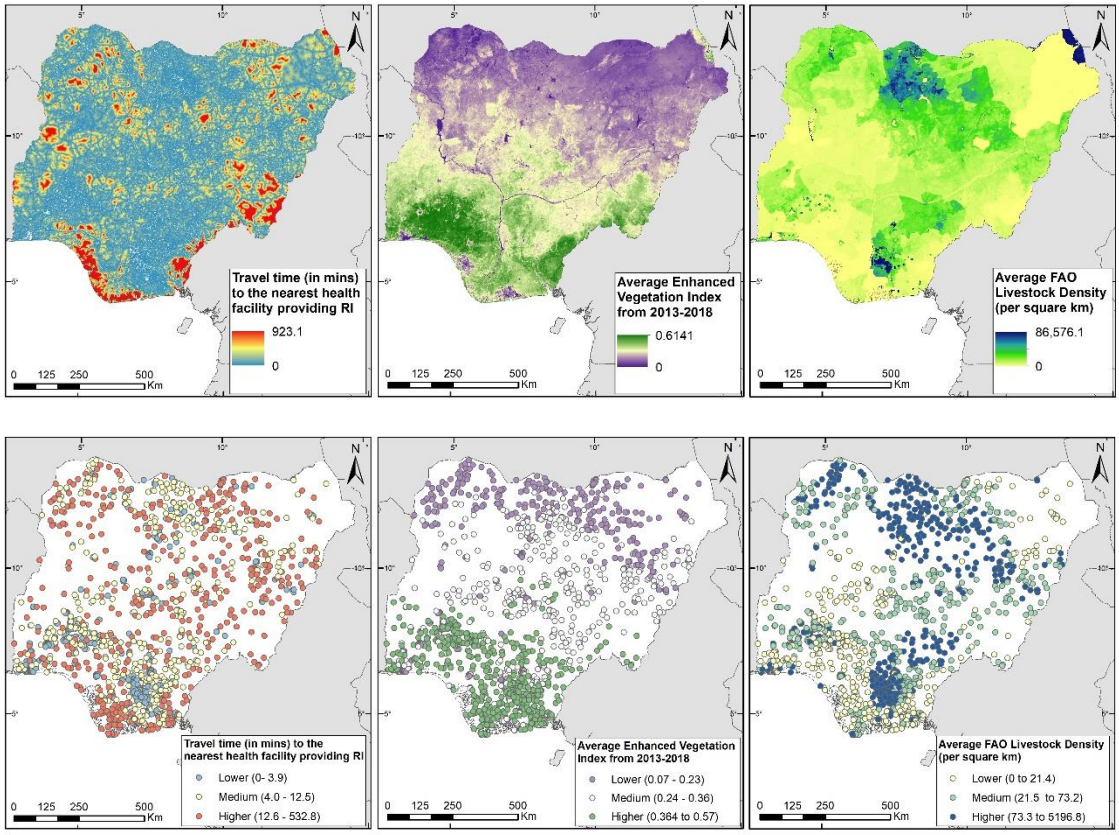

Fig A. Geospatial covariates used in our analyses (top row) and the corresponding cluster-level values (bottom row). The three classes shown in the bottom row for each covariate were obtained using the tertiles of the distribution of the covariate.

Additional information on the data structure for our study

Here, we provided the hierarchical structure of our data that necessitated the use of multilevel modelling framework in our study (Fig B).

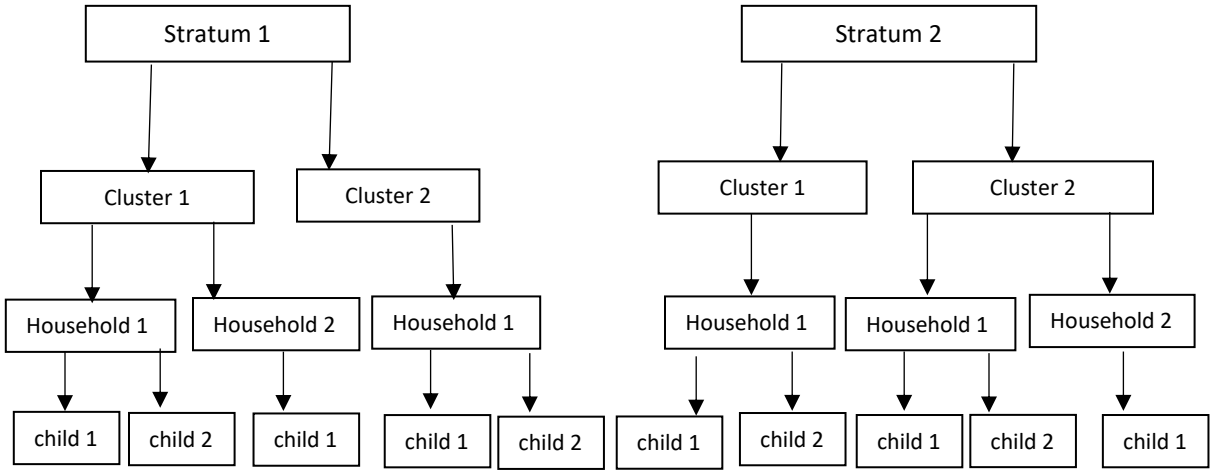

Fig B. The hierarchical structure of the data set used in the study.

Additional information on model-fitting and evaluation

Bayesian multiple multilevel binomial regression model

We fitted Bayesian multilevel [2, 3] binomial regression models to examine factors that are predictive of each outcome. To account for the complex design used in the DHS (stratification and nesting within households and clusters/communities), we introduced a stratification variable and a cluster/community variable as random effects in our model. We did not include a household level random effect in our analysis due to insufficient sample sizes at this level and the resultant potential bias in variance estimates and effect sizes. To incorporate the predictors in our model, we first considered the selected DHS covariates and examined their contributions to the model fit as well as any problems due to multicollinearity. Where there was evidence of multicollinearity in all three indicators, the predictor was excluded from the analysis.

This was followed by the inclusion of the geospatial covariates. We excluded some of the pre-selected geospatial covariates from the analysis due to evidence of multicollinearity between these variables and some DHS covariates. The results of the fitted model were presented as adjusted odds ratios with their associated 95% Bayesian credible intervals. In addition, we presented the variance estimates, measures of variation attributable to the different levels in the data and some model evaluation statistics all of which are described below.

Model building/specification

The Bayesian multiple multilevel binomial regression is described as follows. Let P_{ijk} be the probability that child *i* from community *j* in stratum k received the given vaccination (coded as *yes* = 1 and *no* = 0 for any evidence of vaccination and no evidence of vaccination, respectively), and $\pi_{ijk} = \left(\frac{P_{ijk}}{1 - P_{ijk}}\right)$ the corresponding odds of vaccination. First, we considered an intercept only, three-level model (child, community/cluster and stratum levels) given by:

$$\log\left(\frac{P_{ijk}}{1 - P_{ijk}}\right) = \beta_0 + c_{0jk} + s_{0k} \qquad (1)$$

where β_0 is the intercept or overall probability of vaccination, c_{0j} is the community-level random effect for the jth community, and s_{0k} is the stratum-level random effect for stratum *k*. Further, c_{0j} is assumed to follow a normal distribution with mean zero (0) and variance σ_{c0}^2, while s_{0k} is also assumed to be normally distributed with zero mean and variance σ_s^2. This model was used to evaluate the contribution of covariates in the analyses.

We extended equation (1) to incorporate the set of covariates selected for the study. The full model can be expressed as:

$$\log\left(\frac{P_{ijk}}{1-P_{ijk}}\right) = \beta_0 + \boldsymbol{d}(\boldsymbol{x_{ijk}})'\boldsymbol{\beta} + c_{0jk} + s_{0k} \qquad (2)$$

where $\boldsymbol{d}(.)$ is a vector of predictors that can be defined at the child, household, or community levels and $\boldsymbol{\beta}$ is the corresponding vector of regression coefficients. Other terms in the model are as defined previously. We note that in the model, the child-level (i.e., level-1) residual follows a standard logistic distribution with mean zero and variance $\frac{\pi^2}{3}$ which is approximately 3.29 [4, 5]. Furthermore, we fitted frequentist single level simple logistic regression models to obtain the corresponding crude odds ratios and associated 95% confidence intervals which were later compared with results from the multivariable analyses to determine changes in statistical significance and direction of effects.

The measures of variation considered in the study were: the variance partitioning coefficient (VPC), median odds ratio (MOR), and percentage change in variance (PCV) [6-10]. These are described as follows.

Variance partitioning coefficient (VPC)

We determined the VPC based on the estimated community and stratum variances from the fitted Bayesian multilevel models presented in equation (2). We estimated the VPC as:

$$\text{VPC} = \left(\frac{\sigma_c^2 + \sigma_s^2}{\sigma_c^2 + \sigma_s^2 + {\pi^2}/{3}}\right) \times 100 \qquad (4)$$

where σ_c^2 and σ_s^2 are the cluster and stratum level variances respectively, and ${\pi^2}/{3}$ is the child-level variance. The VPC measures the percentage of residual variation due to differences between communities in different strata.

Median odds ratios (MOR) and Percentage change in variance (PCV)

Similarly, the MOR and PCV were determined based on the estimated residual variances from the fitted model presented in equation (2). The MOR is the median odds ratio between a child in a community with a higher probability of receiving vaccination and a child in a community with a lower probability of receiving vaccination, given similar child level characteristics [11, 12]. Thus, the MOR quantifies residual community level variation (residual contextual heterogeneity) in the model on the odds ratio scale. It is easy to interpret and understand as it is expressed in terms of inter-community variance on the odds ratio scale, similar to the fixed effects [12]. We estimate the MOR based on community random effect as:

$$MOR = exp\left(\sqrt{2 \times \sigma_c^2} \times \varphi^{-1}(0.75)\right) \cong exp\left(0.945 \times \sqrt{\sigma_c^2}\right) \quad (5)$$

where σ_c^2 is the estimated community level variance from model (2) and $\varphi^{-1}(0.75)$ is the 75th centile of the standard normal density which is approximately 0.6745.

The percentage change in variance (PCV) on the other hand is estimated as:

$$\text{PCV} = \left(\frac{V_0 - V_f}{V_0}\right) \times 100 \quad (6)$$

where $V_0 = \sigma_c^2 + \sigma_s^2$ is the variance from the empty model in equation (1) and V_f is the corresponding variance from the full model in equation (2). The PCV measures the change in residual variance due to the inclusion of covariates in the fitted model.

Bayesian multiple multilevel multinomial regression model

Here, we extend equation (2) to allow for modelling of multinomial outcomes for PENTA1 and MV. For each outcome, the vaccination status is classified into three (3) categories: no evidence of vaccination = 0, card invalid/history vaccination = 1, and card valid vaccination = 2. Our interest is in estimating the likelihood of a child having either card invalid/history or card valid

evidence of vaccination relative to no evidence of vaccination whilst adjusting for child, household, and community-level factors. Here again, we included stratification and cluster/community random effects as a way of adjusting for the complex survey design.

We assume that child *i* in community *j* within stratum *k* can be assigned to one of the three categories of vaccination and set the first category (i.e., no evidence of vaccination) to be the reference category. We set up a random intercept model incorporating the same predictors in the previous model in Equation (2). The model has two (2) equations contrasting the log-odds of having each of the evidence of vaccination: card invalid/history (1) and card valid (2) vaccinations against the reference category of no evidence of vaccination (0).

Let $Y_{ijk} \sim \text{Multinomial}\left(\pi_{ijk}^{(1)}, \pi_{ijk}^{(2)}\right)$, where Y_{ijk} is the vaccination status for child *i* in community *j* within stratum *k*, and $\pi_{ijk}^{(1)}$ and$\pi_{ijk}^{(2)}$ are the probabilities of having card invalid/history and card valid evidence of vaccination, respectively.

The multinomial multilevel model[13, 14] is given as follows:

$$\log\left(\frac{\pi_{ijk}^{(1)}}{\pi_{ijk}^{(0)}}\right) = \alpha_0^{(1)} + \boldsymbol{d}(\boldsymbol{x}_{ijk})'\boldsymbol{\beta}^{(1)} + c_{jk}^{(1)} + s_k^{(1)},$$

$$\log\left(\frac{\pi_{ijk}^{(2)}}{\pi_{ijk}^{(0)}}\right) = \alpha_0^{(2)} + \boldsymbol{d}(\boldsymbol{x}_{ijk})'\boldsymbol{\beta}^{(2)} + c_{jk}^{(2)} + s_k^{(2)},$$

$$\begin{pmatrix} c_{jk}^{(1)} \\ c_{jk}^{(2)} \end{pmatrix} \sim MVN\left\{\begin{pmatrix} 0 \\ 0 \end{pmatrix} \begin{pmatrix} \sigma_{c(1)}^2 & \\ \sigma_{c(1,2)}^2 & \sigma_{c(2)}^2 \end{pmatrix}\right\},$$

$$\begin{pmatrix} s_k^{(1)} \\ s_k^{(2)} \end{pmatrix} \sim MVN\left\{\begin{pmatrix} 0 \\ 0 \end{pmatrix} \begin{pmatrix} \sigma_{s(1)}^2 & \\ \sigma_{s(1,2)}^2 & \sigma_{s(2)}^2 \end{pmatrix}\right\}, \quad (3)$$

where, $\alpha_0^{(1)}$ and $\alpha_0^{(2)}$ are the intercepts for card invalid/history and card valid evidence of vaccination, respectively. $\boldsymbol{d}(.)$ is a vector of predictors, and $\boldsymbol{\beta}^{(1)}$ and $\boldsymbol{\beta}^{(2)}$ are the corresponding vectors of regression coefficients. The quantities $c_{jk}^{(1)}$ and $c_{jk}^{(2)}$, and $s_k^{(1)}$ and $s_k^{(2)}$ are assumed to follow multivariate normal distributions. $\sigma_{c(1)}^2$ and $\sigma_{c(2)}^2$ are the community-level variances for card invalid/history and card valid evidence of vaccination, respectively, and their corresponding covariance $\sigma_{c(1,2)}^2$, while $\sigma_{s(1)}^2$ and $\sigma_{s(2)}^2$ are the corresponding stratum-level variances, and their corresponding covariance $\sigma_{s(1,2)}^2$.

Prior distributions for fixed and random effects

We complete our Bayesian specification by placing appropriate prior distributions on the parameters of the models. We specified Gaussian priors for the fixed effect parameters, including the intercept, and Gamma priors for all the variance parameters in both the binomial and multinomial models. Further, we obtained the initial values of all the parameters, as well as the hyperparameters, from frequentist analyses for each indicator and covariate using corresponding multilevel models and the same set of covariates included in the final Bayesian analyses, except the multinomial model for PENTA1 where we set the means of the Gaussian priors of some fixed effect parameters to log(1) due to non-convergence problems. We deemed this approach reasonable due to lack of information on reliable priors for our model parameters [15]. An alternative approach is to use non-informative priors for the model parameters.

Bayesian models

One of our interests in this study is to employ novel Bayesian modelling approach to investigate predictors of childhood vaccination. Undoubtedly, the Bayesian modelling is one of the novel approaches in model fitting and model diagnostics. For example, in the Bayesian approach, two different sources of uncertainties (i.e., uncertainty in the parameter values and sampling uncertainty) in our estimates can be quantified and the 95% credible intervals fixed while the estimated parameters are allowed to vary unlike the frequentist (i.e., classical) approach. Also, the type of the modelling implemented in this study, especially the multiple multilevel multinomial and binomial regression models can effectively and efficiently be implemented in the Bayesian framework compared to the frequentist due to the model complexity and computational cost. These are the key reasons we opted for the Bayesian approach rather than the frequentist.

Multicollinearity assessment

We addressed the problem of (multi)collinearity by computing the generalized variance inflation factors (GVIFs) [16] of the covariates for each country-vaccine combination and excluded variables that had high GVIFs (> 2, on the scale that ensures comparability across the covariates as recommended by Fox and Monette, 1992) [16-18].

Additional results of the binomial analysis for PENTA1

Table C: Factors associated with any evidence of PENTA1 vaccination, cross-tabulation analyses of Nigeria DHS 2018

		PENTA1		
		No	**Yes**	
Variables	**N**	**n (%)**	**n (%)**	**P-value**
N	6059	2122 (35)	3937 (65)	
Sex of child				0.690
Male	3148	1110 (35.3)	2038 (64.7)	
Female	2911	1012 (34.8)	1899 (65.2)	
Birth order				<0.001***
1-2	2279	674 (29.6)	1605 (70.4)	
>2	3780	1448 (38.3)	2332 (61.7)	
Birth quarter				0.052
Jan-Mar	1909	630 (33.0)	1279 (67.0)	
Apr-Jun	1668	592 (35.5)	1076 (64.5)	
Jul-Sep	1628	608 (37.3)	1020 (62.7)	
Oct-Dec	854	292 (34.2)	562 (65.8)	
Skilled birth attendance				<0.001***
No skilled attendant at birth	3328	1772 (53.2)	1556 (46.8)	
Skilled attendant at birth	2731	350 (12.8)	2381 (87.2)	
Health card/document				<0.001***
Does not have health card/document	3113	1934 (62.1)	1179 (37.9)	
Yes, none seen	519	42 (8.1)	477 (91.9)	
Yes, seen	2427	146 (6.0)	2281 (94.0)	
Received vitamin A				<0.001***
No/don’t know	2852	1569 (55.0)	1283 (45.0)	
Yes	3207	553 (17.2)	2654 (82.8)	
Sex of household head				<0.001***
Male	5434	1996 (36.7)	3438 (63.3)	
Female	625	126 (20.2)	499 (79.8)	
Mother's age group				<0.001***
15-19	366	183 (50.0)	183 (50.0)	
20-29	3019	1054 (34.9)	1965 (65.1)	
30-39	2237	684 (30.6)	1553 (69.4)	
40-49	437	201 (46.0)	236 (54.0)	
Marital status of mother				0.002
Never in union	171	38 (22.2)	133 (77.8)	
Married	5730	2029 (35.4)	3701 (64.6)	
Divorced	158	55 (34.8)	103 (65.2)	
Mother employed in the past 12 months				<0.001***
No	1777	854 (48.1)	923 (51.9)	
Yes (currently/in the past 1 year)	4282	1268 (29.6)	3014 (70.4)	

Mother had problem seeking medical advice or treatment				<0.001***
Had problem seeking medical advice or treatment	3397	1387 (40.8)	2010 (59.2)	
Did not have problem seeking medical advice or treatment	2662	735 (27.6)	1927 (72.4)	
Mother's education				<0.001***
No education	2614	1567 (59.9)	1047 (40.1)	
Primary	881	242 (27.5)	639 (72.5)	
Secondary/higher	2564	313 (12.2)	2251 (87.8)	
Mother's religion				<0.001***
Islam	3538	1756 (49.6)	1782 (50.4)	
Christian	2469	343 (13.9)	2126 (86.1)	
Traditionalist/others	52	23 (44.2)	29 (55.8)	
Mother's media exposure				<0.001***
No	3729	1652 (44.3)	2077 (55.7)	
Yes (radio/tv/newspaper at least once a week)	2330	470 (20.2)	1860 (79.8)	
Mother's access to mobile phone/internet				<0.001***
No	3062	1562 (51.0)	1500 (49.0)	
Yes	2997	560 (18.7)	2437 (81.3)	
Mother's land ownership				<0.001***
Does not own land	5236	1927 (36.8)	3309 (63.2)	
Owns land alone and/or jointly	823	195 (23.7)	628 (76.3)	
Mother's knowledge of malaria				0.100
Has no knowledge	386	150 (38.9)	236 (61.1)	
Has knowledge	5673	1972 (34.8)	3701 (65.2)	
Mother had health insurance				<0.001***
No	5925	2102 (35.5)	3823 (64.5)	
Yes	134	20 (14.9)	114 (85.1)	
Household's bed net ownership				<0.001***
No	1780	516 (29.0)	1264 (71.0)	
Yes	4279	1606 (37.5)	2673 (62.5)	
Mother's ethnicity				<0.001***
Hausa/Fulani	2364	1354 (57.3)	1010 (42.7)	
Yoruba	622	86 (13.8)	536 (86.2)	
Igbo	847	60 (7.1)	787 (92.9)	
Others (ekoi, ibibio, etc.)	2226	622 (27.9)	1604 (72.1)	
Household wealth				<0.001***
Poorer/poorest	2784	1486 (53.4)	1298 (46.6)	
Middle	1253	366 (29.2)	887 (70.8)	
Richer/richest	2022	270 (13.4)	1752 (86.6)	
Access to bank account				<0.001***
No	5035	2063 (41.0)	2972 (59.0)	

Yes	1024	59 (5.8)	965 (94.2)	
Household size				<0.001***
Large (>=9)	1464	705 (48.2)	759 (51.8)	
Medium (5 to 8)	2760	906 (32.8)	1854 (67.2)	
Small (<=4)	1835	511 (27.8)	1324 (72.2)	
Length of stay in household				<0.001***
<1year/visitor	174	27 (15.5)	147 (84.5)	
1-3years	711	177 (24.9)	534 (75.1)	
4-5years	438	121 (27.6)	317 (72.4)	
>5years/always	4736	1797 (37.9)	2939 (62.1)	
Rural/urban				<0.001***
Rural	3959	1717 (43.4)	2242 (56.6)	
Urban	2100	405 (19.3)	1695 (80.7)	
Livestock density index				<0.001***
Lower (0-21.4)	1637	434 (26.5)	1203 (73.5)	
Medium (21.5-73.2)	2034	702 (34.5)	1332 (65.5)	
Higher (73.3-5196.8)	2365	981 (41.5)	1384 (58.5)	
Travel time to the nearest health facility (providing RI services)				<0.001***
Lower (0-3.9)	1683	288 (17.1)	1395 (82.9)	
Medium (4.0-12.5)	2000	661 (33.1)	1339 (67.0)	
Higher (12.6-532.8)	2353	1168 (49.6)	1185 (50.4)	
Average enhanced vegetation index (2013-2018)				<0.001***
Lower (0.07-0.23)	2395	1184 (49.4)	1211 (50.6)	
Medium (0.24-0.36)	2202	688 (31.2)	1514 (68.8)	
Higher (0.364-0.57)	1439	245 (17.0)	1194 (83.0)	

*p<0.05; **p<0.01; ***p<0.001

Table D: Percentage of children aged 12 to 23 months with any evidence of PENTA1 vaccination, according to potential determinants of vaccination, univariate and multivariable analyses of Nigeria DHS 2018

Characteristics and categories	Number (%) in category	Percentage with any evidence of PENTA1 [95% CI]	Frequentist single-level model: cOR [95% CI]	Bayesian multilevel model: aOR [95% Cr. I]
N	6059(100.0)			
Sex of child				
Male	3148 (52.0)	64.7 [63.1, 66.4]	1.00 [reference]	1.00 [reference]
Female	2911 (48.0)	65.2 [63.5, 66.9]	1.02 [0.92, 1.14]	0.97 [0.81, 1.15]
Birth order				
1-2	2279 (37.6)	70.4 [68.5, 72.3]	1.00 [reference]	1.00 [reference]
>2	3780 (62.4)	61.7 [60.1, 63.2]	0.68 [0.61, 0.76] ***	1.01 [0.77, 1.30]
Birth quarter				
Jan-Mar	1909 (31.5)	67.0 [64.9, 69.1]	1.05 [0.89, 1.25]	1.28 [0.96, 1.68]
Apr-Jun	1668 (27.5)	64.5 [62.2, 66.8]	0.94 [0.79, 1.12]	1.25 [0.93, 1.65]
Jul-Sep	1628 (26.9)	62.7 [60.3, 65.0]	0.87 [0.73, 1.04]	1.21 [0.90, 1.60]
Oct-Dec	854 (14.1)	65.8 [62.6, 68.9]	1.00 [reference]	1.00 [reference]
Skilled birth attendance				
No skilled attendant at birth	3328 (54.9)	46.8 [45.1, 48.5]	1.00 [reference]	1.00 [reference]
Skilled attendant at birth	2731 (45.1)	87.2 [85.9, 88.4]	7.75 [6.79, 8.83] ***	2.00 [1.56, 2.53] +
Health card/document				

Does not have health card/document	3113 (51.4)	37.9 [36.2, 39.6]	1.00 [reference]	1.00 [reference]
Yes, none seen	519 (8.6)	91.9 [89.2, 94.0]	18.63 [13.48, 25.75] ***	14.34 [9.25, 21.66] +
Yes, seen	2427 (40.1)	94.0 [93.0, 94.9]	25.63 [21.36, 30.75] ***	24.36 [19.02, 31.25] +
Received vitamin A				
No/don’t know	2852 (47.1)	45.0 [43.2, 46.8]	1.00 [reference]	1.00 [reference]
Yes	3207 (52.9)	82.8 [81.4, 84.0]	5.87 [5.22, 6.60] ***	4.08 [3.29, 5.00] +
Sex of household head				
Male	5434 (89.7)	63.3 [62.0, 64.5]	1.00 [reference]	1.00 [reference]
Female	625 (10.3)	79.8 [76.5, 82.8]	2.30 [1.88, 2.82] ***	1.18 [0.84, 1.62]
Mother's age group				
15-19	366 (6.0)	50.0 [44.9, 55.1]	1.00 [reference]	1.00 [reference]
20-29	3019 (49.8)	65.1 [63.4, 66.8]	1.86 [1.50, 2.32] ***	1.30 [0.86, 1.84]
30-39	2237 (36.9)	69.4 [67.5, 71.3]	2.27 [1.82, 2.84] ***	1.24 [0.78, 1.86]
40-49	437 (7.2)	54.0 [49.3, 58.6]	1.17 [0.89, 1.55]	0.84 [0.48, 1.37]
Marital status of mother				
Never in union	171 (2.8)	77.8 [70.9, 83.4]	1.92 [1.33, 2.76] ***	0.78 [0.41, 1.35]
Married	5730 (94.6)	64.6 [63.3, 65.8]	1.00 [reference]	1.00 [reference]
Divorced	158 (2.6)	65.2 [57.4, 72.2]	1.03 [0.74, 1.43]	0.76 [0.43, 1.29]
Mother employed in the past 12 months				

No	1777 (29.3)	51.9 [49.6, 54.3]	1.00 [reference]	1.00 [reference]
Yes (currently/in the past 1 year)	4282 (70.7)	70.4 [69.0, 71.7]	2.20 [1.96, 2.46] ***	1.30 [1.06, 1.59] +
Mother had problem seeking medical advice or treatment				
Did not have problem seeking medical advice or treatment	3397 (56.1)	59.2 [57.5, 60.8]	1.00 [reference]	1.00 [reference]
Had problem seeking medical advice or treatment	2662 (43.9)	72.4 [70.7, 74.1]	1.81 [1.62, 2.02] ***	1.29 [1.06, 1.57] +
Mother's religion				
Islam	3538 (58.4)	50.4 [48.7, 52.0]	1.00 [reference]	1.00 [reference]
Christian	2469 (40.7)	86.1 [84.7, 87.4]	6.11 [5.35, 6.97] ***	1.53 [1.08, 2.10] +
Traditionalist/others	52 (0.9)	55.8 [42.2, 68.5]	1.24 [0.72, 2.16]	0.92 [0.32, 2.20]
Mother's media exposure				
No	3729 (61.5)	55.7 [54.1, 57.3]	1.00 [reference]	1.00 [reference]
Yes (radio/tv/newspaper at least once a week)	2330 (38.5)	79.8 [78.1, 81.4]	3.15 [2.79, 3.55] ***	0.99 [0.79, 1.21]
Mother's access to mobile phone/internet				
No	3062 (50.5)	49.0 [47.2, 50.8]	1.00 [reference]	1.00 [reference]
Yes	2997 (49.5)	81.3 [79.9, 82.7]	4.53 [4.04, 5.09] ***	1.25 [1.01, 1.56] +
Mother's land ownership				
Does not own land	5236 (86.4)	63.2 [61.9, 64.5]	1.00 [reference]	1.00 [reference]
Owns land alone and/or jointly	823 (13.6)	76.3 [73.3, 79.1]	1.88 [1.58, 2.22] ***	1.18 [0.87, 1.56]
Mother's knowledge of malaria				

Has no knowledge	386 (6.4)	61.1 [56.2, 65.9]	1.00 [reference]	1.00 [reference]
Has knowledge	5673 (93.6)	65.2 [64.0, 66.5]	1.19 [0.97, 1.47]	1.23 [0.84, 1.75]
Mother had health insurance				
No	5925 (97.8)	64.5 [63.3, 65.7]	1.00 [reference]	1.00 [reference]
Yes	134 (2.2)	85.1 [78.0, 90.2]	3.13 [1.94, 5.06] ***	2.08 [0.89, 4.26]
Household's bed net ownership				
No	1780 (29.4)	71.0 [68.9, 73.1]	1.00 [reference]	1.00 [reference]
Yes	4279 (70.6)	62.5 [61.0, 63.9]	0.68 [0.60, 0.77] ***	0.97 [0.78, 1.19]
Mother's ethnicity				
Hausa/Fulani	2364 (39.0)	42.7 [40.7, 44.7]	1.00 [reference]	1.00 [reference]
Yoruba	622 (10.3)	86.2 [83.2, 88.7]	8.36 [6.56, 10.64] ***	1.24 [0.69, 2.05]
Igbo	847 (14.0)	92.9 [91.0, 94.5]	17.58 [13.36, 23.15] ***	1.98 [1.01, 3.54] +
Others (ekoi, ibibio, etc.)	2226 (36.7)	72.1 [70.2, 73.9]	3.46 [3.06, 3.91] ***	1.30 [0.95, 1.75]
Household wealth				
Poorer/poorest	2784 (45.9)	46.6 [44.8, 48.5]	1.00 [reference]	1.00 [reference]
Middle	1253 (20.7)	70.8 [68.2, 73.2]	2.77 [2.41, 3.20] ***	1.07 [0.82, 1.37]
Richer/richest	2022 (33.4)	86.6 [85.1, 88.1]	7.43 [6.41, 8.62] ***	1.32 [0.95, 1.80]
Access to bank account				
No	5035 (83.1)	59.0 [57.7, 60.4]	1.00 [reference]	1.00 [reference]

Yes	1024 (16.9)	94.2 [92.6, 95.5]	11.35 [8.68, 14.85] ***	2.69 [1.78, 3.94] +
Household size				
Large (>=9)	1464 (24.2)	51.8 [49.3, 54.4]	0.53 [0.46, 0.60] ***	1.10 [0.87, 1.36]
Medium (5 to 8)	2760 (45.6)	67.2 [65.4, 68.9]	1.00 [reference]	1.00 [reference]
Small (<=4)	1835 (30.3)	72.2 [70.1, 74.2]	1.27 [1.11, 1.44] ***	1.13 [0.87, 1.45]
Length of stay in household				
<1year/visitor	174 (2.9)	84.5 [78.3, 89.1]	2.08 [1.31, 3.29] **	2.32 [1.10, 4.29] +
1-3years	711 (11.7)	75.1 [71.8, 78.1]	1.15 [0.88, 1.51]	1.08 [0.66, 1.67]
4-5years	438 (7.2)	72.4 [68.0, 76.4]	1.00 [reference]	1.00 [reference]
>5years/always	4736 (78.2)	62.1 [60.7, 63.4]	0.62 [0.50, 0.78] ***	1.53 [1.05, 2.17] +
Rural/urban				
Rural	3959 (65.3)	56.6 [55.1, 58.2]	1.00 [reference]	1.00 [reference]
Urban	2100 (34.7)	80.7 [79.0, 82.3]	3.21 [2.83, 3.63] ***	0.94 [0.57, 1.46]
Livestock density index				
Lower (0-21.4)	1637 (27.0)	73.5 [71.3, 75.6]	1.96 [1.71, 2.25] ***	1.66 [1.13, 2.37] +
Medium (21.5-73.2)	2034 (33.6)	65.5 [63.4, 67.5]	1.34 [1.19, 1.52] ***	1.25 [0.90, 1.72]
Higher (73.3-5196.8)	2365 (39.0)	58.5 [56.5, 60.5]	1.00 [reference]	1.00 [reference]
Average enhanced vegetation index (2013-2018)				
Lower (0.07-0.23)	2395 (39.5)	50.6 [48.6, 52.6]	1.00 [reference]	1.00 [reference]

Medium (0.24-0.36)	2202 (36.3)	68.8 [66.8, 70.7]	2.15 [1.91, 2.43] ***	1.45 [1.07, 1.93] +
Higher (0.364-0.57)	1439 (23.7)	83.0 [80.9, 84.8]	4.76 [4.06, 5.59] ***	1.26 [0.80, 1.89]
Variance parameters				**Estimate [95% Cr. I]**
Stratum-level variance				0.39 [0.19, 0.67]
Cluster-level variance				0.74 [0.45, 1.05]

CI: Confidence Interval; Cr. I: Bayesian Credible Interval; cOR: Crude Odds Ratio; aOR: adjusted Odds Ratio; +Significant covariate for the Bayesian model; *p<0.05; **p<0.01; ***p<0.001.

Additional information on the results of the analyses

Derivation of the odds ratios for the interaction between maternal education and travel time to the nearest health facility in the binomial analysis for PENTA1

We found a significant interaction between maternal education and travel time to the nearest health facility in the study for PENTA1. To appropriately interpret this significant interaction, the correct odds ratios need to be computed as demonstrated by Chen [19]. These are given as follows using parameter estimates reported in Table E.

For children born to mothers with primary education (compared to no education), the odds ratio (OR) for those residing in communities with lower travel time to the nearest health facility is given as:

$\widehat{\text{OR}}$ for primary education versus no education $= exp(\hat{\beta}_{primary} + \hat{\beta}_{(primary\ and\ lower\ travel\ time)})$

$= \widehat{OR}_{primary} \times \widehat{OR}_{(primary\ and\ lower\ travel\ time)}$

$= 1.89 \times 0.53 = 1.00$ for lower travel time.

Also, for children born to mothers with primary education (compared to no education), the odds ratio (OR) for those residing in communities with medium travel time to the nearest health facility is given as:

$\widehat{\text{OR}}$ for primary education versus no education $= exp(\hat{\beta}_{primary} + \hat{\beta}_{(primary\ and\ medium\ travel\ time)})$

$= \widehat{OR}_{primary} \times \widehat{OR}_{(primary\ and\ medium\ travel\ time)}$

$= 1.89 \times 0.63 = 1.19$ for medium travel time.

Lastly, for children born to mothers with primary education (compared to no education), the odds ratio (OR) for those residing in communities with higher travel time to the nearest health facility is given as:

$\widehat{\text{OR}}$ for primary education versus no education $= \ exp(\hat{\beta}_{primary})$

$= \widehat{OR}_{primary}$

$= 1.89$ for higher travel time.

Next, for children born to mothers with secondary/higher education (compared to no education), the odds ratios can be calculated similarly as follows:

$\widehat{\text{OR}}$ for secondary/higher education vs no education = 2.59 × 0.43 = 1.11 for lower travel time.

= 2.59 × 0.82 = 2.12 for medium travel time.

= 2.59 for higher travel time.

The corresponding 95% credible intervals for these calculations were estimated using the posterior samples of the relevant parameters in each case, using the *lincom* utility in Stata. These results are also presented in Table E.

Our interpretations are based on the above calculations. However, travel time could also serve as the base variable in these calculations as follows:

$\widehat{\text{OR}}$ for lower travel time versus higher travel time = 2.27 for no education.

= 2.27 × 0.53 = 1.20 for primary education.

= 2.27 × 0.43 = 0.98 for secondary/higher education.

$\widehat{\text{OR}}$ for medium travel time vs higher travel time = 1.64 for no education.

= 1.64 × 0.63 = 1.03 for primary education.

= 2.27 × 0.82 = 1.86 for secondary/higher education.

The corresponding 95% credible intervals for these estimates were also estimated as discussed above (see Table E).

Table E: Maternal education and travel time and the interaction between both variables.

Characteristics and categories	**Number (%) in category**	**Percentage with any evidence of PENTA1 (95% CI)**	**Frequentist single-level model: cOR [95% CI**	**Bayesian multilevel model: aOR [95% Cr. I]**
Mother's education				
No education	2614 (43.1)	40.1 [38.2, 41.9]	1.00 [reference]	1.00 [reference]
Primary	881 (14.5)	72.5 [69.5, 75.4]	3.95 [3.34, 4.67] ***	1.89 [1.24, 2.75] +
Secondary/higher	2564 (42.3)	87.8 [86.5, 89.0]	10.76 [9.34, 12.40] ***	2.59 [1.71, 3.87] +
Travel time to the nearest health facility (providing RI services)				
Lower (0-3.9)	1683 (27.8)	82.9 [81.0, 84.6]	4.83 [4.16, 5.62] ***	2.27 [1.17, 3.97] +
Medium (4.0-12.5)	2000 (33.0)	67.0 [64.9, 69.0]	2.02 [1.78, 2.28] ***	1.64 [1.15, 2.30] +
Higher (12.6-532.8)	2353 (38.8)	50.4 [48.3, 52.4]	1.00 [reference]	1.00 [reference]
Interaction between education and travel time	Number in category	**Number vaccinated** (%)		
Primary education and lower travel time	215	170 (79.1)	-	0.53 [0.24, 1.04]
Secondary/higher education and lower travel time	1192	1077 (90.4)	-	0.43 [0.21, 0.76] +
Primary education and medium travel time	326	232 (71.2)	-	0.63 [0.35, 1.07]
Secondary/higher education and medium travel time	799	713 (89.2)	-	0.82 [0.46, 1.34]
Primary education and higher travel time	338	232 (68.6)	-	-
Secondary/higher education and higher travel time	573	458 (79.9)	-	-

Calculated odds ratios (ORs) for the interaction effects			
	Travel time to the nearest health facility		
Education	Higher (OR)	Medium (OR)	Lower (OR)
Primary versus no education	1.89 [1.25, 2.76]	1.19 [0.73, 1.74]	1.00 [0.49, 1.73]
Secondary/higher versus no education	2.59 [1.68, 3.82]	2.12 [1.30, 3.10]	1.11 [0.61, 1.73]
	Education		
Travel time to the nearest health facility	Secondary/ Higher (OR)	Primary (OR)	No education
Lower versus higher travel time	0.98 [0.50, 1.54]	1.20 [0.54, 2.16]	2.27 [1.18, 3.98]
Medium versus higher travel time	1.86 [0.81, 2.04]	1.03 [0.58, 1.65]	1.64 [1.15, 2.27]

CI: Confidence Interval; Cr. I: Bayesian Credible Interval; cOR: Crude Odds Ratio; aOR: adjusted Odds Ratio; $^{+}$Significant covariate for the Bayesian $_{model;}$ *p<0.05; **p<0.01; ***p<0.001.

Additional results of the binomial analysis for PENTA3/1

Table F: Factors associated with receipt of PENTA3/1 vaccination, cross-tabulation analyses of Nigeria DHS 2018

		PENTA3/1		
		Received PENTA1 but not PENTA3	**Received both**	**P-value**
	N	**n (%)**	**n (%)**	
N		896 (23)	3041 (77)	
Sex of child				0.990
Male	2038	464 (22.8)	1574 (77.2)	
Female	1899	432 (22.7)	1467 (77.3)	
Birth order				0.008
1-2	1605	331 (20.6)	1274 (79.4)	
>2	2332	565 (24.2)	1767 (75.8)	
Birth quarter				0.210
Jan-Mar	1279	302 (23.6)	977 (76.4)	
Apr-Jun	1076	241 (22.4)	835 (77.6)	
Jul-Sep	1020	243 (23.8)	777 (76.2)	
Oct-Dec	562	110 (19.6)	452 (80.4)	
Skilled birth attendance				<0.001***
No skilled attendant at birth	1556	506 (32.5)	1050 (67.5)	
Skilled attendant at birth	2381	390 (16.4)	1991 (83.6)	
Health card/document				<0.001***
Does not have health card/document	1179	476 (40.4)	703 (59.6)	
Yes, none seen	477	119 (24.9)	358 (75.1)	
Yes, seen	2281	301 (13.2)	1980 (86.8)	
Received vitamin A				<0.001***
No/don’t know	1283	445 (34.7)	838 (65.3)	
Yes	2654	451 (17.0)	2203 (83.0)	
Sex of household head				0.190
Male	3438	794 (23.1)	2644 (76.9)	
Female	499	102 (20.4)	397 (79.6)	
Mother's age group				<0.001***
15-19	183	65 (35.5)	118 (64.5)	
20-29	1965	479 (24.4)	1486 (75.6)	
30-39	1553	298 (19.2)	1255 (80.8)	
40-49	236	54 (22.9)	182 (77.1)	
Marital status of mother				0.330
Never in union	133	35 (26.3)	98 (73.7)	
Married	3701	833 (22.5)	2868 (77.5)	

Divorced	103	28 (27.2)	75 (72.8)	
Mother employed in the past 12 months				0.001
No	923	246 (26.7)	677 (73.3)	
Yes (currently/in the past 1 year)	3014	650 (21.6)	2364 (78.4)	
Mother had problem seeking medical advice or treatment				<0.001***
Had problem seeking medical advice or treatment	2010	516 (25.7)	1494 (74.3)	
Did not have problem seeking medical advice or treatment	1927	380 (19.7)	1547 (80.3)	
Mother's education				<0.001***
No education	1047	388 (37.1)	659 (62.9)	
Primary	639	161 (25.2)	478 (74.8)	
Secondary/higher	2251	347 (15.4)	1904 (84.6)	
Mother's religion				<0.001***
Islam	1782	531 (29.8)	1251 (70.2)	
Christian	2126	361 (17.0)	1765 (83.0)	
Traditionalist/others	29	4 (13.8)	25 (86.2)	
Mother's media exposure				<0.001***
No	2077	564 (27.2)	1513 (72.8)	
Yes (radio/tv/newspaper at least once a week)	1860	332 (17.8)	1528 (82.2)	
Mother's access to mobile phone/internet				<0.001***
No	1500	473 (31.5)	1027 (68.5)	
Yes	2437	423 (17.4)	2014 (82.6)	
Mother's land ownership				0.005
Does not own land	3309	780 (23.6)	2529 (76.4)	
Owns land alone and/or jointly	628	116 (18.5)	512 (81.5)	
Mother's knowledge of malaria				0.003
Has no knowledge	236	72 (30.5)	164 (69.5)	
Has knowledge	3701	824 (22.3)	2877 (77.7)	
Mother had health insurance				0.024
No	3823	880 (23.0)	2943 (77.0)	
Yes	114	16 (14.0)	98 (86.0)	
Household's bed net ownership				0.005
No	1264	253 (20.0)	1011 (80.0)	
Yes	2673	643 (24.1)	2030 (75.9)	
Mother's ethnicity				<0.001***
Hausa/Fulani	1010	345 (34.2)	665 (65.8)	
Yoruba	536	84 (15.7)	452 (84.3)	
Igbo	787	96 (12.2)	691 (87.8)	
Others (ekoi, ibibio, etc.)	1604	371 (23.1)	1233 (76.9)	
Household wealth				<0.001***
Poorer/poorest	1298	429 (33.1)	869 (66.9)	
Middle	887	205 (23.1)	682 (76.9)	

Richer/richest	1752	262 (15.0)	1490 (85.0)	
Access to bank account				<0.001***
No	2972	771 (25.9)	2201 (74.1)	
Yes	965	125 (13.0)	840 (87.0)	
Household size				0.001
Large (>=9)	759	207 (27.3)	552 (72.7)	
Medium (5 to 8)	1854	420 (22.7)	1434 (77.3)	
Small (<=4)	1324	269 (20.3)	1055 (79.7)	
Length of stay in household				<0.001***
<1year/visitor	147	35 (23.8)	112 (76.2)	
1-3years	534	80 (15.0)	454 (85.0)	
4-5years	317	50 (15.8)	267 (84.2)	
>5years/always	2939	731 (24.9)	2208 (75.1)	
Rural/urban				<0.001***
Rural	2242	631 (28.1)	1611 (71.9)	
Urban	1695	265 (15.6)	1430 (84.4)	
Livestock density index				<0.001***
Lower (0-21.4)	1203	227 (18.9)	976 (81.1)	
Medium (21.5-73.2)	1332	347 (26.1)	985 (73.9)	
Higher (73.3-5196.8)	1384	320 (23.1)	1064 (76.9)	
Travel time to the nearest health facility (providing RI services)				<0.001***
Lower (0-3.9)	1395	213 (15.3)	1182 (84.7)	
Medium (4.0-12.5)	1339	310 (23.2)	1029 (76.8)	
Higher (12.6-532.8)	1185	371 (31.3)	814 (68.7)	
Average enhanced vegetation index (2013-2018)				<0.001***
Lower (0.07-0.23)	1211	345 (28.5)	866 (71.5)	
Medium (0.24-0.36)	1514	321 (21.2)	1193 (78.8)	
Higher (0.364-0.57)	1194	228 (19.1)	966 (80.9)	

*p<0.05; **p<0.01; ***p<0.001

Table G: Percentage of children aged 12 to 23 months with receipt of PENTA3 among those who received PENTA1 vaccinations, according to potential determinants of vaccination, univariate and multivariable analyses of Nigeria DHS 2018

Characteristics and categories	Number (%) in category	Percentage of receiving PENTA3/1 (95% CI)	Frequentist single-level model: cOR [95% CI	Bayesian multilevel model: aOR [95% Cr. I]
N	3937(100.0)			
Sex of child				
Male	2038 (33.6)	77.2 [75.4, 79.0]	1.00 [reference]	1.00 [reference]
Female	1899 (31.3)	77.3 [75.3, 79.1]	1.00 [0.86, 1.16]	1.02 [0.86, 1.21]
Birth order				
1-2	1605 (26.5)	79.4 [77.3, 81.3]	1.00 [reference]	1.00 [reference]
>2	2332 (38.5)	75.8 [74.0, 77.5]	0.81 [0.70, 0.95] **	0.83 [0.64, 1.06]
Birth quarter				
Jan-Mar	1279 (21.1)	76.4 [74.0, 78.6]	0.79 [0.62, 1.01]	0.77 [0.56, 1.01]
Apr-Jun	1076 (17.8)	77.6 [75.0, 80.0]	0.84 [0.65, 1.09]	0.82 [0.60, 1.09]
Jul-Sep	1020 (16.8)	76.2 [73.5, 78.7]	0.78 [0.60, 1.00]	0.85 [0.62, 1.13]
Oct-Dec	562 (9.3)	80.4 [76.9, 83.5]	1.00 [reference]	1.00 [reference]
Skilled birth attendance				
No skilled attendant at birth	1556 (25.7)	67.5 [65.1, 69.8]	1.00 [reference]	1.00 [reference]
Skilled attendant at birth	2381 (39.3)	83.6 [82.1, 85.1]	2.46 [2.11, 2.86] ***	1.25 [0.99, 1.55]
Health card/document				

Does not have health card/document	1179 (19.5)	59.6 [56.8, 62.4]	1.00 [reference]	1.00 [reference]
Yes, none seen	477 (7.9)	75.1 [71.0, 78.7]	2.04 [1.61, 2.58] ***	1.74 [1.30, 2.32] +
Yes, seen	2281 (37.6)	86.8 [85.4, 88.1]	4.45 [3.77, 5.27] ***	5.14 [4.16, 6.32] +
Received vitamin A				
No/don't know	1283 (21.2)	65.3 [62.7, 67.9]	1.00 [reference]	1.00 [reference]
Yes	2654 (43.8)	83.0 [81.5, 84.4]	2.59 [2.23, 3.02] ***	2.20 [1.79, 2.68] +
Sex of household head				
Male	3438 (56.7)	76.9 [75.5, 78.3]	1.00 [reference]	1.00 [reference]
Female	499 (8.2)	79.6 [75.8, 82.9]	1.17 [0.93, 1.47]	1.03 [0.76, 1.36]
Mother's age group				
15-19	183 (3.0)	64.5 [57.3, 71.1]	1.00 [reference]	1.00 [reference]
20-29	1965 (32.4)	75.6 [73.7, 77.5]	1.71 [1.24, 2.35] **	1.74 [1.14, 2.52] +
30-39	1553 (25.6)	80.8 [78.8, 82.7]	2.32 [1.67, 3.22] ***	2.42 [1.46, 3.66] +
40-49	236 (3.9)	77.1 [71.3, 82.0]	1.86 [1.21, 2.85] **	2.39 [1.29, 4.08] +
Marital status of mother				
Never in union	133 (2.2)	73.7 [65.6, 80.5]	0.81 [0.55, 1.21]	0.77 [0.44, 1.28]
Married	3701 (61.1)	77.5 [76.1, 78.8]	1.00 [reference]	1.00 [reference]
Divorced	103 (1.7)	72.8 [63.4, 80.5]	0.78 [0.50, 1.21]	0.74 [0.41, 1.25]
Mother employed in the past 12 months				

No	923 (15.2)	73.3 [70.4, 76.1]	1.00 [reference]	1.00 [reference]
Yes (currently/in the past 1 year)	3014 (49.7)	78.4 [76.9, 79.9]	1.32 [1.12, 1.57] **	1.11 [0.88, 1.36]
Mother had problem seeking medical advice or treatment				
Did not have problem seeking medical advice or treatment	2010 (33.2)	74.3 [72.4, 76.2]	1.00 [reference]	1.00 [reference]
Had problem seeking medical advice or treatment	1927 (31.8)	80.3 [78.4, 82.0]	1.41 [1.21, 1.63] ***	0.98 [0.80, 1.18]
Mother's education				
No education	1047 (17.3)	62.9 [60.0, 65.8]	1.00 [reference]	1.00 [reference]
Primary	639 (10.5)	74.8 [71.3, 78.0]	1.75 [1.41, 2.17] ***	1.25 [0.93, 1.65]
Secondary/higher	2251 (37.2)	84.6 [83.0, 86.0]	3.23 [2.73, 3.83] ***	1.70 [1.27, 2.25] +
Mother's religion				
Islam	1782 (29.4)	70.2 [68.0, 72.3]	1.00 [reference]	1.00 [reference]
Christian	2126 (35.1)	83.0 [81.4, 84.6]	2.08 [1.78, 2.42] ***	1.11 [0.82, 1.48]
Traditionalist/others	29 (0.5)	86.2 [68.5, 94.7]	2.65 [0.92, 7.66]	5.50 [1.20, 17.45] +
Mother's media exposure				
No	2077 (34.3)	72.8 [70.9, 74.7]	1.00 [reference]	1.00 [reference]
Yes (radio/tv/newspaper at least once a week)	1860 (30.7)	82.2 [80.3, 83.8]	1.72 [1.47, 2.00] ***	0.95 [0.77, 1.17]
Mother's access to mobile phone/internet				
No	1500 (24.8)	68.5 [66.1, 70.8]	1.00 [reference]	1.00 [reference]

Yes	2437 (40.2)	82.6 [81.1, 84.1]	2.19 [1.89, 2.55] ***	1.23 [0.99, 1.53]
Mother's land ownership				
Does not own land	3309 (54.6)	76.4 [75.0, 77.8]	.. [0.00, 0.00] ***	1.00 [reference]
Owns land alone and/or jointly	628 (10.4)	81.5 [78.3, 84.4]	1.36 [1.10, 1.69] **	0.98 [0.74, 1.29]
Mother's knowledge of malaria				
Has no knowledge	236 (3.9)	69.5 [63.3, 75.0]	1.00 [reference]	1.00 [reference]
Has knowledge	3701 (61.1)	77.7 [76.4, 79.0]	1.53 [1.15, 2.04] **	1.58 [1.11, 2.21] +
Mother had health insurance				
No	3823 (63.1)	77.0 [75.6, 78.3]	1.00 [reference]	1.00 [reference]
Yes	114 (1.9)	86.0 [78.3, 91.2]	1.83 [1.07, 3.12] *	1.23 [0.63, 2.27]
Household's bed net ownership				
No	1264 (20.9)	80.0 [77.7, 82.1]	1.00 [reference]	1.00 [reference]
Yes	2673 (44.1)	75.9 [74.3, 77.5]	0.79 [0.67, 0.93] **	0.99 [0.80, 1.22]
Mother's ethnicity				
Hausa/Fulani	1010 (16.7)	65.8 [62.9, 68.7]	1.00 [reference]	1.00 [reference]
Yoruba	536 (8.8)	84.3 [81.0, 87.2]	2.79 [2.14, 3.64] ***	1.20 [0.69, 1.88]
Igbo	787 (13.0)	87.8 [85.3, 89.9]	3.73 [2.91, 4.79] ***	1.36 [0.76, 2.26]
Others (ekoi, ibibio, etc.)	1604 (26.5)	76.9 [74.7, 78.9]	1.72 [1.45, 2.05] ***	1.31 [0.94, 1.78]
Household wealth				

Poorer/poorest	1298 (21.4)	66.9 [64.3, 69.5]	1.00 [reference]	1.00 [reference]
Middle	887 (14.6)	76.9 [74.0, 79.5]	1.64 [1.35, 1.99] ***	1.05 [0.80, 1.36]
Richer/richest	1752 (28.9)	85.0 [83.3, 86.6]	2.81 [2.36, 3.34] ***	1.24 [0.90, 1.68]
Access to bank account				
No	2972 (49.1)	74.1 [72.5, 75.6]	1.00 [reference]	1.00 [reference]
Yes	965 (15.9)	87.0 [84.8, 89.0]	2.35 [1.92, 2.89] ***	1.06 [0.79, 1.38]
Household size				
Large (>=9)	759 (12.5)	72.7 [69.4, 75.8]	0.78 [0.64, 0.95] *	1.19 [0.93, 1.50]
Medium (5 to 8)	1854 (30.6)	77.3 [75.4, 79.2]	1.00 [reference]	1.00 [reference]
Small (<=4)	1324 (21.9)	79.7 [77.4, 81.8]	1.15 [0.97, 1.36]	1.01 [0.78, 1.27]
Length of stay in household				
<1year/visitor	147 (2.4)	76.2 [68.6, 82.4]	0.60 [0.37, 0.97] *	0.71 [0.38, 1.23]
1-3years	534 (8.8)	85.0 [81.7, 87.8]	1.06 [0.72, 1.56]	0.98 [0.61, 1.48]
4-5years	317 (5.2)	84.2 [79.8, 87.8]	1.00 [reference]	1.00 [reference]
>5years/always	2939 (48.5)	75.1 [73.5, 76.7]	0.57 [0.41, 0.77] ***	0.78 [0.53, 1.10]
Rural/urban				
Rural	2242 (37.0)	71.9 [70.0, 73.7]	1.00 [reference]	1.00 [reference]
Urban	1695 (28.0)	84.4 [82.6, 86.0]	2.11 [1.80, 2.48] ***	1.18 [0.74, 1.77]
Livestock density index				

Lower (0-21.4)	1203 (19.9)	81.1 [78.8, 83.2]	1.29 [1.07, 1.57] **	1.29 [0.90, 1.80]
Medium (21.5-73.2)	1332 (22.0)	73.9 [71.5, 76.2]	0.85 [0.72, 1.02]	0.98 [0.73, 1.27]
Higher (73.3-5196.8)	1384 (22.8)	76.9 [74.6, 79.0]	1.00 [reference]	1.00 [reference]
Travel time to the nearest health facility (providing RI services)				
Lower (0-3.9)	1395 (23.0)	84.7 [82.7, 86.5]	2.67 [2.20, 3.23] ***	1.21 [0.79, 1.78]
Medium (4.0-12.5)	1339 (22.1)	76.8 [74.5, 79.0]	1.54 [1.29, 1.84] ***	1.16 [0.90, 1.48]
Higher (12.6-532.8)	1185 (19.6)	68.7 [66.0, 71.3]	1.00 [reference]	1.00 [reference]
Average enhanced vegetation index (2013-2018)				
Lower (0.07-0.23)	1211 (20.0)	71.5 [68.9, 74.0]	1.00 [reference]	1.00 [reference]
Medium (0.24-0.36)	1514 (25.0)	78.8 [76.7, 80.8]	1.48 [1.24, 1.76] ***	1.33 [0.99, 1.77]
Higher (0.364-0.57)	1194 (19.7)	80.9 [78.6, 83.0]	1.69 [1.39, 2.04] ***	0.94 [0.65, 1.33]
Variance parameters				**Estimate [95% Cr. I]**
Stratum-level variance				0.44 [0.24, 0.74]
Cluster-level variance				0.14 [0.00, 0.39]

CI: Confidence Interval; Cr. I: Bayesian Credible Interval; cOR: Crude Odds Ratio; aOR: adjusted Odds Ratio; $^{+}$Significant covariate for the Bayesian model; *p<0.05; **p<0.01; ***p<0.001.

Interpretation of factors associated with PENTA3/1 vaccination in the binomial analysis

In multivariable analysis, the effect of having a HBR was smaller than for PENTA1 and presence of a SBA at birth just failed to reach statistical significance (aOR=1.25, 95% Cr.I: 0.99, 1.55). Factors significantly associated with higher odds of PENTA3/1 receipt are health card/document (yes, none seen: aOR=1.74, 95% Cr.I: 1.30, 2.32; yes, seen: aOR=5.14, 95% Cr.I: 4.16, 6.32), receipt of vitamin A (aOR=2.20, 95% Cr.I: 1.79, 2.68), maternal age (age 20-29: aOR=1.74, 95% Cr.I: 1.14, 2.52; age 30-39: aOR=2.42, 95% Cr.I: 1.46, 3.66; age 40-49: aOR=2.39, 95% Cr.I: 1.29, 4.08), secondary/higher maternal education (aOR=1.70, 95% Cr.I: 1.27, 2.25) and mothers who had knowledge about malaria (aOR=1.58, 95% Cr.I: 1.11, 2.21).

Christian religion was no longer significant but PENTA3/1 receipt was much higher in children of the small number of mothers with traditional or other religions (aOR=5.50, 95% Cr.I: 1.20, 17.45) compared with those from mothers who practice Islamic religion. Access to a bank account or mobile phone/internet, length of stay in residence and geospatial variables were not significantly associated with completion of the PENTA series. No significant interaction terms were observed between PENTA3/1 and significant predictors (Table G).

Additional results of the binomial analysis for MV

Table H: Factors associated with any evidence of MV vaccination, cross-tabulation analyses of Nigeria DHS 2018

		MV		
		No	**Yes**	
Variables	**N**	**n (%)**	**n (%)**	**P-value**
N	11839	5206 (44)	6633 (56)	
Sex of child				0.420
Male	6050	2682 (44.3)	3368 (55.7)	
Female	5789	2524 (43.6)	3265 (56.4)	
Birth order				<0.001***
1-2	4485	1769 (39.4)	2716 (60.6)	
>2	7354	3437 (46.7)	3917 (53.3)	
Birth quarter				<0.001***
Jan-Mar	3801	1611 (42.4)	2190 (57.6)	
Apr-Jun	3237	1471 (45.4)	1766 (54.6)	
Jul-Sep	3194	1478 (46.3)	1716 (53.7)	
Oct-Dec	1607	646 (40.2)	961 (59.8)	
Skilled birth attendance				<0.001***
No skilled attendant at birth	6509	3887 (59.7)	2622 (40.3)	
Skilled attendant at birth	5330	1319 (24.7)	4011 (75.3)	
Health card/document				<0.001***
Does not have health card/document	6600	3884 (58.8)	2716 (41.2)	
Yes, none seen	1104	231 (20.9)	873 (79.1)	
Yes, seen	4135	1091 (26.4)	3044 (73.6)	
Received vitamin A				<0.001***
No/don’t know	5658	3595 (63.5)	2063 (36.5)	
Yes	6181	1611 (26.1)	4570 (73.9)	
Sex of household head				<0.001***
Male	10662	4826 (45.3)	5836 (54.7)	
Female	1177	380 (32.3)	797 (67.7)	
Mother's age group				<0.001***
15-19	587	370 (63.0)	217 (37.0)	
20-29	5766	2617 (45.4)	3149 (54.6)	
30-39	4508	1748 (38.8)	2760 (61.2)	
40-49	978	471 (48.2)	507 (51.8)	
Marital status of mother				<0.001***
Never in union	287	96 (33.4)	191 (66.6)	
Married	11222	4982 (44.4)	6240 (55.6)	
Divorced	330	128 (38.8)	202 (61.2)	
Mother employed in the past 12 months				<0.001***
No	3403	1926 (56.6)	1477 (43.4)	

Yes (currently/in the past 1 year)	8436	3280 (38.9)	5156 (61.1)	
Mother had problem seeking medical advice or treatment				<0.001***
Had problem seeking medical advice or treatment	6529	3256 (49.9)	3273 (50.1)	
Did not have problem seeking medical advice or treatment	5310	1950 (36.7)	3360 (63.3)	
Mother's education				<0.001***
No education	5112	3262 (63.8)	1850 (36.2)	
Primary	1784	770 (43.2)	1014 (56.8)	
Secondary/higher	4943	1174 (23.8)	3769 (76.2)	
Mother's religion				<0.001***
Islam	6901	3849 (55.8)	3052 (44.2)	
Christian	4835	1321 (27.3)	3514 (72.7)	
Traditionalist/others	103	36 (35.0)	67 (65.0)	
Mother's media exposure				<0.001***
No	7247	3868 (53.4)	3379 (46.6)	
Yes (radio/tv/newspaper at least once a week)	4592	1338 (29.1)	3254 (70.9)	
Mother's access to mobile phone/internet				<0.001***
No	5867	3424 (58.4)	2443 (41.6)	
Yes	5972	1782 (29.8)	4190 (70.2)	
Mother's land ownership				<0.001***
Does not own land	10247	4671 (45.6)	5576 (54.4)	
Owns land alone and/or jointly	1592	535 (33.6)	1057 (66.4)	
Mother's knowledge of malaria				<0.001***
Has no knowledge	685	347 (50.7)	338 (49.3)	
Has knowledge	11154	4859 (43.6)	6295 (56.4)	
Mother had health insurance				<0.001***
No	11578	5151 (44.5)	6427 (55.5)	
Yes	261	55 (21.1)	206 (78.9)	
Household's bed net ownership				<0.001***
No	3543	1432 (40.4)	2111 (59.6)	
Yes	8296	3774 (45.5)	4522 (54.5)	
Mother's ethnicity				<0.001***
Hausa/Fulani	4728	2899 (61.3)	1829 (38.7)	
Yoruba	1201	294 (24.5)	907 (75.5)	
Igbo	1667	367 (22.0)	1300 (78.0)	
Others (ekoi, ibibio, etc.)	4243	1646 (38.8)	2597 (61.2)	
Household wealth				<0.001***
Poorer/poorest	5353	3205 (59.9)	2148 (40.1)	
Middle	2478	1039 (41.9)	1439 (58.1)	
Richer/richest	4008	962 (24.0)	3046 (76.0)	

Access to bank account				<0.001***
No	9844	4923 (50.0)	4921 (50.0)	
Yes	1995	283 (14.2)	1712 (85.8)	
Household size				<0.001***
Large (>=9)	2946	1599 (54.3)	1347 (45.7)	
Medium (5 to 8)	5518	2287 (41.4)	3231 (58.6)	
Small (<=4)	3375	1320 (39.1)	2055 (60.9)	
Length of stay in household				<0.001***
<1year/visitor	345	106 (30.7)	239 (69.3)	
1-3years	1205	413 (34.3)	792 (65.7)	
4-5years	864	315 (36.5)	549 (63.5)	
>5years/always	9425	4372 (46.4)	5053 (53.6)	
Rural/urban				<0.001***
Rural	7622	3908 (51.3)	3714 (48.7)	
Urban	4217	1298 (30.8)	2919 (69.2)	
Livestock density index				<0.001***
Lower (0-21.4)	3189	1096 (34.4)	2093 (65.6)	
Medium (21.5-73.2)	4029	1830 (45.4)	2199 (54.6)	
Higher (73.3-5196.8)	4621	2280 (49.3)	2341 (50.7)	
Travel time to the nearest health facility (providing RI services)				<0.001***
Lower (0-3.9)	3406	995 (29.2)	2411 (70.8)	
Medium (4.0-12.5)	3968	1713 (43.2)	2255 (56.8)	
Higher (12.6-532.8)	4465	2498 (55.9)	1967 (44.1)	
Average enhanced vegetation index (2013-2018)				<0.001***
Lower (0.07-0.23)	4759	2502 (52.6)	2257 (47.4)	
Medium (0.24-0.36)	4270	1815 (42.5)	2455 (57.5)	
Higher (0.364-0.57)	2810	889 (31.6)	1921 (68.4)	

*p<0.05; **p<0.01; ***p<0.001

Table I: Percentage of children aged 12 to 35 months with any evidence of MV vaccination, according to potential determinants of vaccination, univariate and multivariable analyses of Nigeria DHS 2018

Characteristics and categories	Number (%) in category	Percentage with any evidence of MV (95% CI)	Frequentist single-level model: cOR [95% CI	Bayesian multilevel model: aOR [95% Cr. I]
N	**11839**			
Sex of child				
Male	6050 (51.1)	55.7 [54.4, 56.9]	1.00 [reference]	1.00 [reference]
Female	5789 (48.9)	56.4 [55.1, 57.7]	1.03 [0.94, 1.11]	1.03 [0.94, 1.13]
Birth order				
1-2	4485 (37.9)	60.6 [59.1, 62.0]	1.00 [reference]	1.00 [reference]
>2	7354 (62.1)	53.3 [52.1, 54.4]	0.74 [0.69, 0.80] ***	0.83 [0.72, 0.95] +
Birth quarter				
Jan-Mar	3801 (32.1)	57.6 [56.0, 59.2]	0.91 [0.81, 1.03]	0.99 [0.85, 1.15]
Apr-Jun	3237 (27.3)	54.6 [52.8, 56.3]	0.81 [0.71, 0.91] **	0.90 [0.77, 1.04]
Jul-Sep	3194 (27.0)	53.7 [52.0, 55.4]	0.78 [0.69, 0.88] ***	0.89 [0.75, 1.03]
Oct-Dec	1607 (13.6)	59.8 [57.4, 62.2]	1.00 [reference]	1.00 [reference]
Skilled birth attendance				
No skilled attendant at birth	6509 (55.0)	40.3 [39.1, 41.5]	1.00 [reference]	1.00 [reference]
Skilled attendant at birth	5330 (45.0)	75.3 [74.1, 76.4]	4.51 [4.16, 4.88] ***	1.66 [1.46, 1.88] +
Health card/document				

Does not have health card/document	6600 (55.7)	41.2 [40.0, 42.3]	1.00 [reference]	1.00 [reference]
Yes, none seen	1104 (9.3)	79.1 [76.6, 81.4]	5.40 [4.64, 6.30] ***	3.43 [2.81, 4.13] +
Yes, seen	4135 (34.9)	73.6 [72.3, 74.9]	3.99 [3.67, 4.34] ***	2.17 [1.94, 2.42] +
Received vitamin A				
No/don't know	5658 (47.8)	36.5 [35.2, 37.7]	1.00 [reference]	1.00 [reference]
Yes	6181 (52.2)	73.9 [72.8, 75.0]	4.94 [4.57, 5.35] ***	3.42 [3.06, 3.82] +
Sex of household head				
Male	10662 (90.1)	54.7 [53.8, 55.7]	1.00 [reference]	1.00 [reference]
Female	1177 (9.9)	67.7 [65.0, 70.3]	1.73 [1.53, 1.97] ***	1.04 [0.87, 1.24]
Mother's age group				
15-19	587 (5.0)	37.0 [33.2, 41.0]	1.00 [reference]	1.00 [reference]
20-29	5766 (48.7)	54.6 [53.3, 55.9]	2.05 [1.72, 2.45] ***	1.57 [1.24, 1.94] +
30-39	4508 (38.1)	61.2 [59.8, 62.6]	2.69 [2.25, 3.22] ***	1.88 [1.45, 2.38] +
40-49	978 (8.3)	51.8 [48.7, 55.0]	1.84 [1.49, 2.26] ***	1.55 [1.12, 2.03] +
Marital status of mother				
Never in union	287 (2.4)	66.6 [60.9, 71.8]	1.59 [1.24, 2.04] ***	1.07 [0.76, 1.46]
Married	11222 (94.8)	55.6 [54.7, 56.5]	1.00 [reference]	1.00 [reference]
Divorced	330 (2.8)	61.2 [55.8, 66.3]	1.26 [1.01, 1.58] *	1.15 [0.85, 1.55]
Mother employed in the past 12 months				

No	3403 (28.7)	43.4 [41.7, 45.1]	1.00 [reference]	1.00 [reference]
Yes (currently/in the past 1 year)	8436 (71.3)	61.1 [60.1, 62.2]	2.05 [1.89, 2.22] ***	1.35 [1.20, 1.50] +
Mother had problem seeking medical advice or treatment				
Did not have problem seeking medical advice or treatment	6529 (55.1)	50.1 [48.9, 51.3]	1.00 [reference]	1.00 [reference]
Had problem seeking medical advice or treatment	5310 (44.9)	63.3 [62.0, 64.6]	1.71 [1.59, 1.85] ***	1.19 [1.06, 1.32] +
Mother's education				
No education	5112 (43.2)	36.2 [34.9, 37.5]	1.00 [reference]	1.00 [reference]
Primary	1784 (15.1)	56.8 [54.5, 59.1]	2.32 [2.08, 2.59] ***	1.18 [1.00, 1.36] +
Secondary/higher	4943 (41.8)	76.2 [75.0, 77.4]	5.66 [5.19, 6.17] ***	1.50 [1.28, 1.75] +
Mother's religion				
Islam	6901 (58.3)	44.2 [43.1, 45.4]	1.00 [reference]	1.00 [reference]
Christian	4835 (40.8)	72.7 [71.4, 73.9]	3.35 [3.10, 3.63] ***	1.15 [0.95, 1.38]
Traditionalist/others	103 (0.9)	65.0 [55.4, 73.6]	2.35 [1.56, 3.53] ***	1.60 [0.88, 2.74]
Mother's media exposure				
No	7247 (61.2)	46.6 [45.5, 47.8]	1.00 [reference]	1.00 [reference]
Yes (radio/tv/newspaper at least once a week)	4592 (38.8)	70.9 [69.5, 72.2]	2.78 [2.57, 3.01] ***	1.21 [1.08, 1.36] +
Mother's access to mobile phone/internet				
No	5867 (49.6)	41.6 [40.4, 42.9]	1.00 [reference]	1.00 [reference]

Yes	5972 (50.4)	70.2 [69.0, 71.3]	3.30 [3.05, 3.56] ***	1.22 [1.08, 1.36] +
Mother's land ownership				
Does not own land	10247 (86.6)	54.4 [53.4, 55.4]	1.00 [reference]	1.00 [reference]
Owns land alone and/or jointly	1592 (13.4)	66.4 [64.0, 68.7]	1.66 [1.48, 1.85] ***	1.13 [0.96, 1.32]
Mother's knowledge of malaria				
Has no knowledge	685 (5.8)	49.3 [45.6, 53.1]	1.00 [reference]	1.00 [reference]
Has knowledge	11154 (94.2)	56.4 [55.5, 57.4]	1.33 [1.14, 1.55] ***	1.10 [0.89, 1.35]
Mother had health insurance				
No	11578 (97.8)	55.5 [54.6, 56.4]	1.00 [reference]	1.00 [reference]
Yes	261 (2.2)	78.9 [73.6, 83.5]	3.00 [2.22, 4.05] ***	1.59 [1.03, 2.40] +
Household's bed net ownership				
No	3543 (29.9)	59.6 [58.0, 61.2]	1.00 [reference]	1.00 [reference]
Yes	8296 (70.1)	54.5 [53.4, 55.6]	0.81 [0.75, 0.88] ***	1.16 [1.04, 1.30] +
Mother's ethnicity				
Hausa/Fulani	4728 (39.9)	38.7 [37.3, 40.1]	1.00 [reference]	1.00 [reference]
Yoruba	1201 (10.1)	75.5 [73.0, 77.9]	4.89 [4.23, 5.65] ***	1.22 [0.88, 1.66]
Igbo	1667 (14.1)	78.0 [75.9, 79.9]	5.61 [4.93, 6.39] ***	1.56 [1.08, 2.20] +
Others (ekoi, ibibio, etc.)	4243 (35.8)	61.2 [59.7, 62.7]	2.50 [2.30, 2.72] ***	1.24 [1.03, 1.48] +
Household wealth				

Poorer/poorest	5353 (45.2)	40.1 [38.8, 41.4]	1.00 [reference]	1.00 [reference]
Middle	2478 (20.9)	58.1 [56.1, 60.0]	2.07 [1.88, 2.28] ***	1.09 [0.94, 1.25]
Richer/richest	4008 (33.9)	76.0 [74.7, 77.3]	4.72 [4.31, 5.17] ***	1.31 [1.09, 1.55] +
Access to bank account				
No	9844 (83.1)	50.0 [49.0, 51.0]	1.00 [reference]	1.00 [reference]
Yes	1995 (16.9)	85.8 [84.2, 87.3]	6.05 [5.30, 6.90] ***	1.79 [1.50, 2.12] +
Household size				
Large (>=9)	2946 (24.9)	45.7 [43.9, 47.5]	0.60 [0.54, 0.65] ***	0.96 [0.85, 1.08]
Medium (5 to 8)	5518 (46.6)	58.6 [57.2, 59.8]	1.00 [reference]	1.00 [reference]
Small (<=4)	3375 (28.5)	60.9 [59.2, 62.5]	1.10 [1.01, 1.20] *	0.96 [0.84, 1.09]
Length of stay in household				
<1year/visitor	345 (2.9)	69.3 [64.2, 73.9]	1.29 [0.99, 1.69]	1.20 [0.83, 1.65]
1-3years	1205 (10.2)	65.7 [63.0, 68.4]	1.10 [0.92, 1.32]	1.10 [0.87, 1.40]
4-5years	864 (7.3)	63.5 [60.3, 66.7]	1.00 [reference]	1.00 [reference]
>5years/always	9425 (79.6)	53.6 [52.6, 54.6]	0.66 [0.57, 0.77] ***	1.15 [0.95, 1.40]
Rural/urban				
Rural	7622 (64.4)	48.7 [47.6, 49.9]	1.00 [reference]	1.00 [reference]
Urban	4217 (35.6)	69.2 [67.8, 70.6]	2.37 [2.19, 2.56] ***	0.98 [0.68, 1.37]
Livestock density index				

Lower (0-21.4)	3189 (26.9)	65.6 [64.0, 67.3]	1.86 [1.69, 2.04] ***	1.62 [1.28, 2.06] +
Medium (21.5-73.2)	4029 (34.0)	54.6 [53.0, 56.1]	1.17 [1.08, 1.27] ***	1.15 [0.94, 1.39]
Higher (73.3-5196.8)	4621 (39.0)	50.7 [49.2, 52.1]	1.00 [reference]	1.00 [reference]
Travel time to the nearest health facility (providing RI services)				
Lower (0-3.9)	3406 (28.8)	70.8 [69.2, 72.3]	3.16 [2.88, 3.48] ***	1.14 [0.87, 1.46]
Medium (4.0-12.5)	3968 (33.5)	56.8 [55.3, 58.4]	1.69 [1.55, 1.84] ***	1.23 [1.03, 1.44] +
Higher (12.6-532.8)	4465 (37.7)	44.1 [42.6, 45.5]	1.00 [reference]	1.00 [reference]
Variance parameters				**Estimate (95% Cr. I)**
Stratum-level variance				0.39 [0.25, 0.59]
Cluster-level variance				0.40 [0.30, 0.50]

CI: Confidence Interval; Cr. I: Bayesian Credible Interval; cOR: Crude Odds Ratio; aOR: adjusted Odds Ratio; +Significant covariate for the Bayesian model; *p<0.05; **p<0.01; ***p<0.001.

Interpretation of factors associated with MV vaccination in the binomial analysis

Presence of SBA at the child's delivery (aOR=1.66, 95% Cr.I: 1.46, 1.88), health card (yes, none seen: aOR=3.43, 95% Cr.I: 2.81, 4.13; yes, seen: aOR=2.17, 95% Cr.I: 1.94, 2.42), receipt of Vitamin A (aOR=3.42, 95% Cr.I: 3.06, 3.82) were individual variables associated with increased odds for receipt of MV. Maternal or household factors significantly associated with higher odds of MV receipt include maternal age (age 20-29: aOR=1.57, 95% Cr.I: 1.24, 1.94; age 30-39: aOR=1.88, 95% Cr.I: 1.45, 2.38; age 40-49: aOR=1.55, 95% Cr.I: 1.12, 2.03), mothers who are currently employed (aOR=1.35, 95% Cr.I: 1.20, 1.50), problem seeking medical advice (aOR=1.19, 95% Cr.I: 1.06, 1.32), maternal education (primary: aOR=1.18, 95% Cr.I: 1.00, 1.36; secondary: aOR=1.50, 95% Cr.I: 1.28, 1.75), mother's exposed to the media (aOR=1.21, 95% Cr.I: 1.08, 1.36), access to mobile phone/internet (aOR=1.22, 95% Cr.I: 1.08, 1.36), health insurance (aOR=1.59, 95% Cr.I: 1.03, 2.40), households bed net ownership (aOR=1.16, 95% Cr.I: 1.04, 1.30), ethnicity (Igbo: aOR=1.56, 95% Cr.I: 1.08, 2.20; Others (Ekoi, Ibibio, etc): aOR=1.24, 95% Cr.I: 1.03, 1.48), richer/richest wealth category (aOR=1.31, 95% Cr.I: 1.09, 1.55) and access to bank account (aOR=1.79, 95% Cr.I: 1.50, 2.12). Higher birth order (aOR=0.83, 95% Cr.I: 0.72, 0.95) was associated with decreased odds of receipt of MV. Of the community/geospatial variables, only residence in communities with lower livestock density index (aOR=1.62, 95% Cr.I: 1.28, 2.06) and medium travel time to nearest health facility (aOR=1.23, 95% Cr.I: 1.03, 1.44) were significantly associated with increased odds of MV receipt. (Table I).

Predictive accuracy of the Bayesian multiple multilevel binomial models for PENTA1, PENTA3/1 and MV

Even though this is not the main goal of the study, we attempt to evaluate the discriminatory or predictive power of our Bayesian multilevel binomial multivariable models for correctly predicting PENTA1, PENTA3/1, and MV vaccination coverages in this group of children via the Area Under the Receiver Operating Characteristic (AUROC) curve. The AUROC curve value of 91.3% for PENTA1 in Fig C is suggestive of an outstanding discriminatory/predictive ability[20] for our model to correctly predict PENTA1 vaccination coverage. Also, the AUROC curve value of 77.1% and 80.2% in Fig S3 for PENTA3/1 and MV respectively indicates good predictive ability [20] of the fitted models to correctly predict PENTA3/1, and MV. This is an indication that routine vaccination (PENTA1) is relatively more predictable compared to vaccinations through campaigns (MV).

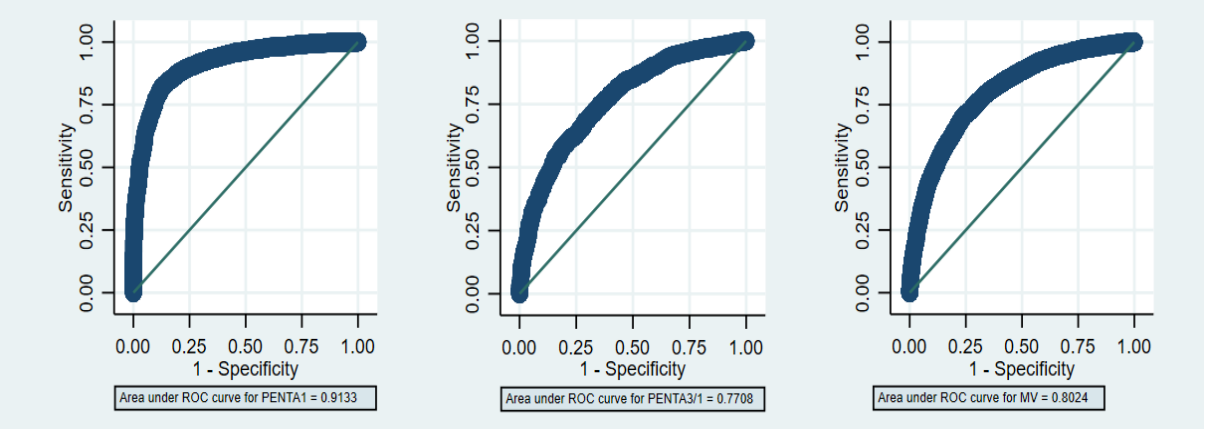

Fig C. Area Under Receiver Operating Characteristic curve of the Bayesian multilevel binomial multivariable models for predicting PENTA1 (1st column), PENTA3/1 (2nd column) and MV (3rd column) vaccination coverages in Nigeria.

Additional results for the multinomial analyses

Presented in this section are additional results from the Bayesian multiple multilevel multinomial analyses for PENTA1 and MV.

PENTA1

Table J: Factors associated with PENTA1 vaccination in the multinomial cross-tabulation analyses of Nigeria DHS 2018

		PENTA1			
		No evidence of vaccination	**Card invalid/ history**	**Card valid**	
Factor	**N**	**n (%)**	**n (%)**	**n (%)**	**P-value**
N	6059	2122 (35.0)	1898 (31.3)	2039 (33.7)	
Sex of child					0.820
Male	3148	1110 (35.3)	990 (31.4)	1048 (33.3)	
Female	2911	1012 (34.8)	908 (31.2)	991 (34.0)	
Birth order					<0.001***
1-2	2279	674 (29.6)	742 (32.6)	863 (37.9)	
>2	3780	1448 (38.3)	1156 (30.6)	1176 (31.1)	
Birth quarter					0.170
Jan-Mar	1909	630 (33.0)	616 (32.3)	663 (34.7)	
Apr-Jun	1668	592 (35.5)	516 (30.9)	560 (33.6)	
Jul-Sep	1628	608 (37.3)	483 (29.7)	537 (33.0)	
Oct-Dec	854	292 (34.2)	283 (33.1)	279 (32.7)	
Skilled birth attendance					<0.001***
No skilled attendant at birth	3328	1772 (53.2)	778 (23.4)	778 (23.4)	
Skilled attendant at birth	2731	350 (12.8)	1120 (41.0)	1261 (46.2)	
Health card/document					<0.001***
Does not have health card/document	3113	1934 (62.1)	1179 (37.9)	0 (0.0)	
Yes, none seen	519	42 (8.1)	477 (91.9)	0 (0.0)	
Yes, seen	2427	146 (6.0)	242 (10.0)	2039 (84.0)	

Received vitamin A					<0.001***
No/don’t know	2852	1569 (55.0)	662 (23.2)	621 (21.8)	
Yes	3207	553 (17.2)	1236 (38.5)	1418 (44.2)	
Sex of household head					<0.001***
Female	5434	1996 (36.7)	1632 (30.0)	1806 (33.2)	
Male	625	126 (20.2)	266 (42.6)	233 (37.3)	
Mother's age group					<0.001***
15-19	366	183 (50.0)	80 (21.9)	103 (28.1)	
20-29	3019	1054 (34.9)	962 (31.9)	1003 (33.2)	
30-39	2237	684 (30.6)	743 (33.2)	810 (36.2)	
40-49	437	201 (46.0)	113 (25.9)	123 (28.1)	
Marital status of mother					0.004
Never in union	171	38 (22.2)	66 (38.6)	67 (39.2)	
Married	5730	2029 (35.4)	1774 (31.0)	1927 (33.6)	
Divorced	158	55 (34.8)	58 (36.7)	45 (28.5)	
Mother employed in the past 12 months					<0.001***
No	1777	854 (48.1)	418 (23.5)	505 (28.4)	
Yes (currently/in the past 1 year)	4282	1268 (29.6)	1480 (34.6)	1534 (35.8)	
Mother had problem seeking medical advice or treatment					<0.001***
Had problem seeking medical advice or treatment	3397	1387 (40.8)	984 (29.0)	1026 (30.2)	
Did not have problem seeking medical advice or treatment	2662	735 (27.6)	914 (34.3)	1013 (38.1)	
Mother’s education					<0.001***
No education	2614	1567 (59.9)	552 (21.1)	495 (18.9)	
Primary	881	242 (27.5)	309 (35.1)	330 (37.5)	
Secondary/higher	2564	313 (12.2)	1037 (40.4)	1214 (47.3)	
Religion					<0.001***
Islam	3538	1756 (49.6)	894 (25.3)	888 (25.1)	
Christian	2469	343 (13.9)	982 (39.8)	1144 (46.3)	
Traditionalist/others	52	23 (44.2)	22 (42.3)	7 (13.5)	
Mother’s media exposure					<0.001***
No	3729	1652 (44.3)	1012 (27.1)	1065 (28.6)	
Yes (radio/tv/newspaper at least once a week)	2330	470 (20.2)	886 (38.0)	974 (41.8)	

Mother's access to mobile phone/internet					<0.001***
No	3062	1562 (51.0)	740 (24.2)	760 (24.8)	
Yes	2997	560 (18.7)	1158 (38.6)	1279 (42.7)	
Mother's land ownership					<0.001***
Does not own land	5236	1927 (36.8)	1594 (30.4)	1715 (32.8)	
Owns land alone and/or jointly	823	195 (23.7)	304 (36.9)	324 (39.4)	
Mother's knowledge of malaria					0.009
Has no knowledge	386	150 (38.9)	94 (24.4)	142 (36.8)	
Has knowledge	5673	1972 (34.8)	1804 (31.8)	1897 (33.4)	
Mother had health insurance					<0.001***
No	5925	2102 (35.5)	1847 (31.2)	1976 (33.4)	
Yes	134	20 (14.9)	51 (38.1)	63 (47.0)	
Household's bed net ownership					<0.001***
No	1780	516 (29.0)	608 (34.2)	656 (36.9)	
Yes	4279	1606 (37.5)	1290 (30.1)	1383 (32.3)	
Mother's ethnicity					<0.001***
Hausa/Fulani	2364	1354 (57.3)	519 (22.0)	491 (20.8)	
Yoruba	622	86 (13.8)	288 (46.3)	248 (39.9)	
Igbo	847	60 (7.1)	343 (40.5)	444 (52.4)	
Others (ekoi, ibibio, etc.)	2226	622 (27.9)	748 (33.6)	856 (38.5)	
Household wealth					<0.001***
Poorer/poorest	2784	1486 (53.4)	685 (24.6)	613 (22.0)	
Middle	1253	366 (29.2)	402 (32.1)	485 (38.7)	
Richer/richest	2022	270 (13.4)	811 (40.1)	941 (46.5)	
Access to bank account					<0.001***
No	5035	2063 (41.0)	1450 (28.8)	1522 (30.2)	
Yes	1024	59 (5.8)	448 (43.8)	517 (50.5)	
Household size					<0.001***
Large (>=9)	1464	705 (48.2)	389 (26.6)	370 (25.3)	
Medium (5 to 8)	2760	906 (32.8)	893 (32.4)	961 (34.8)	
Small (<=4)	1835	511 (27.8)	616 (33.6)	708 (38.6)	
Length of stay in household					<0.001***
<1year/visitor	174	27 (15.5)	100 (57.5)	47 (27.0)	
1-3years	711	177 (24.9)	217 (30.5)	317 (44.6)	
4-5years	438	121 (27.6)	142 (32.4)	175 (40.0)	
>5years/always	4736	1797 (37.9)	1439 (30.4)	1500 (31.7)	
Rural/urban					<0.001***

Rural	3959	1717 (43.4)	1094 (27.6)	1148 (29.0)	
Urban	2100	405 (19.3)	804 (38.3)	891 (42.4)	
Livestock density index					<0.001***
Lower (0-21.4)	1637	434 (26.5)	569 (34.8)	634 (38.7)	
Medium (21.5-73.2)	2034	702 (34.5)	691 (34.0)	641 (31.5)	
Higher (73.3-5196.8)	2365	981 (41.5)	628 (26.6)	756 (32.0)	
Travel time to the nearest health facility (providing RI services)					<0.001***
Lower (0-3.9)	1683	288 (17.1)	610 (36.2)	785 (46.6)	
Medium (4.0-12.5)	2000	661 (33.1)	658 (32.9)	681 (34.1)	
Higher (12.6-532.8)	2353	1168 (49.6)	620 (26.3)	565 (24.0)	
Average enhanced vegetation index (2013-2018)					<0.001***
Lower (0.07-0.23)	2395	1184 (49.4)	616 (25.7)	595 (24.8)	
Medium (0.24-0.36)	2202	688 (31.2)	685 (31.1)	829 (37.6)	
Higher (0.364-0.57)	1439	245 (17.0)	587 (40.8)	607 (42.2)	

*p<0.05; **p<0.01; ***p<0.001.

Table K: Factors associated with PENTA1 in the Bayesian multilevel multinomial logistic regression model, multivariable analyses of Nigeria DHS 2018

	PENTA 1	
	Card Invalid/history	**Card valid**
Variables	**aRR (95% CI)**	**aRR (95% CI)**
Sex of child		
Male	1.00 [reference]	1.00 [reference]
Female	1.02 [0.86, 1.19]	1.08 [0.91, 1.27]
Birth order		
1-2	1.00 [reference]	1.00 [reference]
>2	1.04 [0.82, 1.31]	0.94 [0.72, 1.21]
Birth quarter		
Jan-Mar	1.28 [0.98, 1.62]	1.49 [1.13, 1.91] +
Apr-Jun	1.17 [0.90, 1.49]	1.38 [1.03, 1.78] +
Jul-Sep	1.08 [0.82, 1.39]	1.37 [1.03, 1.78] +
Oct-Dec	1.00 [reference]	1.00 [reference]
Skilled birth attendance		
No skilled attendant at birth	1.00 [reference]	1.00 [reference]
Skilled attendant at birth	2.36 [1.89, 2.92] +	2.37 [1.88, 2.97] +
Received vitamin A		
No/don’t know	1.00 [reference]	1.00 [reference]
Yes	3.90 [3.21, 4.68] +	5.12 [4.17, 6.23] +

Sex of household head		
Female	1.00 [reference]	1.00 [reference]
Male	1.22 [0.88, 1.67]	0.97 [0.68, 1.33]
Mother's age group		
15-19	1.00 [reference]	1.00 [reference]
20-29	1.27 [0.87, 1.81]	1.02 [0.69, 1.44]
30-39	1.18 [0.76, 1.73]	1.08 [0.69, 1.61]
40-49	0.79 [0.46, 1.26]	0.80 [0.47, 1.27]
Marital status of mother		
Never in union	0.77 [0.43, 1.32]	0.76 [0.41, 1.31]
Married	1.00 [reference]	1.00 [reference]
Divorced	0.77 [0.43, 1.25]	0.57 [0.31, 0.98] +
Mother employed in the past 12 months		
No	1.00 [reference]	1.00 [reference]
Yes (currently/in the past 1 year)	1.39 [1.15, 1.68] +	1.23 [0.98, 1.50]
Mother had problem seeking medical advice or treatment		
Had problem seeking medical advice or treatment	1.00 [reference]	1.00 [reference]
Did not have problem seeking medical advice or treatment	1.37 [1.12, 1.65] +	1.44 [1.19, 1.76] +
Mother's education		
No education	1.00 [reference]	1.00 [reference]
Primary	1.47 [1.12, 1.92] +	1.73 [1.30, 2.27] +
Secondary/higher	2.02 [1.52, 2.65] +	2.49 [1.81, 3.28] +
Religion		
Islam	1.00 [reference]	1.00 [reference]
Christian	1.56 [1.11, 2.11] +	1.58 [1.08, 2.22] +
Traditionalist/others	1.15 [0.40, 2.65]	0.50 [0.12, 1.33]
Mother's media exposure		
No	1.00 [reference]	1.00 [reference]
Yes (radio/tv/newspaper at least once a week)	1.11 [0.89, 1.36]	1.09 [0.87, 1.35]
Mother's access to mobile phone/internet		
No	1.00 [reference]	1.00 [reference]
Yes	1.33 [1.07, 1.62] +	1.23 [1.00, 1.51] +
Mother's land ownership		
Does not own land	1.00 [reference]	1.00 [reference]
Owns land alone and/or jointly	1.19 [0.88, 1.55]	1.08 [0.79, 1.43]
Mother's knowledge of malaria		
Has no knowledge	1.00 [reference]	1.00 [reference]
Has knowledge	1.34 [0.92, 1.87]	0.93 [0.62, 1.32]
Mother had health insurance		
No	1.00 [reference]	1.00 [reference]
Yes	1.53 [0.68, 3.04]	1.54 [0.66, 3.20]
Household's bed net ownership		

No	1.00 [reference]	1.00 [reference]
Yes	1.03 [0.83, 1.26]	1.15 [0.92, 1.42]
Mother's ethnicity		
Hausa/Fulani	1.00 [reference]	1.00 [reference]
Yoruba	1.34 [0.77, 2.15]	1.01 [0.54, 1.68]
Igbo	2.30 [1.17, 4.05] +	2.38 [1.14, 4.35] +
Others (ekoi, ibibio, etc.)	1.37 [1.01, 1.80] +	1.42 [1.02, 1.91] +
Household wealth		
Poorer/poorest	1.00 [reference]	1.00 [reference]
Middle	1.08 [0.83, 1.37]	1.52 [1.15, 1.95] +
Richer/richest	1.35 [0.98, 1.78]	1.75 [1.26, 2.36] +
Access to bank account		
No	1.00 [reference]	1.00 [reference]
Yes	2.41 [1.65, 3.45] +	2.15 [1.47, 3.08] +
Household size		
Large (>=9)	1.17 [0.93, 1.43]	1.01 [0.80, 1.26]
Medium (5 to 8)	1.00 [reference]	1.00 [reference]
Small (<=4)	1.12 [0.89, 1.41]	1.18 [0.92, 1.47]
Length of stay in household		
<1year/visitor	2.78 [1.37, 5.25] +	1.03 [0.47, 1.99]
1-3years	1.19 [0.76, 1.78]	1.36 [0.85, 2.09]
4-5years	1.00 [reference]	1.00 [reference]
>5years/always	1.51 [1.03, 2.17] +	1.43 [0.95, 2.06] +
Rural/urban		
Rural	1.00 [reference]	1.00 [reference]
Urban	0.99 [0.62, 1.49]	0.79 [0.46, 1.25]
Livestock density index		
Lower (0-21.4)	1.52 [1.05, 2.15] +	1.39 [0.92, 2.02]
Medium (21.5-73.2)	1.39 [1.01, 1.85] +	1.16 [0.81, 1.60]
Higher (73.3-5196.8)	1.00 [reference]	1.00 [reference]
Travel time to the nearest health facility (providing RI services)		
Lower (0-3.9)	1.36 [0.85, 2.08]	2.38 [1.40, 3.76] +
Medium (4.0-12.5)	1.51 [1.14, 1.97] +	1.97 [1.42, 2.69] +
Higher (12.6-532.8)	1.00 [reference]	1.00 [reference]
Average enhanced vegetation index (2013-2018)		
Lower (0.07-0.23)	1.00 [reference]	1.00 [reference]
Medium (0.24-0.36)	1.36 [1.00, 1.81] +	1.60 [1.13, 2.21] +
Higher (0.364-0.57)	1.26 [0.80, 1.84]	1.36 [0.83, 2.05]
Variance parameter estimates	**Posterior mean [95% Cr.I]**	
Stratum level		
$\hat{\sigma}^2_{s(1)}$ (variance for card invalid/history)	0.39 [0.21, 0.66]	

$\hat{\sigma}^2_{s(2)}$ (variance for card valid)	0.57 [0.32, 0.93]
$\hat{\sigma}^2_{s(1,2)}$ (covariance between card invalid/history and card valid)	0.35 [0.16, 0.62]
Cluster level	
$\hat{\sigma}^2_{c(1)}$ (variance for card invalid/history)	0.73 [0.47, 1.03]
$\hat{\sigma}^2_{c(2)}$ (variance for card valid)	1.24 [0.90, 1.63]
$\hat{\sigma}^2_{c(1,2)}$ (covariance between card invalid/history and card valid)	0.68 [0.42, 0.95]

aRR: adjusted relative risk; Cr.I: Bayesian Credible Interval; [+]Significant covariate for the Bayesian model

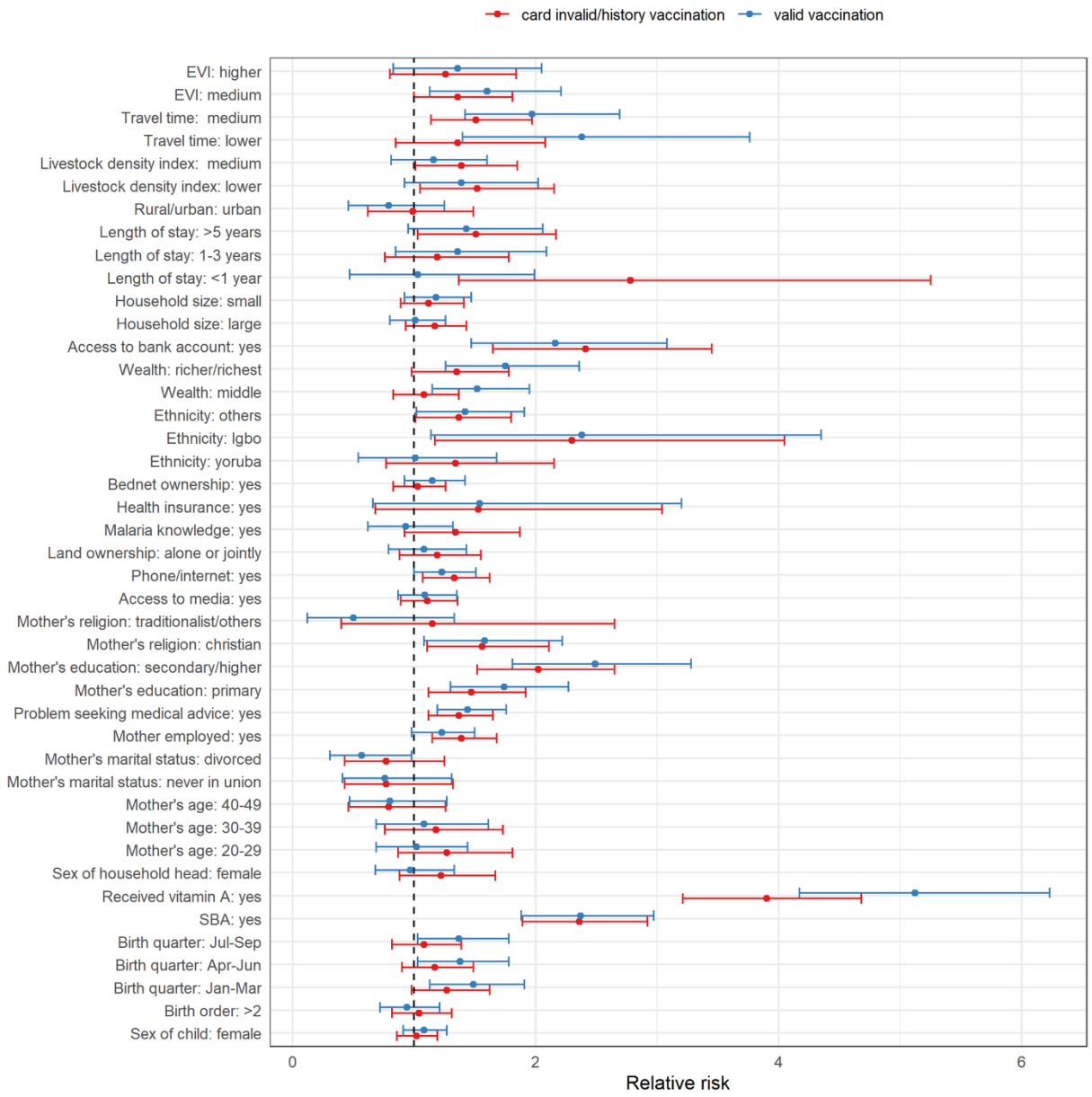

Fig D. Plots of relative risks and corresponding 95% credible interval based on Bayesian multilevel multinomial analysis for PENTA1 vaccination coverage. The vertical dotted line marks the relative risk of 1.

Interpretation of relative risk estimates for PENTA1 in the multinomial analysis

Presented in Table K and Fig D are the Bayesian multiple multilevel multinomial results for PENTA1. Birth quarter (Jan-Mar: aRR=1.49, 95% Cr.I: 1.13, 1.91; Apr-Jun: aRR=1.38, 95% Cr.I: 1.03, 1.78; Jul-Sep: aRR=1.37, 95% Cr.I: 1.03, 1.78) was significantly associated with higher likelihood for receipt of card valid vaccination relative to no evidence of vaccination for PENTA1, but not for card invalid/history, while skilled attendance at birth was associated with increased likelihood for receipt of both card invalid/history (aRR=2.36, 95% Cr.I: 1.89, 2.92) and card valid (aRR=2.37, 95% Cr.I: 1.88, 2.97) vaccinations relative to no evidence of vaccination. Similarly, receipt of vitamin A was associated with higher likelihood for both card invalid/history (aRR=3.90, 95% Cr.I: 3.21, 4.68) and card valid (aRR=5.12, 95% Cr.I: 4.17, 6.23) vaccinations relative to no evidence of vaccination. Belonging to a divorced mother (aRR=0.57, 95% Cr.I: 0.31, 0.98) was predictive of card valid vaccination only, and having a mother who is employed (aRR=1.39, 95% Cr.I: 1.15, 1.68) was predictive of card invalid/history vaccination only. Having a mother who had problem seeking medical advice or treatment is associated with both card invalid/history (aRR=1.37, 95% Cr.I: 1.12, 1.65) and card valid (aRR=1.44, 95% Cr.I: 1.19, 1.76) vaccination. Maternal education was associated with both card invalid/history (primary: aRR=1.47, 95% Cr.I: 1.12, 1.92; secondary/higher: aRR=2.02, 95% Cr.I: 1.52, 2.65) and card valid (primary: aRR=1.73, 95% Cr.I: 1.30, 2.27; secondary/higher: aRR=2.49, 95% Cr.I: 1.81, 3.28) vaccination.

Having a Christian mother was associated with higher likelihood for receipt of both card invalid/history (aRR=1.56, 95% Cr.I: 1.11, 2.11) and card valid (aRR=1.58, 95% Cr.I: 1.08, 2.22) vaccinations. Similarly, mother's access to mobile phone/internet was associated with increased likelihood of both card invalid/history (aRR=1.33, 95% Cr.I: 1.07, 1.62) and card valid

(aRR=1.23, 95% Cr.I: 1.00, 1.51) vaccinations. Igbo ethnic group was predictive of both card invalid/history (aRR=2.30, 95% Cr.I: 1.17, 4.05) and valid card (aRR=2.38, 95% Cr.I: 1.14, 4.35) vaccination while other ethnic groups (e.g., Ekoi, Ibibio) was predictive of both card invalid/history (aRR=1.37, 95% Cr.I: 1.01, 1.80]) and card valid (aRR=1.42, 95% Cr.I: 1.02, 1.91) vaccinations. Household wealth (middle: aRR=1.52, 95% Cr.I: 1.15, 1.95; and richest: aRR=1.75, 95% Cr.I: 1.26, 2.36) was only predictive of card valid vaccination. Having a mother who had access to bank account was predictive of both card invalid/history (aRR=2.41, 95% Cr.I: 1.65, 3.45) and card valid (aRR=2.15, 95% Cr.I: 1.47, 3.08) vaccination.

Furthermore, residing in household for less than one year (aRR=2.78, 95% Cr.I: 1.37, 5.25) was predictive of card invalid/history vaccination only but residing in household for more than 5 years or always was predictive of both card invalid/history (aRR=1.51, 95% Cr.I: 1.03, 2.17) and card valid (aRR=1.43, 95% Cr.I: 0.95, 2.06) vaccinations. Livestock index (lower: aRR=1.52, 95% Cr.I: 1.05, 2.15, and medium: aRR=1.39, 95% Cr.I: 1.01, 1.85) was associated with increased likelihood of receipt of card invalid/history vaccination only. Residing within lower travel times (aRR=2.38, 95% Cr.I: 1.40, 3.76) to the nearest health facility was predictive of card valid vaccination only while residing in medium travel times to health facility was predictive of both card invalid/history (aRR=1.51, 95% Cr.I: 1.14, 1.97) and card valid (aRR=1.97, 95% Cr.I: 1.42, 2.69) vaccination. Residing in communities with medium enhanced vegetation index was predictive of both card invalid/history (aRR=1.36, 95% Cr.I: 1.00, 1.81) and card valid (aRR=1.60, 95% Cr.I: 1.13, 2.21) vaccination (Table K).

MV

Table L: Factors associated with MV vaccination in the multinomial cross-tabulation analyses of Nigeria DHS 2018

		MV			
Variables		**No evidence of vaccination**	**Card invalid/ history**	**Card valid**	**P-value**
	N	**n (%)**	**n (%)**	**n (%)**	
N	11839	5206(44.0)	4522(38.2)	2111(17.8)	
Sex of child					0.720
Male	6050	2682 (44.3)	2299 (38.0)	1069 (17.7)	
Female	5789	2524 (43.6)	2223 (38.4)	1042 (18.0)	
Birth order					<0.001***
1-2	4485	1769 (39.4)	1760 (39.2)	956 (21.3)	
>2	7354	3437 (46.7)	2762 (37.6)	1155 (15.7)	
Birth quarter					<0.001***
Jan-Mar	3801	1611 (42.4)	1490 (39.2)	700 (18.4)	
Apr-Jun	3237	1471 (45.4)	1203 (37.2)	563 (17.4)	
Jul-Sep	3194	1478 (46.3)	1162 (36.4)	554 (17.3)	
Oct-Dec	1607	646 (40.2)	667 (41.5)	294 (18.3)	
Skilled birth attendance					<0.001***
No skilled attendant at birth	6509	3887 (59.7)	1979 (30.4)	643 (9.9)	
Skilled attendant at birth	5330	1319 (24.7)	2543 (47.7)	1468 (27.5)	
Health card/document					<0.001***
Does not have health card/document	6600	3884 (58.8)	2716 (41.2)	0 (0.0)	
Yes, none seen	1104	231 (20.9)	873 (79.1)	0 (0.0)	
Yes, seen	4135	1091 (26.4)	933 (22.6)	2111 (51.1)	
Received vitamin A					<0.001***

No/don’t know	5658	3595 (63.5)	1626 (28.7)	437 (7.7)	
Yes	6181	1611 (26.1)	2896 (46.9)	1674 (27.1)	
Sex of household head					<0.001***
Female	10662	4826 (45.3)	3947 (37.0)	1889 (17.7)	
Male	1177	380 (32.3)	575 (48.9)	222 (18.9)	
Mother's age group					<0.001***
15-19	587	370 (63.0)	151 (25.7)	66 (11.2)	
20-29	5766	2617 (45.4)	2157 (37.4)	992 (17.2)	
30-39	4508	1748 (38.8)	1861 (41.3)	899 (19.9)	
40-49	978	471 (48.2)	353 (36.1)	154 (15.7)	
Marital status of mother					<0.001***
Never in union	287	96 (33.4)	129 (44.9)	62 (21.6)	
Married	11222	4982 (44.4)	4242 (37.8)	1998 (17.8)	
Divorced	330	128 (38.8)	151 (45.8)	51 (15.5)	
Mother employed in the past 12 months					<0.001***
No	3403	1926 (56.6)	1040 (30.6)	437 (12.8)	
Yes (currently/in the past 1 year)	8436	3280 (38.9)	3482 (41.3)	1674 (19.8)	
Mother had problem seeking medical advice or treatment					<0.001***
Had problem seeking medical advice or treatment	6529	3256 (49.9)	2287 (35.0)	986 (15.1)	
Did not have problem seeking medical advice or treatment	5310	1950 (36.7)	2235 (42.1)	1125 (21.2)	
Mother’s education					<0.001***
No education	5112	3262 (63.8)	1479 (28.9)	371 (7.3)	
Primary	1784	770 (43.2)	688 (38.6)	326 (18.3)	
Secondary/higher	4943	1174 (23.8)	2355 (47.6)	1414 (28.6)	
Religion					<0.001***
Islam	6901	3849 (55.8)	2289 (33.2)	763 (11.1)	
Christian	4835	1321 (27.3)	2172 (44.9)	1342 (27.8)	
Traditionalist/others	103	36 (35.0)	61 (59.2)	6 (5.8)	

Mother's media exposure					<0.001***
No	7247	3868 (53.4)	2414 (33.3)	965 (13.3)	
Yes (radio/tv/newspaper at least once a week)	4592	1338 (29.1)	2108 (45.9)	1146 (25.0)	
Mother's access to mobile phone/internet					<0.001***
No	5867	3424 (58.4)	1805 (30.8)	638 (10.9)	
Yes	5972	1782 (29.8)	2717 (45.5)	1473 (24.7)	
Mother's land ownership					<0.001***
Does not own land	10247	4671 (45.6)	3806 (37.1)	1770 (17.3)	
Owns land alone and/or jointly	1592	535 (33.6)	716 (45.0)	341 (21.4)	
Mother's knowledge of malaria					<0.001***
Has no knowledge	685	347 (50.7)	208 (30.4)	130 (19.0)	
Has knowledge	11154	4859 (43.6)	4314 (38.7)	1981 (17.8)	
Mother had health insurance					<0.001***
No	11578	5151 (44.5)	4392 (37.9)	2035 (17.6)	
Yes	261	55 (21.1)	130 (49.8)	76 (29.1)	
Household's bed net ownership					<0.001***
No	3543	1432 (40.4)	1392 (39.3)	719 (20.3)	
Yes	8296	3774 (45.5)	3130 (37.7)	1392 (16.8)	
Mother's ethnicity					<0.001***
Hausa/Fulani	4728	2899 (61.3)	1464 (31.0)	365 (7.7)	
Yoruba	1201	294 (24.5)	600 (50.0)	307 (25.6)	
Igbo	1667	367 (22.0)	755 (45.3)	545 (32.7)	
Others (ekoi, ibibio, etc.)	4243	1646 (38.8)	1703 (40.1)	894 (21.1)	
Household wealth					<0.001***
Poorer/poorest	5353	3205 (59.9)	1666 (31.1)	482 (9.0)	
Middle	2478	1039 (41.9)	981 (39.6)	458 (18.5)	
Richer/richest	4008	962 (24.0)	1875 (46.8)	1171 (29.2)	

Access to bank account					<0.001***
No	9844	4923 (50.0)	3516 (35.7)	1405 (14.3)	
Yes	1995	283 (14.2)	1006 (50.4)	706 (35.4)	
Household size					<0.001***
Large (>=9)	2946	1599 (54.3)	1012 (34.4)	335 (11.4)	
Medium (5 to 8)	5518	2287 (41.4)	2200 (39.9)	1031 (18.7)	
Small (<=4)	3375	1320 (39.1)	1310 (38.8)	745 (22.1)	
Length of stay in household					<0.001***
<1year/visitor	345	106 (30.7)	190 (55.1)	49 (14.2)	
1-3years	1205	413 (34.3)	469 (38.9)	323 (26.8)	
4-5years	864	315 (36.5)	340 (39.4)	209 (24.2)	
>5years/always	9425	4372 (46.4)	3523 (37.4)	1530 (16.2)	
Rural/urban					<0.001***
Rural	7622	3908 (51.3)	2666 (35.0)	1048 (13.7)	
Urban	4217	1298 (30.8)	1856 (44.0)	1063 (25.2)	
Livestock density index					<0.001***
Lower (0-21.4)	3189	1096 (34.4)	1356 (42.5)	737 (23.1)	
Medium (21.5-73.2)	4029	1830 (45.4)	1534 (38.1)	665 (16.5)	
Higher (73.3-5196.8)	4621	2280 (49.3)	1632 (35.3)	709 (15.3)	
Travel time to the nearest health facility (providing RI services)					<0.001***
Lower (0-3.9)	3406	995 (29.2)	1477 (43.4)	934 (27.4)	
Medium (4.0-12.5)	3968	1713 (43.2)	1576 (39.7)	679 (17.1)	
Higher (12.6-532.8)	4465	2498 (55.9)	1469 (32.9)	498 (11.2)	

*p<0.05; **p<0.01; ***p<0.001.

Table M: Factors associated with MV in the Bayesian multilevel multinomial logistic regression model, multivariable analyses of Nigeria DHS 2018

	MV	
	Card Invalid/history	**Card valid**
Variables	**aRR (95% Cr.I)**	**aRR (95% Cr.I)**
Sex of child		
Male	1.00 [reference]	1.00 [reference]
Female	1.02 [0.93, 1.13]	1.04 [0.91, 1.18]
Birth order		
1-2	1.00 [reference]	1.00 [reference]
>2	0.83 [0.72, 0.97] +	0.82 [0.69, 0.98] +
Birth quarter		
Jan-Mar	0.96 [0.82, 1.13]	1.09 [0.88, 1.33]
Apr-Jun	0.87 [0.74, 1.01]	0.98 [0.79, 1.20]
Jul-Sep	0.87 [0.73, 1.02]	0.98 [0.79, 1.21]
Oct-Dec	1.00 [reference]	1.00 [reference]
Skilled birth attendance		
No skilled attendant at birth	1.00 [reference]	1.00 [reference]
Skilled attendant at birth	1.76 [1.54, 2.00] +	1.86 [1.57, 2.20] +
Received vitamin A		
No/don't know	1.00 [reference]	1.00 [reference]
Yes	3.18 [2.83, 3.55] +	5.66 [4.85, 6.58] +
Sex of household head		
Female	1.00 [reference]	1.00 [reference]
Male	1.15 [0.96, 1.38]	0.81 [0.64, 1.01]
Mother's age group		
15-19	1.00 [reference]	1.00 [reference]
20-29	1.58 [1.22, 2.00] +	1.46 [1.02, 2.06] +
30-39	1.87 [1.40, 2.42] +	1.77 [1.19, 2.54] +
40-49	1.52 [1.08, 2.05] +	1.58 [0.98, 2.38]
Marital status of mother		
Never in union	1.07 [0.75, 1.47]	1.01 [0.64, 1.49]
Married	1.00 [reference]	1.00 [reference]
Divorced	1.17 [0.85, 1.56]	0.92 [0.59, 1.34]
Mother employed in the past 12 months		
No	1.00 [reference]	1.00 [reference]
Yes (currently/in the past 1 year)	1.38 [1.21, 1.55] +	1.36 [1.16, 1.58] +
Mother had problem seeking medical advice or treatment		
Had problem seeking medical advice or treatment	1.00 [reference]	1.00 [reference]
Did not have problem seeking medical advice or treatment	1.20 [1.07, 1.34] +	1.24 [1.07, 1.42] +
Mother's education		
No education	1.00 [reference]	1.00 [reference]
Primary	1.19 [1.01, 1.39] +	1.52 [1.21, 1.88] +
Secondary/higher	1.52 [1.29, 1.78] +	1.95 [1.57, 2.39] +

Religion		
Islam	1.00 [reference]	1.00 [reference]
Christian	1.17 [0.96, 1.43]	1.24 [0.97, 1.55]
Traditionalist/others	1.73 [0.94, 2.99]	0.58 [0.18, 1.39]
Mother's media exposure		
No	1.00 [reference]	1.00 [reference]
Yes (radio/tv/newspaper at least once a week)	1.22 [1.08, 1.37] +	1.26 [1.08, 1.46] +
Mother's access to mobile phone/internet		
No	1.00 [reference]	1.00 [reference]
Yes	1.26 [1.11, 1.42] +	1.13 [0.96, 1.32]
Mother's land ownership		
Does not own land	1.00 [reference]	1.00 [reference]
Owns land alone and/or jointly	1.24 [1.05, 1.45] +	0.94 [0.76, 1.14]
Mother's knowledge of malaria		
Has no knowledge	1.00 [reference]	1.00 [reference]
Has knowledge	1.18 [0.92, 1.48]	0.95 [0.70, 1.23]
Mother had health insurance		
No	1.00 [reference]	1.00 [reference]
Yes	1.57 [1.00, 2.37] +	1.33 [0.78, 2.12]
Household's bed net ownership		
No	1.00 [reference]	1.00 [reference]
Yes	1.13 [1.00, 1.27] +	1.26 [1.08, 1.45] +
Mother's ethnicity		
Hausa/Fulani	1.00 [reference]	1.00 [reference]
Yoruba	1.30 [0.91, 1.79]	1.24 [0.83, 1.82]
Igbo	1.53 [1.04, 2.21] +	2.05 [1.35, 3.10] +
Others (ekoi, ibibio, etc.)	1.20 [0.99, 1.45]	1.56 [1.21, 1.98] +
Household wealth		
Poorer/poorest	1.00 [reference]	1.00 [reference]
Middle	1.07 [0.92, 1.23]	1.39 [1.12, 1.70] +
Richer/richest	1.30 [1.09, 1.55] +	1.79 [1.40, 2.24] +
Access to bank account		
No	1.00 [reference]	1.00 [reference]
Yes	1.74 [1.45, 2.09] +	2.08 [1.69, 2.55] +
Household size		
Large (>=9)	0.98 [0.86, 1.11]	0.89 [0.73, 1.07]
Medium (5 to 8)	1.00 [reference]	1.00 [reference]
Small (<=4)	0.92 [0.80, 1.05]	1.11 [0.93, 1.31]
Length of stay in household		
<1year/visitor	1.57 [1.09, 2.21] +	0.60 [0.36, 0.92] +
1-3years	1.10 [0.84, 1.40]	1.13 [0.83, 1.52]
4-5years	1.00 [reference]	1.00 [reference]
>5years/always	1.16 [0.93, 1.42]	1.09 [0.84, 1.38]
Rural/urban		
Rural	1.00 [reference]	1.00 [reference]
Urban	1.01 [0.70, 1.44]	0.86 [0.57, 1.20]
Livestock density index		
Lower (0-21.4)	1.62 [1.26, 2.05] +	1.57 [1.16, 2.11] +

Medium (21.5-73.2)	1.16 [0.94, 1.40]	1.11 [0.85, 1.42]
Higher (73.3-5196.8)	1.00 [reference]	1.00 [reference]
Travel time to the nearest health facility (providing RI services)		
Lower (0-3.9)	1.05 [0.79, 1.37]	1.50 [1.05, 2.08] $^{+}$
Medium (4.0-12.5)	1.21 [1.00, 1.44] $^{+}$	1.48 [1.13, 1.86] $^{+}$
Higher (12.6-532.8)	1.00 [reference]	1.00 [reference]
Variance parameter estimates	**Posterior mean [95% Cr.I]**	
Stratum level		
$\hat{\sigma}^2_{s(1)}$ (variance for card invalid/history)	0.45 [0.29, 0.67]	
$\hat{\sigma}^2_{s(2)}$ (variance for card valid)	0.35 [0.20, 0.56]	
$\hat{\sigma}^2_{s(1,2)}$ (covariance between card invalid/history and card valid)	0.25 [0.12, 0.43]	
Cluster level		
$\hat{\sigma}^2_{c(1)}$ (variance for card invalid/history)	0.43 [0.33, 0.54]	
$\hat{\sigma}^2_{c(2)}$ (variance for card valid)	0.76 [0.59, 0.96]	
$\hat{\sigma}^2_{c(1,2)}$ (covariance between card invalid/history and card valid)	0.36 [0.26, 0.48]	

aRR: adjusted relative risk; Cr.I: Bayesian Credible Interval; $^{+}$Significant covariate for the Bayesian model

Interpretation of relative risk estimates for MV in the multinomial analysis

Table M presents the results from the Bayesian multiple multilevel multinomial analysis for MV. Receipt of assistance from a SBA was associated with higher likelihood for receipt of both card invalid/history (aRR=1.76, 95% Cr.I: 1.54, 2.00) and card valid (aRR=1.86, 95% Cr.I: 1.57, 2.20) vaccinations for MV, while receipt of vitamin A was predictive of higher likelihood of receipt of both card invalid/history (aRR=3.18, 95% Cr.I: 2.83, 3.55) and card valid (aRR=5.66, 95% Cr.I: 4.85, 6.58) vaccinations for MV. Similarly, maternal age was associated with higher likelihood of receipt of both card invalid/history (20-29: aRR=1.58, 95% Cr.I: 1.22, 2.00, 30-39: aRR=1.87, 95% Cr.I: 1.40, 2.42, and 40-49: aRR=1.52, 95% Cr.I: 1.08, 2.05) and card valid (20-29: aRR=1.46, 95% Cr.I: 1.02, 2.06, 30-39: aRR=1.77, 95% Cr.I: 1.19, 2.54, but not for age 40-49) vaccinations for MV. Maternal employment was associated with increased likelihood of receipt of both card invalid/history (aRR=1.38, 95%

Cr.I: 1.21, 1.55) and card valid (aRR=1.36, 95% Cr.I: 1.16, 1.58) for MV vaccinations, while belonging to mothers who had problem seeking medical advice or treatment was associated with significantly higher likelihood for receipt of card invalid/history (aRR=1.20, 95% Cr.I: 1.07, 1.34) and card valid (aRR=1.24, 95% Cr.I: 1.07, 1.42) vaccinations for MV. Maternal education was predictive of higher likelihood of receipt of both card invalid/history (primary: aRR=1.19, 95% Cr.I: 1.01, 1.39, secondary: aRR=1.52, 95% Cr.I: 1.29, 1.78) and card valid history (primary: aRR=1.52, 95% Cr.I: 1.21, 1.88, secondary: aRR=1.95, 95% Cr.I: 1.57, 2.39) vaccinations for MV. Having a mother who was exposed to the media was predictive of increased likelihood of receipt of both card invalid/history (aRR=1.22, 95% Cr.I: 1.08, 1.37) and card valid (aRR=1.26, 95% Cr.I: 1.08, 1.46) MV receipt, while access to phone/internet (aRR=1.26, 95% Cr.I: 1.11, 1.42), mothers who owned land (aRR=1.24, 95% Cr.I: 1.05, 1.45), health insurance (aRR=1.57, 95% Cr.I: 1.00, 2.37) were significant predictors of higher likelihood of receipt of card invalid/history of MV but not for card valid. Children from households that owned bed net was associated with higher odds of receipt of both card invalid/history (aRR=1.13, 95% Cr.I: 1.00, 1.27) and card valid (aRR=1.26, 95% Cr.I: 1.08, 1.45) MV receipt. Ethnicity was associated with increased likelihood of receipt of both card invalid/history (Igbo: aRR=1.53, 95% Cr.I: 1.04, 2.21, but not others) and card valid (Igbo: aRR=2.05, 95% Cr.I: 1.35, 3.10, Others (Ekoi, Ibibio, etc): aRR=1.56, 95% Cr.I: 1.21, 1.98) MV. Wealth was associated with increased likelihood of receipt of both card invalid/history (richer/richest: aRR=1.30, 95% Cr.I: 1.09, 1.55, but not for middle category) and card valid (middle: aRR=1.39, 95% Cr.I: 1.12, 1.70, richer/richest: aRR=1.79, 95% Cr.I: 1.40, 2.24) MV. Having mothers who had access to bank accounts was predictive of increased likelihood of receipt of both card invalid/history (aRR=1.74, 95% Cr.I: 1.45, 2.09) and card valid (aRR=2.08, 95% Cr.I: 1.69, 2.55) MV. Staying in a household for less than one (1) year was predictive of higher likelihood of receipt of card invalid/history (aRR=1.57,

95% Cr.I: 1.09, 2.21), but was predictive of reduced likelihood of receipt of card valid (aRR=0.60, 95% Cr.I: 0.36, 0.92) MV. Higher birth order was associated with reduced likelihood for receipt of both invalid/history (aRR=0.83, 95% Cr.I: .72, 0.97) and card valid (aRR=0.82, 95% Cr.I: 0.69, 0.98) MV. Finally, residing in communities with lower livestock density index was predictive of increased likelihood of receipt of both card invalid/history (aRR=1.62, 95% Cr.I: 1.26, 2.05) and card valid (aRR=1.57, 95% Cr.I: 1.16, 2.11) MV, while lower travel time was predictive of higher odds of receipt of card valid (aRR=1.50, 95% Cr.I: 1.05, 2.08) MV only. Medium travel time was associated with higher likelihood of receipt of both card invalid/history (aRR=1.21, 95% Cr.I: 1.00, 1.44) and card valid (aRR=1.48, 95% Cr.I: 1.13, 1.86) MV (Table M).

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