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Complete List of Authors:	Zhang, Xingna; University of Liverpool, Department of Public Health, Policy & Systems Tulloch, John; University of Liverpool, HPRU EZI Knott, Shane; Liverpool Liverpool City Council Allison, Rachel; Russells Hall Hospital Parvulescu, Paula; Liverpool City Council Buchan, Iain; University of Liverpool, Public Health and Policy Garcia-Finana, Marta; University of Liverpool, Department of Health Data Science; Clinical Trials Research Centre, Piroddi, Roberta; University of Liverpool, Department of Public Health, Policy & Systems Green, Mark; University of Liverpool, Geography & Planning Baird, Sophie; The UK Health Security Agency Barr, Ben ; University of Liverpool, Department Public Health and Policy
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Evaluating the impact of using mobile vaccination units to increase COVID-19 vaccination uptake: A synthetic control analysis

Xingna Zhang[1], John Tulloch[2], Shane Knott[3], Rachel Allison[4], Paula Parvulescu[5], Iain Buchan[6], Marta García-Fiñana[7], Roberta Piroddi[8], Mark A. Green[9], Sophie Baird[10], Ben Barr[11]

[1] Research Associate, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[2] Tenure Track Fellow, Department of Livestock and One Health in the Institute of Infection, Veterinary and Ecological Science, University of Liverpool, Liverpool, UK

[3] Senior Public Health Practitioner (Healthcare), Liverpool City Council, Liverpool, UK

[4] FY1 Doctor, Russells Hall Hospital, Dudley, UK

[5] Consultant in Public Health Medicine, Liverpool City Council, Liverpool, UK

[6] Chair in Public Health and Clinical Informatics, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[7] Professor of Health Data Science, Department of Health Data Science, University of Liverpool, Liverpool, UK

[8] Research Fellow, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[9] Reader in Health Geography, Department of Geography & Planning, University of Liverpool, Liverpool, UK

[10] Public Health Registrar, The UK Health Security Agency, UK

[11] Chair in Applied Public Health Research, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

Corresponding author:

Xingna Zhang

xingna.zhang@liverpool.ac.uk

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ABSTRACT

Objective To assess the impact on COVID-19 vaccine uptake of mobile vaccination units; vaccine provision that is temporally introduced into a neighbourhood using a large vehicle such as a bus or 'pop-up clinic'. We further investigate whether such an effect differed by deprivation, ethnicity and age.

Design Synthetic control analysis.

Setting The population registered with General Practices in nine local authority areas in Cheshire and Merseyside in the Northwest of England.

Intervention Mobile vaccination units that visited 37 sites on 54 occasions between 12th April and 28th June 2021. We defined populations as having received the intervention if they lived within 1km of a mobile vaccination site. A weighted combination of neighbourhoods that had not received the intervention was used to construct a synthetic control group.

Outcome The weekly number of first-dose vaccines received among people aged 18 and over as a proportion of the population.

Results The introduction of a mobile vaccination unit into a neighbourhood increased the number of first vaccinations conducted in the neighbourhood by 25% (95% CI: 21% to 28%) within three weeks after the first visit to a neighbourhood, compared to the synthetic control group. This effect was smaller amongst 30–65-year-olds compared to 18-30-year-olds, amongst Asian and Black ethnic groups compared to White ethnic groups, and the most socioeconomically deprived populations compared to the least deprived areas.

Conclusions Mobile vaccination units are effective interventions to increase vaccination uptake, at least in the short-term. While mobile units can be geographically targeted to reduce inequalities, we found evidence that they may increase inequalities in vaccine uptake within targeted areas, as the intervention was less effective amongst groups that tended to have lower vaccination uptake. Mobile vaccination units should be used in combination with activities to maximise outreach with Black and Asian communities and socioeconomically disadvantaged groups.

Strengths and limitations of this study

- The synthetic control method for microdata offers a rigorous method for identifying control areas that experienced similar levels of COVID-19 vaccine uptake as the intervention areas prior to the introduction of mobile vaccination units, supporting a casual interpretation of the finding of increased uptake in areas with mobile vaccination visits following their introduction.
- The use of individual-level data enabled us to construct weighted Poisson regression models to offer robust estimation of the observed effect, with interaction analysis to reveal whether this effect varied by level of deprivation, age groups and ethnicity.
- We excluded individuals that had used the mobile vaccination units but had not been registered with the GP (general practice) at time of our study, which could lead to the underestimation of the effect.
- As our analysis covers a relatively short follow-up period, we are unable to determine whether the observed effect is due to people being vaccinated earlier than they would otherwise have been or they would have never taken up vaccine without the mobile unit intervention.
- There may also be other differences between places being visited by the mobile vaccination units and those that were not and differences in individual characteristics, beyond those included in this study, that led to the differences in the observed effect.

Introduction

Vaccination is one of the most effective public health interventions for improving health and saving lives.[1] Since the national rollout of the COVID-19 vaccine program on 8th December 2020 in the UK, relatively high uptake of vaccinations has helped reduce the risk of hospitalisation and mortality from COVID-19.[2] Nevertheless, vaccine uptake was lower among young people, socioeconomically disadvantaged groups and ethnic minorities.[3–6] These groups have also often experienced disproportionately greater levels of infections, hospitalisations and deaths during the pandemic. With emerging new SARS-CoV-2 strains like Omicron, additional booster vaccinations are needed to give sufficient protection. Uptake inequalities of these subsequent doses are even greater than first and second doses,[7] potentially undermining responses to new variants that rely largely on increased uptake of booster vaccinations. Currently the UK government is investing £22.5 million to help areas increase uptake amongst 'hard-to-reach' groups.[8] A central part of this strategy is to use mobile vaccination units such as pop-up sites and vaccine buses – "taking the vaccines into the hearts of local communities".[9]

Mobile vaccination units have been used in many countries to increase uptake in disadvantaged communities.[10] These generally involve vaccination clinics based in large vehicles such as buses or temporary pop-up clinics in community settings. As well as bringing vaccines into targeted communities, they usually involve outreach programmes (e.g., leaflet campaigns to advertise vaccination units and explain the benefits of vaccination). The use of mobile vaccination units to increase uptake is based on the premise that geographic accessibility and convenience of vaccination services are potentially important determinants of uptake and that they support uptake from people who have difficulty in accessing existing sites due to information or travel barriers, childcare or healthcare responsibilities, or being excluded from the official healthcare system.[11]

There has been limited research evaluating interventions that aim to increase COVID-19 vaccine uptake. One Randomised Controlled Trial (RCT) shows that provision of information on personal benefit reduces hesitancy,[12] another RCT indicates that text message reminders lead to small increases in uptake.[13] One study of a community-based strategy in an underserved Latinx population in San Francisco found that mobile units reached the intended recipients, but the study was unable to estimate the impact on vaccination uptake.[14] A few studies investigated the impact of interventions aiming to increase Influenza and pneumococcal vaccination, including one systematic review,[15] five RCTs [16–20] and two cluster RCTs.[21,22] Of these, three were published in the United Kingdom,[16,17,21] three in the United States [15,18,19] and two in Hong Kong.[20,22] They

show that sending out reminders, telephone calls and educational outreach tend to increase uptake. We found no studies that investigated the impact of mobile vaccination units.

Mobile vaccination units could be useful to increase uptake in disadvantaged communities, or alternatively largely be used by people who would have attended existing static vaccination clinics, when mobile units had not visited their neighbourhood. It is also unknown if they are effective at increasing uptake amongst socioeconomically disadvantaged and ethnic minority groups. The lack of existing evidence is concerning, considering their central role in current strategies to reduce vaccine uptake inequalities. We therefore used a synthetic control approach to investigate the impact of mobile vaccination units in the Northwest of England and how this varied by age, socioeconomic status, and ethnicity.

Methods

Data

We utilised anonymised electronic health records (EHR) on all people aged 18 years old and over registered with a General Practice (GP) in Cheshire and Merseyside, England, between 22nd February and 19th July 2021.[23] This data included vaccination status, vaccination date, age, sex, ethnicity, chronic health conditions diagnosed in primary care (chronic obstructive pulmonary disease, chronic heart disease, diabetes, chronic kidney disease asthma, cancer, obesity, depression , and stroke/transient ischaemic attack), whether people were in contact with social care, whether they were a paid carer, travel time to the nearest static vaccination site and the Lower Super Output Areas (LSOA) of residence. LSOAs are small geographical areas of England, with approximately 1500 residents each. Ethnicity was based on information of primary care records. Where this is unavailable, ethnicity was taken from hospital, community, or social care records if available in these datasets. Ethnic group was categorised in these datasets using the 17 standard Office for National Statistics Categories. These were then re-coded to 5 categories for analysis (White/White British, Asian/Asian British, Black/Black British, Mixed, and Other).

We linked the EHR data to LSOA-level data, including 2019's indices of multiple deprivation (IMD), an over-crowded housing measure (the proportion of households with at least one-bedroom fewer than they need) based on 2011's Census, and population density using 2019's mid-year population estimates from the Office for National Statistics. The public health teams of the nine local authorities in the Cheshire and Merseyside region were asked to provide a list of locations and dates of mobile vaccination units in their areas between May and November 2021. Six local authorities provided this

information and two local authorities reported that they had had no mobile vaccination units. Analysis was therefore limited to these eight local authorities.

Intervention

Six local authorities operated mobile vaccination units, that visited 37 sites on 54 occasions, between 12th April and 28th June 2021. This included 52 visits from vaccine buses and two from two pop-up clinics. Units were primarily focused on offering first-dose COVID-19 vaccinations to those that had not received a vaccine at any of the city's existing static vaccination sites and were eligible for vaccination at the time.[24] Vaccines were offered on a drop-in basis with no appointment needed. The number of vaccinations received at these mobile units was unavailable for one local authority (Warrington). The total number of first dose vaccinations for the remaining five local authorities was 3824. Sites visited by mobile vaccination units were identified by local public health and health service teams based on their knowledge of vaccine uptake, practicalities of having space and permissions to locate the vaccination unit, and relationships with local community groups.

We defined intervention neighbourhoods as being located within 1km of mobile vaccination sites, and identified 216 LSOAs that were either hosts for mobile vaccination units or had population weighted centroids within a 1km radius of mobile vaccination units. We calculated the start time of the intervention as the week a mobile vaccination unit first visited. This left 1112 non-intervention LSOAs within the eight participating local authorities that had not been visited by mobile vaccination units. We then applied a 'placebo' start time to each of these non-intervention LSOAs, generated uniformly at random in the same weekly proportion as the distribution of intervention start dates for the intervention LSOAs.

Statistical analysis

We aggregated the individual-level data to construct a panel of weekly measures at the LSOA level from seven weeks (22nd February 2021) before the first mobile vaccination unit visit on 12th April 2021 to three weeks (19th July 2021) after the last mobile vaccination unit visit on 28th June 2021. This included LSOA-level measures of total GP registered population size, the proportion of Black/Black British people, the proportion of Asian/Asian British people, the proportion of people of mixed ethnicity, mean age of residents, population density, the proportion of women, the IMD score, the proportion of households living in overcrowded housing, the average travel time to the nearest static vaccine site, the cumulative number of first dose administered at the intervention start time, and the number of new first dose vaccinations administered per week.

We apply the synthetic control method for microdata developed by Robbins et al. to estimate the effect of mobile vaccination units on vaccine uptake.[25,26] The synthetic control method is a generalisation of difference-in-difference methods.[27] An untreated version of the intervention areas (i.e. a synthetic control) is created using a weighted combination of areas that were unexposed to the intervention. The intervention effect is estimated by comparing the trend in outcomes in the intervention areas to that in the synthetic control areas following the intervention.[28]

The weights are calculated using the raking [29] method so that the weighted averages of all characteristics, for all the variables outlined above in the synthetic control group were the same as for the intervention group. The weighting algorithm derives weights that meet two constraints. Firstly, the sum of first-dose vaccines in the control group equals first-dose vaccines administered in the intervention areas for each of the seven weeks prior to the intervention. Secondly, the weighted average of each local area characteristic, outlined above in the control group equals the average for the intervention areas.[25] Figure A1 in Appendix 1 presents the geographical distribution of these weights and illustrates how the synthetic control group is constructed. The estimated effect of the mobile vaccination unit on the weekly number of first doses, was calculated as the difference between the intervention and the (weighted) synthetic control cohorts in the weekly number of vaccines received over a three-week period after the intervention. Using a weighted regression model to estimate this effect would potentially underestimate standard errors and p-values as this would not account for complex aspects of the process used to generate the synthetic control weights. To estimate the sampling distribution of the treatment effect, and the permuted p-values and 95% confidence intervals, we applied a permutation procedure outlined by Robbins et al. by repeating the analysis through 250 placebo permutations randomly allocating non-intervention LSOAs to the intervention group.[26]

As our area-based analysis could be biased by not sufficiently accounting for confounders at the individual level, we additionally conducted analysis using individual-level data on all people aged over 18 living in the intervention and non-intervention LSOAs (as defined above), who had been unvaccinated before the mobile vaccination unit first visited their neighbourhood. We used a weighted Poisson regression model, with robust sandwich variance estimators that has been shown to be a valid alternative to the logistic regression model for the analysis of binary outcomes,[30,31] to compare the vaccine rates between these two groups in the three weeks following the intervention. Accounting for systematic area-based differences, we weighted this regression using the synthetic control weights as highlighted above, after additionally controlling for the following individual-level potential confounders: age, sex, ethnicity, health conditions (as described above), whether people were in contact with social care, whether they were paid carers and the travel time by car from each

person's address to the nearest static vaccination centre. 18.62% and 0.01% of ethnicity and sex were missing respectively, leaving 233278 records for the main complete case analysis. Appendix 2 presented a sensitivity test removing ethnicity from the main model. We used a Poison regression model using a sandwich variance estimator to estimate the relative risk of vaccination.[30,31]

To explore whether the mobile vaccination unit effect differed by level of deprivation, ethnicity and age, we fitted another weighted Poisson model including interaction terms between the intervention indicator (mobile vaccination unit) and IMD tercile within Cheshire and Merseyside, ethnic group and age group respectively (see Appendix 3 for detailed results). Additionally, we conducted a sensitivity test by excluding the two pop-up sites from the analysis to check for the robustness of our results (see Appendix 4).

Patient and public involvement

The local authorities delivering the intervention engaged with various community groups in promoting the intervention and identifying intervention sites. Patients and the public were, however, not directly involved in designing this analysis.

Results

Figure 1 shows the intervention (yellow) and the non-intervention areas (purple). The red dots represent the mobile vaccination sites included in our analysis. The map in Appendix 1 shows the weights that were applied to the non-intervention areas to construct the synthetic control.

Figure 1 is about here

Table 1 presents summary statistics for the non-intervention and intervention areas. The average vaccination rate of the first dose was much higher in the non-intervention areas before the introduction of the intervention. On average, residents of the non-intervention areas had to travel slightly longer to get to the nearest static vaccine site. The intervention areas were younger and more deprived, and had a higher proportion of overcrowded households, higher proportions of Asian/Asian British and Black/Black British ethnic minority groups, and higher population density. There were no differences in terms of the proportion of mixed ethnicity. As the matching algorithm achieved an exact match, the *weighted* average of each variable in Table 1 was identical in the synthetic control to those in the intervention areas.

Table 1. The comparison between the intervention and the synthetic control areas at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

	Non-intervention areas	Intervention areas
Total population	1495582	338006

% women	51	49
Population density – people per hectare	40	61
Mean age	43	39
% Asian/Asian British	1	3
% Black/Black British	0	2
% Mixed people	1	2
IMD score	29	40
% households with at least one-bedroom fewer than they need	3	4
Average travel time to the nearest stationary vaccine site - minutes	4	3
First dose vaccine uptake among adults prior to intervention (%)	69	53
Average weekly first dose vaccination rate among adults in the 7 weeks prior to intervention (%)	2	2
Number of LSOAs	1112	216

Figure 2 shows the trend in weekly vaccination rate in the intervention and synthetic control areas, during a 11-week period (seven weeks before and three weeks after the introduction of the mobile vaccination unit). For the pre-intervention period, trends were indistinguishable, as the synthetic control algorithm has achieved an exact match by successfully calibrating the weights. From the time point of the intervention being introduced, weekly vaccination rates increased from 1.5% to 1.9% in the intervention areas. Trends in the matched synthetic control areas that were not visited by a mobile vaccination unit remained fairly flat, with a small decrease in the post-intervention period. From two weeks post intervention, 95% CIs stopped overlapping.

Figure 2 is about here

Table 2 shows the estimated effect of the mobile vaccination units on vaccine uptake using two models based on area-level and individual-level data respectively. The two analyses show similar results. The area-based analysis indicates that vaccination rates in the neighbourhoods visited by mobile vaccination units were 23% higher in the three weeks after the first visit, compared to what would have been the case without the mobile vaccination units' visits (RR = 1.23, 95% CI: 1.11 to 1.36). The relative risks adjusted for individual-level characteristics is slightly higher than that of the area-based model (RR = 1.25, 95% CI: 1.21 to 1.28). This overall effect size estimates 3723 additional vaccinations over three weeks of follow-up across the study area, similar to the actual number of people vaccinated in the mobile units (n=3824). This suggests that at least in the short term most of the vaccinations in the mobile units were additional. In other words, among the mobile units' users there were few people, who would have otherwise gone to static centres to get their vaccine. Analysis excluding

ethnicity and the two pop-up sites showed similar results (see Appendix 2 and Appendix 4 respectively).

Table 2. Estimated effect of mobile vaccination units on vaccine uptake, the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1 uses LSOA level data, accounting for area-based differences between intervention and non-intervention areas, with permuted p-values and confidence intervals. Whilst model 2 additionally controls for individual differences between intervention and non-intervention groups.

	RR	95% CI		p-value
		LCL	UCL	
Model 1. LSOA level synthetic control analysis	1.23	1.11	1.36	<0.001
Model 2. Individual level weighted Poisson regression analysis	1.25	1.21	1.28	<0.001

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Interaction analyses investigated effective modification by deprivation, ethnicity and age (see Table A2 in Appendix 3). We found lower impact of the mobile vaccination unit on the vaccination rate for the most deprived areas ($p<0.001$) compared to more affluent areas, a lower impact for Asian/Asian British ($p=0.006$), Black/Black British ($p=0.005$) or other ethnic groups ($p=0.010$), compared to White/White British people, and a lower impact on vaccine uptake for people aged 31-65 compared to 18-30 year olds ($p<0.001$).

Figure 3 is about here

Figure 3 shows the estimated impact of the mobile vaccination units for all the subgroups based on the linear combination of parameters from the regression model including interaction terms for deprivation, ethnicity and age group (Figure 3). Due to the small sample sizes within each of these 45 subgroups, these results should be treated with caution. However, they indicate the likely pattern of effects of the intervention across these groups. Overall, White, 18-30 age group living in neighbourhoods of intermediated deprivation appeared to benefit the most from visits of the mobile vaccination unit (Figure 3). Effects were lowest for older age groups in the most deprived areas. Although the effect of the mobile vaccination unit may be lower for the most deprived population and for people from Black, Asian and other ethnic minority groups, the mobile vaccination unit does still appear to have increased uptake in these groups, particularly for younger people.

Discussion

Our study presents much-needed empirical evidence of the effectiveness of mobile vaccination units in promoting COVID-19 vaccination, indicating that they can increase uptake in their targeted neighbourhoods. Within those neighbourhoods, however, the intervention tended to increase uptake most amongst younger people, white people and less socioeconomically deprived areas. However, the targeted neighbourhoods were mostly highly deprived. Our analysis indicated that the intervention was similarly effective in the least deprived and intermediate levels of deprivation *within* these targeted neighbourhoods. It is only in areas with IMD score of over 53, the lower bound of the most deprived, that the effectiveness declined. However, 53 is at the 95th percentile of the national distribution of IMD scores, representing very deprived areas nationwide. Our findings indicate therefore that the intervention was effective at increasing uptake amongst young people in relatively deprived areas (although not in extremely deprived areas) and across young people from all ethnic groups in these areas.

Our study has limitations. We only had data on individuals who had been registered with the GP at time of our study. Although unregistered people attending for mobile units were encouraged and can register with a GP at their appointment, there may have been people vaccinated who did not wish to be registered, such as undocumented immigrants, homeless populations, travellers, and displaced people. We were unable to estimate the impact of the intervention in these groups. The mobile vaccination unit could have increased uptake due to improved accessibility through the mobile vaccination unit itself and/or the awareness raising and publicity associated with visits of these units. Unfortunately, in our analysis we are unable to distinguish between these effects.

Our analysis covers a relatively short period of follow-up. We are therefore unable to determine whether the observed effect is due to people being vaccinated earlier than they would otherwise have been or if they would have never taken up vaccine without the intervention. Although we have accounted for observed differences between places visited by the mobile vaccination units and those not and differences in individual characteristics, it is still possible that unmeasured confounding could bias the results.

Conclusion

Our study has implications for strategies aiming to increase vaccine uptake. By improving geographic accessibility of the COVID-19 vaccine, the mobile vaccination unit shows promise for improving vaccine uptake of the first dose. The evidence indicating greater effects in less deprived areas and in the White/White British population raises concerns that the intervention could however lead to an increase in inequalities in uptake within targeted areas. It is important to ensure the mobile

vaccination units are effectively targeted to the communities with low uptake and combined with comprehensive engagement and outreach with Black and Asian ethnic groups and with more socioeconomically disadvantaged communities. With emerging new variants and the need for multiple doses to achieve sufficient immunity, rapidly increasing uptake and reducing inequalities in uptake has become of critical public health importance. Deployment of mobile units alongside other effective approaches to increase uptake in disadvantaged groups can contribute to this goal.

Transparency statement

The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned (and, if relevant, registered) have been explained.

Author contribution statement

B.B. conceived the original idea, devised the project, the main conceptual ideas and proof outline. X.Z. contributed to the literature review, collected the data, and carried out the data analysis. R.A. conducted the initial literature review. X.Z. drafted the manuscript and designed the figures with support from B.B. and M.G.. J.T., S.K. and P.P. assisted with the data access and commented on the manuscript. R.P. assisted in coding. M.GF and M.G. aided in commenting on the manuscript. I.B. aided in supervising the project and commented on the manuscript. S.B. helped to improve the language and visualisation. All authors provided critical feedback and helped to shape the research manuscript.

Conflicts of interest statement

We have no conflicts of interest to disclose.

Ethics statements

Patient consent for publication

Not required.

Ethics approval

University Research Ethics Committee review is not required by the University of Liverpool for the secondary analysis of data which have been anonymised by an external party and are provided to the research team in a fully anonymised format.

Data sharing statement

The individual-level data is sensitive and could not be shared. But statistical codes are available from the corresponding author upon request.

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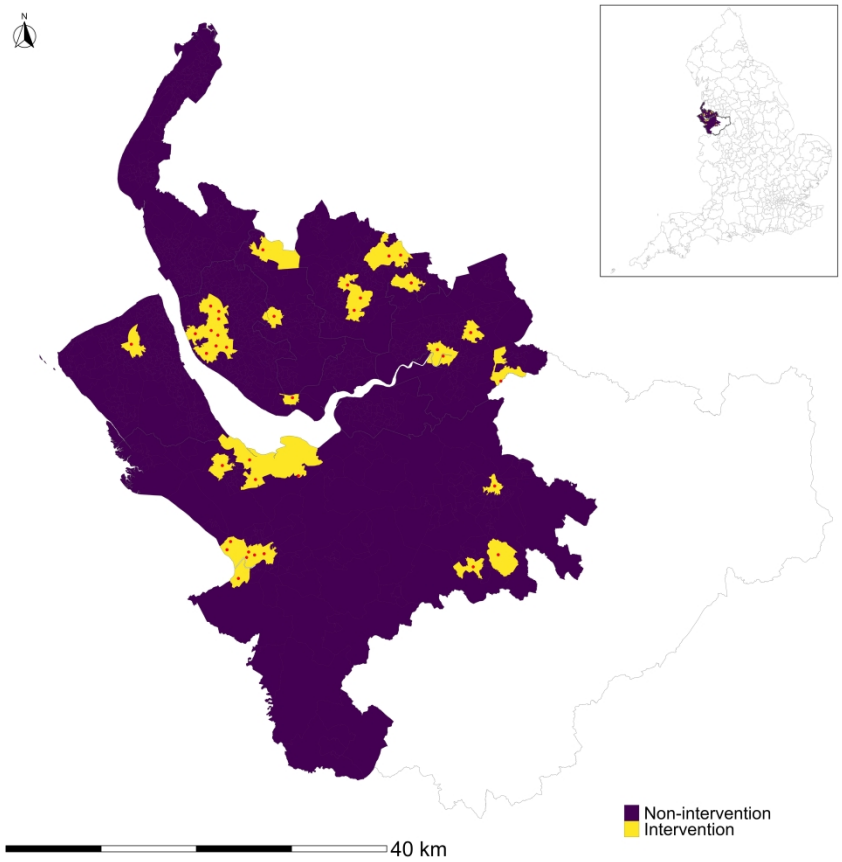
Figure 1. Location of eligible mobile vaccination units (red dots) and the non-intervention (purple) and intervention (yellow) areas across Cheshire and Merseyside. The sub-map in the box of the top right shows the location of Cheshire and Merseyside in England.

Figure 2. The trend in the weekly vaccination rate with their 95% confidence intervals in the intervention and synthetic control areas.

Figure 3. Heatmap of the estimated impact of the mobile vaccination units for all the subgroups based on interaction analysis.



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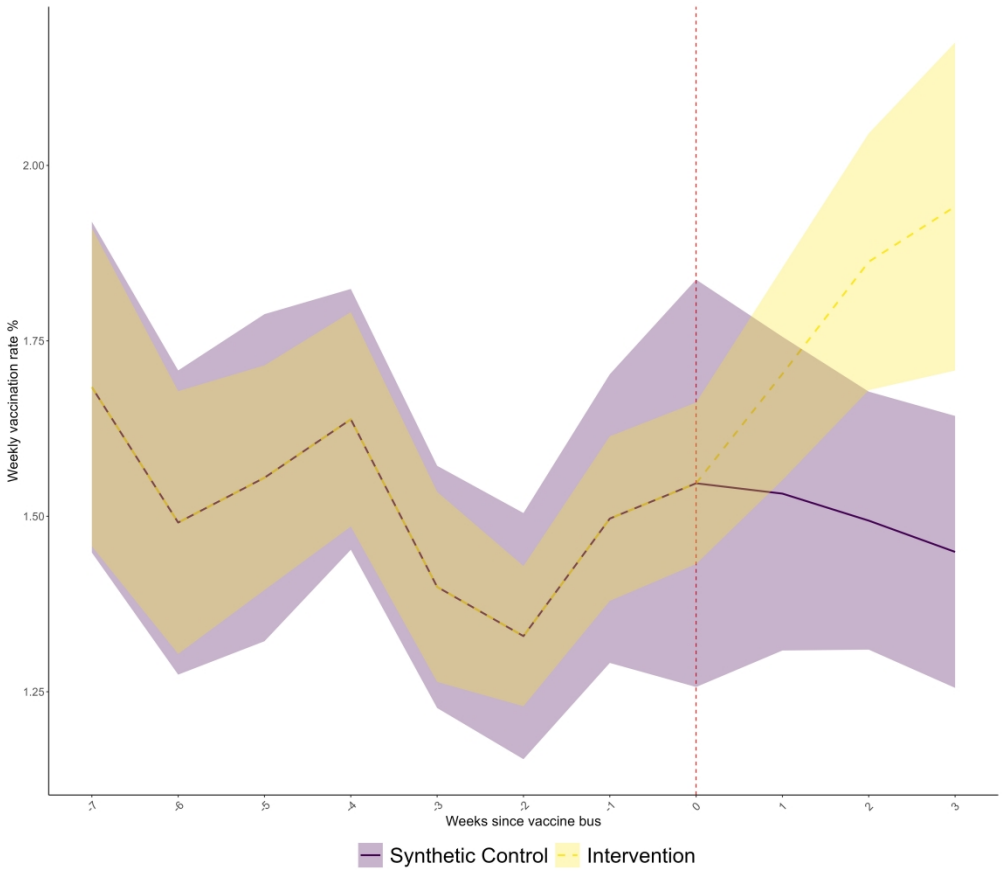

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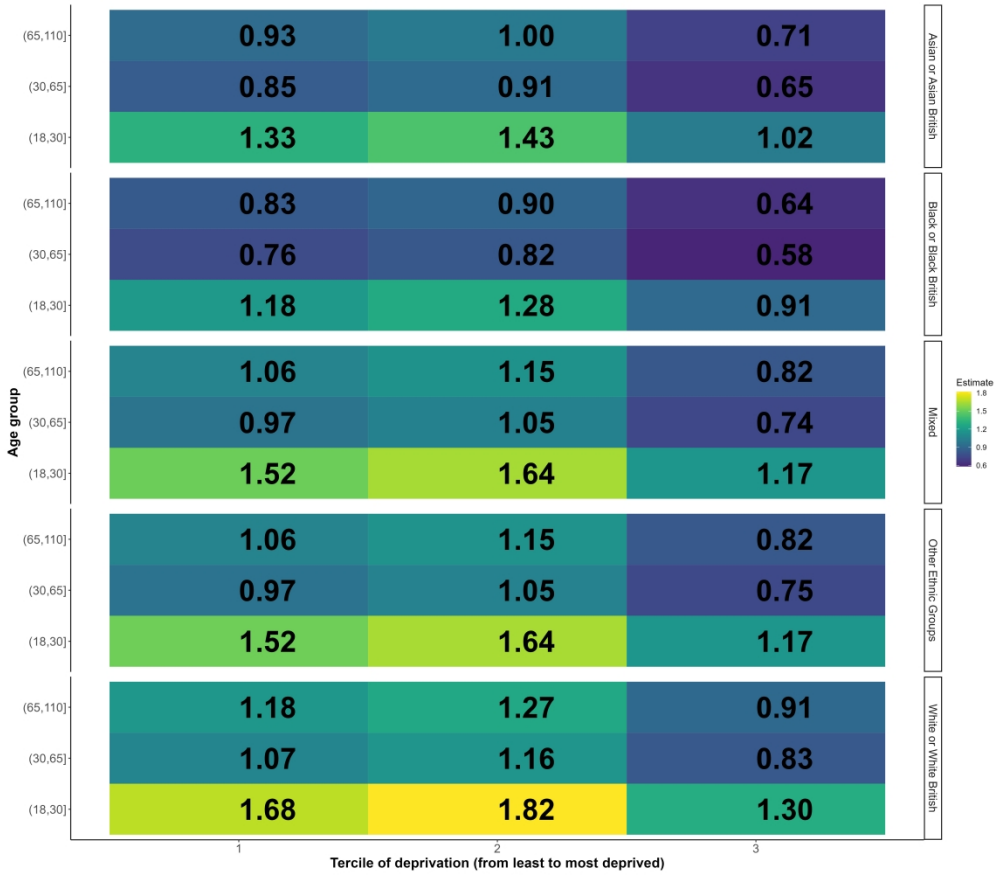

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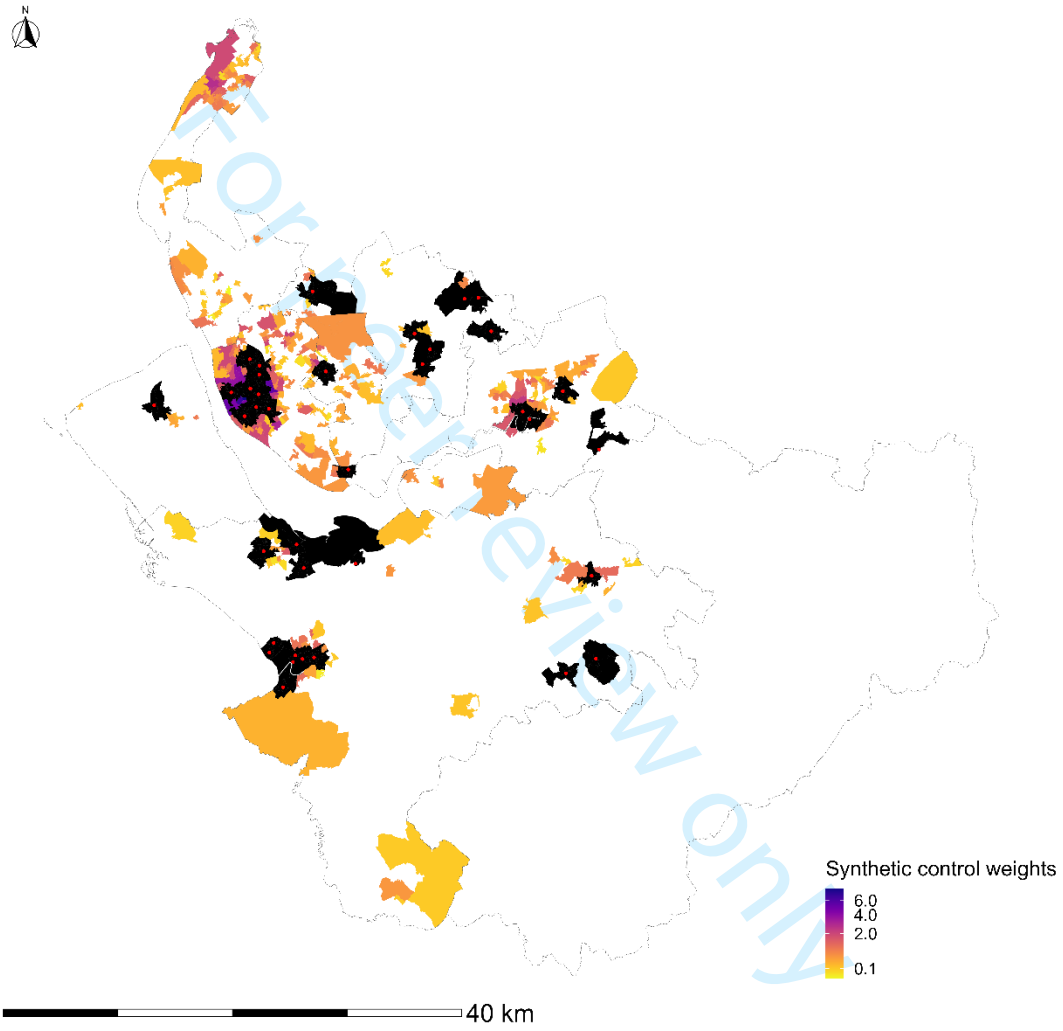
Appendices

Appendix 1. Geographical pattern of weights in area-based synthetic control analysis.

Figure A1. Weighting of areas outside of the catchment of the mobile vaccination unit to construct the synthetic control group. Areas within the catchment of the mobile vaccination unit are coloured black, whilst locations of the mobile vaccination unit are represented by red dots. The white non-intervention areas are those that have been allocated zero weights in constructing the synthetic control.



Appendix 2. Sensitivity test – excluding ethnicity from the main model

Table A1. Results of analysis for adult individuals of all ages, excluding ethnicity.

	RR	95% CI		p-value
		LCL	UCL	
Model 2. Individual level weighted Poisson regression analysis	1.24	1.21	1.28	<0.001

Results of Table A1 and Table 2 are almost identical, implying that excluding cases with missing information on ethnicity did not affect the robustness of our results.

Appendix 3. Regression output for the interaction model based on adult individuals.

Table A2. Regression output for the interaction model based on adult individuals. The table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention.

Variables	RR	95% CI		p-value
		LCL	UCL	
Mobile vaccination unit	1.68	1.58	1.79	<0.001
Age group (reference: 18-30 years old)				
(30,65]	1.25	1.19	1.31	<0.001
65+	0.20	0.15	0.28	<0.001
Sex (reference: Women)				
Men	1.01	0.98	1.04	0.400
Ethnicity (reference: White/White British)				
Asian/Asian British	0.92	0.79	1.07	0.300
Black/Black British	0.75	0.60	0.93	0.008
Mixed	0.75	0.61	0.91	0.005
Other ethnic groups	0.80	0.75	0.86	<0.001
IMD tercile (reference: Least deprived)				
Intermediate deprivation	0.79	0.74	0.83	<0.001
Most deprived areas	0.67	0.63	0.72	<0.001
Chronic health conditions	1.10	1.08	1.12	<0.001
Carer	0.32	0.27	0.37	<0.001
Social care receiver	0.98	0.76	1.25	0.900
Travel time to the nearest static vaccine centre (minutes)	1.09	1.08	1.09	<0.001
Interaction between age groups and mobile vaccination unit (reference: 18-30 years old with mobile vaccination unit)				
30-65 years old with mobile vaccination unit	0.64	0.60	0.68	<0.001
65+ years old with mobile vaccination unit	0.70	0.48	1.03	0.070
Interaction between ethnicity and mobile vaccination unit (reference: White/White British with mobile vaccination unit)				
Asian/Asian British with mobile vaccination unit	0.79	0.66	0.94	0.006
Black/Black British with mobile vaccination unit	0.70	0.55	0.90	0.005
Mixed with mobile vaccination unit	0.90	0.71	1.14	0.400
Other ethnic groups with mobile vaccination unit	0.90	0.84	0.98	0.010
Interaction between IMD tercile and mobile vaccination unit (reference: Least deprived with mobile vaccination unit)				
Intermediate deprivation with mobile vaccination unit	1.08	1.01	1.16	0.024
Most deprived areas with mobile vaccination unit	0.77	0.72	0.83	<0.001

Note: The intercept is excluded from the output.

Appendix 4. Sensitivity test – excluding the two pop-up sites across C&M

Table A3. Results of analysis for adult individuals of all ages, excluding the two pop-up sites.

	RR	95% CI		p-value
		LCL	UCL	
Model 2. Individual level weighted Poisson regression analysis	1.23	1.18	1.29	<0.001

Table A3 shows very similar results to those of Table 2, indicating that it is unlikely that the use of pop-up sites rather than vaccine bus type approaches influenced our results.

Reporting checklist for cross sectional study.

Based on the STROBE cross sectional guidelines.

Instructions to authors

Complete this checklist by entering the page numbers from your manuscript where readers will find each of the items listed below.

Your article may not currently address all the items on the checklist. Please modify your text to include the missing information. If you are certain that an item does not apply, please write "n/a" and provide a short explanation.

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In your methods section, say that you used the STROBE cross sectionalreporting guidelines, and cite them as:

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		Reporting Item	Page Number
Title and abstract			1-2
Title	#1a	Indicate the study's design with a commonly used term in the title or the abstract	1
Abstract	#1b	Provide in the abstract an informative and balanced summary	2

		of what was done and what was found	
Introduction			4-5
Background / rationale	#2	Explain the scientific background and rationale for the investigation being reported	4-5
Objectives	#3	State specific objectives, including any prespecified hypotheses	5
Methods			5-8
Study design	#4	Present key elements of study design early in the paper	5-8
Setting	#5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5-6
Eligibility criteria	#6a	Give the eligibility criteria, and the sources and methods of selection of participants.	5-6
	#7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-8
Data sources / measurement	#8	For each variable of interest give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group. Give information separately for exposed and unexposed groups if applicable.	5-6
Bias	#9	Describe any efforts to address potential sources of bias	7-8
Study size	#10	Explain how the study size was arrived at	7-8

Quantitative variables	#11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	5-6
Statistical methods	#12a	Describe all statistical methods, including those used to control for confounding	6-8
Statistical methods	#12b	Describe any methods used to examine subgroups and interactions	8
Statistical methods	#12c	Explain how missing data were addressed	7-8
Statistical methods	#12d	If applicable, describe analytical methods taking account of sampling strategy	
Statistical methods	#12e	Describe any sensitivity analyses	7-8
Results			8-10
Participants	#13a	Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed. Give information separately for for exposed and unexposed groups if applicable.	
Participants	#13b	Give reasons for non-participation at each stage	
Participants	#13c	Consider use of a flow diagram	
Descriptive data	#14a	Give characteristics of study participants (eg demographic,	8-9

		clinical, social) and information on exposures and potential confounders. Give information separately for exposed and unexposed groups if applicable.	
Descriptive data	#14b	Indicate number of participants with missing data for each variable of interest	
Outcome data	#15	Report numbers of outcome events or summary measures. Give information separately for exposed and unexposed groups if applicable.	9
Main results	#16a	Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	9-10
Main results	#16b	Report category boundaries when continuous variables were categorized	
Main results	#16c	If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	10
Other analyses	#17	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses	10
Discussion			10-12
Key results	#18	Summarise key results with reference to study objectives	10-11
Limitations	#19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias.	11

Interpretation	#20	Give a cautious overall interpretation considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence.	11-12
Generalisability	#21	Discuss the generalisability (external validity) of the study results	11-12

Other Information

Funding	#22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	13

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Evaluating the impact of using mobile vaccination units to increase COVID-19 vaccination uptake in Cheshire and Merseyside, UK: A synthetic control analysis.

Xingna Zhang[1], John Tulloch[2], Shane Knott[3], Rachel Allison[4], Paula Parvulescu[5], Iain Buchan[6], Marta García-Fiñana[7], Roberta Piroddi[8], Mark A. Green[9], Sophie Baird[10], Ben Barr[11]

[1] Tenure Track Fellow, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[2] Tenure Track Fellow, Department of Livestock and One Health in the Institute of Infection, Veterinary and Ecological Science, University of Liverpool, Liverpool, UK

[3] Senior Public Health Practitioner (Healthcare), Liverpool City Council, Liverpool, UK

[4] FY1 Doctor, Russells Hall Hospital, Dudley, UK

[5] Consultant in Public Health Medicine, Liverpool City Council, Liverpool, UK

[6] Chair in Public Health and Clinical Informatics, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[7] Professor of Health Data Science, Department of Health Data Science, University of Liverpool, Liverpool, UK

[8] Research Fellow, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[9] Reader in Health Geography, Department of Geography & Planning, University of Liverpool, Liverpool, UK

[10] Public Health Registrar, The UK Health Security Agency, UK

[11] Chair in Applied Public Health Research, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

Corresponding author:

Xingna Zhang

xingna.zhang@liverpool.ac.uk

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ABSTRACT

Objective To evaluate the impact of mobile vaccination units on COVID-19 vaccine uptake of the first dose, the percentage of vaccinated people among the total eligible population. We further investigate whether such an effect differed by deprivation, ethnicity, and age.

Design Synthetic control analysis.

Setting The population registered with General Practices (GPs) in nine local authority areas in Cheshire and Merseyside in Northwest England, UK.

Intervention Mobile vaccination units that visited 37 sites on 54 occasions between 12th April and 28th June 2021. We defined populations as having received the intervention if they lived within 1km of a mobile vaccination site (338,006 individuals). A weighted combination of neighbourhoods that had not received the intervention (1,495,582 individuals) was used to construct a synthetic control group.

Outcome The weekly number of first-dose vaccines received among people aged 18 years and over as a proportion of the population.

Results The introduction of a mobile vaccination unit into a neighbourhood increased the number of first vaccinations conducted in the neighbourhood by 25% (95% CI: 21% to 28%) within three weeks after the first visit to a neighbourhood, compared to the synthetic control group. This effect was smaller amongst 30–65–year–olds compared to 18–30–year–olds, amongst Asian and Black ethnic groups compared to White ethnic groups, and the most socioeconomically deprived populations compared to the least deprived areas.

Conclusions Mobile vaccination units are effective interventions for increasing vaccination uptake, at least in the short-term. While mobile units can be geographically targeted to reduce inequalities, we found evidence that they may increase inequalities in vaccine uptake within targeted areas, as the intervention was less effective amongst groups that tended to have lower vaccination uptake. Mobile vaccination units should be used in combination with activities to maximise outreach with Black and Asian communities and socioeconomically disadvantaged groups.

Strengths and limitations of this study

- The synthetic control method for microdata offers a rigorous method for identifying control areas that experienced similar levels of COVID-19 vaccine uptake as the intervention areas prior to the introduction of mobile vaccination units, supporting a possible causal interpretation of the finding of increased uptake in areas with mobile vaccination visits following their introduction.
- The use of individual-level data enabled us to construct weighted Poisson regression models to offer robust estimation of the observed effect, with interaction analysis to reveal whether this effect varied by level of deprivation, age groups and ethnicity.
- We were not able to include individuals that had used the mobile vaccination units but had not been registered with the GP at time of our study, which could lead to the underestimation of the effect given that the main vaccination programme was provided through GPs.
- As our analysis covers a relatively short follow-up period, the results may not reflect the sustained impact of the intervention over longer periods of time.
- There may also be other differences between places being visited by the mobile vaccination units and those that were not and differences in individual characteristics, beyond those included in this study, that led to the differences in the observed effect.

Introduction

Vaccination is one of the most effective public health interventions for improving health and saving lives.[1] Following the national rollout of the COVID-19 vaccine program on 8th December 2020 in the UK, relatively high vaccine uptake has helped reduce the risk of hospitalisation and mortality from COVID-19.[2] Nevertheless, vaccine uptake was lower among young people, socioeconomically disadvantaged groups and ethnic minorities for a combination of factors including vaccine eligibility (Appendix 1 presents the timeline for age eligibility of the first dose of the COVID-19 vaccine in England) and hesitancy, health disparities and inequalities, convenience and access, language and cultural barriers, and trust in healthcare systems.[3–6] Some of these groups have also often experienced disproportionately greater levels of infections, hospitalisations and deaths during the pandemic. With successive SARS-CoV-2 variants, additional booster vaccinations were needed to give sufficient protection. Inequalities in uptake of these subsequent doses were greater than with the initial doses,[7] potentially undermining responses to new variants that rely largely on increased uptake of booster vaccinations. The UK government invested £22.5 million to help areas increase uptake amongst hard-to-reach groups in December 2021, as tackling health inequalities is a core government priority.[8] A central part of this strategy was to use mobile vaccination units such as pop-up sites and vaccine buses – "taking the vaccines into the hearts of local communities".[9]

Mobile vaccination units have been used in many countries to increase uptake in disadvantaged communities.[10] These generally involve vaccination clinics based in large vehicles such as buses or temporary pop-up clinics in community settings. As well as bringing vaccines into targeted communities, they usually involve outreach programmes (e.g., leaflet campaigns to advertise vaccination units and explain the benefits of vaccination). The use of mobile vaccination units to increase uptake is based on the premise that geographic accessibility and convenience of vaccination services are potentially important determinants of uptake and that they support uptake from people who have difficulty in accessing existing sites due to information or travel barriers, childcare or healthcare responsibilities, or being excluded from the official healthcare system.[11]

Although former studies found mobile units as useful tools to reduce health inequalities in administering other forms of preventative care such as cancer screening,[12–15] there has been limited research evaluating interventions that aim to increase COVID-19 vaccine uptake. One Randomised Controlled Trial (RCT) shows that provision of information on personal benefit reduces hesitancy,[16] with another RCT indicating that text message reminders lead to small increases in uptake.[17] One study of a community-based strategy in an underserved Latinx population in San Francisco found that mobile units reached their intended recipients, but the study was unable to

estimate the impact on vaccination uptake.[18] Another study found that users of the COVID-19 mobile vaccination units tended to be younger, non-White race, and Hispanic ethnicity compared to the general vaccinated populations in the Greater Boston area, suggesting the potential benefits of mobile vaccination units without estimating the average treatment effect.[19] A few studies investigated the impact of interventions aiming to increase Influenza and pneumococcal vaccination, including one systematic review,[20] five RCTs [21–25] and two cluster RCTs.[26,27] Of these, three were published in the United Kingdom,[21,22,26] three in the United States [20,23,24] and two in Hong Kong.[25,27] They all show that sending out reminders, telephone calls and educational outreach tend to increase uptake. We found no studies that quantified the effect of introducing mobile vaccination units on COVID-19 vaccine uptake.

It also remains largely uncertain how effective mobile vaccination units are at increasing uptake amongst disadvantaged groups, having been deployed to improve vaccine access for those communities.[2,18,19] The lack of existing evidence is concerning, considering their central role in the strategies to reduce vaccine uptake inequalities. We therefore used a synthetic control approach to investigate the impact of mobile vaccination units in the Northwest of England and how this varied by age, socioeconomic status, and ethnicity.

Methods

Data

We utilised anonymised electronic health records (EHR) on all people aged 18 and over, registered with a General Practice (GP) in Cheshire and Merseyside, England, between 22nd February and 19th July 2021.[28] This data included vaccination status, vaccination date, age, sex, ethnicity, chronic health conditions diagnosed in primary care (chronic obstructive pulmonary disease, chronic heart disease, diabetes, chronic kidney disease asthma, cancer, obesity, depression, and stroke/transient ischaemic attack), whether people were in contact with social care, whether they were a paid carer, travel time by car to the nearest conventional static vaccination site requiring booking in advance and the Lower Super Output Areas (LSOA) of residence. LSOAs are small geographical areas of England, with approximately 1500 residents each. Ethnicity was based on information of primary care records. Where unavailable, ethnicity was taken from hospital, community, or social care records if available in these datasets. Ethnicity was categorised in these datasets using the 17 standard Office for National Statistics Categories. These were then re-coded to 5 categories for analysis (White/White British, Asian/Asian British, Black/Black British, Mixed, and Other).

We linked the EHR data to LSOA-level data, including 2019's indices of multiple deprivation (IMD) – a composite measure of deprivation across seven domains (income, employment, education, health, crime, barriers to housing & services, and living environment), an over-crowded housing measure (the proportion of households with at least one-bedroom fewer than they need) based on 2011's Census, and population density using 2019's mid-year population estimates from the Office for National Statistics. The public health teams of the nine local authorities in the Cheshire and Merseyside region were asked to provide a list of locations and dates of mobile vaccination units in their areas between May and November 2021. Six local authorities provided this information and two local authorities reported that they had had no mobile vaccination units. Analysis was therefore limited to these eight local authorities.

Intervention

Six local authorities operated mobile vaccination units, that visited 37 sites on 54 occasions, between 12th April and 28th June 2021. This included 52 visits from vaccine buses and two from two pop-up static clinics (different from conventional static vaccination sites, these two pop-up sites offered walk-in services without the need to book in advance). Six sites were visited more than once during our study period, with repeated visits scheduled either consecutively or at least one week apart. Vaccines were offered typically from 9am to 4.30pm or 5pm on the day of most visits, with four visits operating from 8am to 6pm, 9am to 3pm, 9.15am to 2.30pm and 10am to 2pm respectively. We chose to treat all sites uniformly in our analysis to avoid potentially overemphasising the impact of sites with multiple visits and minimise the potential influence of site-specific factors. This simplifying assumption offers us a more conservative approach and allows us to focus on the overall effect of the intervention rather than site-specific variations, thus enabling clearer interpretation and generalisability of the results. The deployment of the mobile vaccination units also involved outreach programmes to advertise vaccination units and explain the benefits of vaccination for each visit. Units were primarily focused on offering first-dose COVID-19 vaccinations to those that had not received a vaccine at any of the city's existing conventional static vaccination sites and were eligible for vaccination at the time.[29] Vaccines were offered on a drop-in basis with no appointment needed. The number of vaccinations received at these mobile units was unavailable for one local authority (Warrington). The total number of first dose vaccinations for the remaining five local authorities that had deployed the mobile vaccination units was 3824. Sites visited by mobile vaccination units were identified by local public health and health service teams based on their knowledge of vaccine uptake (I.e., the percentage of adults who have received the first dose of the COVID-19 vaccine among the total eligible adult population in our study), practicalities of having space and permissions to locate the vaccination unit, and relationships with local community groups.

We defined intervention neighbourhoods as being located within 1km of mobile vaccination sites and identified 216 LSOAs that were either hosts for mobile vaccination units or had population weighted centroids within a 1km radius of mobile vaccination units. We calculated the start time of the intervention as the week a mobile vaccination unit first visited. This left 1112 non-intervention LSOAs within the eight participating local authorities that had not been visited by mobile vaccination units. We then applied a 'placebo' start time to each of these non-intervention LSOAs, generated uniformly at random in the same weekly proportion as the distribution of intervention start dates for the intervention LSOAs.

Statistical analysis

We aggregated the individual-level data to construct a panel of weekly measures at the LSOA level from seven weeks (22nd February 2021) before the first mobile vaccination unit visit on 12th April 2021 to three weeks (19th July 2021) after the last mobile vaccination unit visit on 28th June 2021. We chose seven weeks as our pre-intervention period after evaluating trends of the accumulated uptake, overall and by ethnic and socio-economic groups, with consideration of the rollout of the vaccine prioritised by age groups (Appendix 1 and 2). A seven-week pre-intervention period allowed us to capture trends for most people eligible for the vaccine and focus on the intervention at a relatively stable stage of the pandemic. We then chose a three-week follow-up period due to the policy change in July 2021 to prioritise administrating the second doses. A three-week period avoided spill-over effect of this prioritisation and allowed us to estimate the effect of repeated visits in some sites and the accompanying outreach programmes. We therefore aimed to investigate the short-term effect of the intervention here. The weekly panel data included LSOA-level measures of total GP registered population size, the proportion of Black/Black British people, the proportion of Asian/Asian British people, the proportion of people of mixed ethnicity, mean age of residents, population density, the proportion of women, the IMD score, the proportion of households living in overcrowded housing, the average travel time by car to the nearest conventional static vaccine site, the cumulative number of first dose administered at the start of the pre-intervention period, and the number of new first dose vaccinations administered per week (Appendix 3 compares these measures between the intervention and the rest of Cheshire and Merseyside).

We apply the synthetic control method for microdata developed by Robbins et al. to estimate the effect of mobile vaccination units on vaccine uptake. Our outcome variable, weekly vaccine uptake, is the percentage of adults who have received the first dose of the COVID-19 vaccine during each week among the total eligible adult population.[30,31] The synthetic control method is a generalisation of difference-in-difference methods.[32] An untreated version of the intervention areas (i.e. a synthetic

control) is created using a weighted combination of areas that were unexposed to the intervention. The intervention effect is estimated by comparing the trend in outcomes in the intervention areas to that in the synthetic control areas following the intervention.[33]

The weights are calculated using the raking [34] method so that the weighted averages for all the variables outlined above in the synthetic control group were the same as for the intervention group. The weighting algorithm derives weights that meet two constraints. Firstly, the sum of first-dose vaccines in the control group equals first-dose vaccines administered in the intervention areas for each of the seven weeks prior to the intervention (Appendix 4). The total number of the first dose administered at the end of the pre-intervention period is matched automatically as the sum of two matched variables (the cumulative number of the first dose administered at the start of the pre-intervention and the weekly number of the first dose administered within the pre-intervention period). It would co-linear with two variables above in the algorithm if specifically added to the weighting. Secondly, the weighted average of each local area characteristic, outlined above in the control group equals the average for the intervention areas.[30] Appendix 5 presents the geographical distribution of these weights and illustrates how the synthetic control group is constructed. The estimated effect of the mobile vaccination unit on the weekly number of first doses, was calculated as the difference between the intervention and the (weighted) synthetic control cohorts in the weekly number of vaccines received over a three-week period after the intervention. To estimate the sampling distribution of the treatment effect, and the permuted p-values and 95% confidence intervals, we applied a permutation procedure outlined by Robbins et al. by repeating the analysis through 250 placebo permutations randomly allocating non-intervention LSOAs to the intervention group.[31]

As our area-based analysis could be biased by insufficiently accounting for confounders at the individual level, we additionally conducted analysis using individual-level data on all adults registered with the GP and living in the intervention and non-intervention LSOAs (as defined above), who had been unvaccinated before the mobile vaccination unit first visited their neighbourhood. We used a weighted Poisson regression model with robust sandwich variance estimators, which has been shown to be a valid alternative to the logistic regression model for the analysis of binary outcomes,[35,36] to estimate the relative risk of vaccination by comparing the vaccine rates between these two groups in the three weeks following the intervention. Using a weighted Poisson regression model to estimate this effect without considering the differences between the intervention and non-intervention areas on the aggregate level would potentially underestimate standard errors and p-values, as this would not account for complex aspects of the process used to generate the synthetic control weights for LSOAs. We therefore weighted this regression using the synthetic control weights as highlighted above

to account for systematic LSOA-level differences, after additionally controlling for the following individual-level potential confounders: age, sex, ethnicity, health conditions (as defined above), whether people were in contact with social care, whether they were paid carers and the travel time by car from each person's address to the nearest conventional static vaccination centre. 18.62% and 0.01% of ethnicity and sex were missing respectively, leaving 233278 records for the main complete case analysis.

To explore whether the mobile vaccination unit effect differed by deprivation, ethnicity, and age, we fitted another weighted Poisson model including interaction terms between the intervention indicator (mobile vaccination unit) and IMD tercile within Cheshire and Merseyside, ethnic group, and age group respectively (see Appendix 6 and 7 for detailed results). Apart from the sensitivity test of excluding ethnicity (Appendix 8) and the two pop-up sites (Appendix 9) from the analysis to assess the potential impact of the missing data and two pop-up static sites on our results respectively, we have additionally conducted a series of sensitivity tests on the dose effect of distance threshold used to construct the intervention and non-intervention areas (Appendix 10), the potential spatial spill-over effect of the intervention (Appendix 11), and survival analyses (Appendix 12) to further check the robustness of our results.

Patient and public involvement

The local authorities delivering the intervention engaged with various community groups in promoting the intervention and identifying intervention sites. Patients and the public were, however, not directly involved in designing this analysis.

Results

Figure 1 shows the intervention (yellow) and the non-intervention areas (purple). The red and cyan dots represent the mobile and pop-up static vaccination sites respectively. The map in Appendix 5 shows the weights that were applied to the non-intervention areas to construct the synthetic control.

Figure 1 is about here

Table 1 presents summary statistics for the intervention and non-intervention areas (see Appendix 3 for the comparison between the intervention and the rest of Cheshire and Merseyside). The average vaccination rate of the first dose was much higher in the non-intervention areas before the introduction of the intervention. On average, residents of the non-intervention areas had to travel slightly longer to get to the nearest conventional static vaccine site. The intervention areas were younger and more deprived, and had a higher proportion of overcrowded households, higher proportions of Asian/Asian British and Black/Black British ethnic minority groups, and higher

population density. There were no differences in terms of the proportion of mixed ethnicity. As the matching algorithm achieved an exact match, the *weighted* average of each variable in Table 1 was identical in the synthetic control to those in the intervention areas.

Table 1. The summary statistics for the intervention and non-intervention areas at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

	Non-intervention areas	Intervention areas
Total population	1495582	338006
% women	50.84	48.92
Population density – people per hectare	38.84	65.11
Mean age	42.71	38.03
% Asian/Asian British	1.10	3.28
% Black/Black British	0.52	2.37
% Mixed people	1.48	1.87
IMD score	28.71	40.38
% households with at least one-bedroom fewer than they need	2.69	4.77
Average travel time by car to the nearest conventional static vaccine site - minutes	4.14	2.83
First dose vaccine uptake among adults (the percentage of adults who have received the first dose of COVID-19 vaccine among the total eligible adult population prior to pre-intervention) (%)	69.28	52.65
Average weekly first dose vaccination rate among adults in the 7 weeks prior to intervention (%)	1.85	1.51
Number of LSOAs	1112	216

Figure 2 shows the trend in weekly vaccination rate in the intervention and synthetic control areas, during a 11-week period (seven weeks before and three weeks after the introduction of the mobile vaccination unit). For the pre-intervention period, trends were indistinguishable, as the synthetic control algorithm has achieved an exact match by successfully calibrating the weights. From the time point of the intervention being introduced, weekly vaccination rates increased from 1.5% to 1.9% in the intervention areas. Trends in the matched synthetic control areas that were not visited by a mobile vaccination unit remained fairly flat, with a small decrease in the post-intervention period. From two weeks post intervention, 95% CIs stopped overlapping.

Figure 2 is about here

Table 2 shows the estimated effect of the mobile vaccination units on weekly vaccination rate, the percentage of adults who have received the first dose of the COVID-19 vaccine in each week among the total eligible adult population, using two models based on area-level and individual-level data

respectively. The two analyses show similar results. The area-based analysis indicates that vaccination rates in the neighbourhoods visited by mobile vaccination units were 23% higher in the three weeks after the first visit, compared to what would have been the case without the mobile vaccination units' visits (RR = 1.23, 95% CI: 1.11 to 1.36). The relative risks adjusted for individual-level characteristics is slightly higher than that of the area-based model (RR = 1.25, 95% CI: 1.21 to 1.28). This overall effect size estimates 3723 additional vaccinations over three weeks of follow-up across the study area, similar to the actual number of people vaccinated in the mobile units (n=3824). Sensitivity tests excluding ethnicity and the two pop-up sites showed similar results with those of model 2 (see Appendix 8 and 9 respectively). Whilst sensitivity tests on the distance threshold demonstrated the spatially sensitive nature of our analysis (Appendix 10), our results are relatively robust against the spatial spill-over effect once an appropriate distance threshold was chosen (Appendix 11).

Table 2. Estimated effect of mobile vaccination units on weekly vaccination rate (the percentage of adults who have received the first dose of the COVID-19 vaccine in each week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1 uses LSOA level data, accounting for area-based differences between intervention and non-intervention areas, with permuted p-values and confidence intervals. Whilst model 2 additionally controls for individual differences between intervention and non-intervention groups.

	RR	95% CI		p-value
		LCL	UCL	
Model 1. LSOA level synthetic control analysis	1.23	1.11	1.36	<0.001
Model 2. Individual level weighted Poisson regression analysis	1.25	1.21	1.28	<0.001

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Interaction analyses investigated effective modification by deprivation, ethnicity, and age (see Appendix 6). We found lower impact of the mobile vaccination unit on the vaccination rate for the most deprived areas (p<0.001) compared to more affluent areas, a lower impact for Asian/Asian British (p=0.006), Black/Black British (p=0.005) or other ethnic groups (p=0.010), compared to White/White British people, and a lower impact on vaccine uptake for people aged 31–65 compared to 18–30–year–olds (p<0.001).

Figure 3 is about here

Figure 3 shows the estimated effect of mobile vaccination units on weekly vaccine uptake for all the subgroups using the combination of the effect on the reference group (18–30–year–olds of white ethnicity living in the least deprived neighbourhoods that were visited by the mobile vaccination unit) and the interaction terms for deprivation, ethnicity, and age group. The relative effect of the intervention for the reference group is shown in the bottom left cell of Figure 3, indicating that the intervention increased vaccine uptake by 68% (RR 1.68). For people of same ethnic and age group but living in intermediately deprivated areas, the effect was slightly larger (RR 1.82, 82% increase; calculated as the combination of the effect on the reference group and the interaction term for intermediate deprivation with mobile vaccination units: 1.683*1.081=1.82; see Appendix 6), whilst for those living in the most deprived areas it was lower (RR 1.30, 30% increase; calculated as 1.683*0.770 in the same manner as above). Effects of other subgroups could be interpreted in the same way. Due to the small sample sizes of these 45 subgroups (see Appendix 7), these results should be treated with caution. However, they indicate the likely pattern of effects of the intervention across these groups. Overall, White, 18–30–year–olds living in neighbourhoods of intermediated deprivation appeared to benefit the most from visits of the mobile vaccination unit (Figure 3). Effects were lowest for older age groups in the most deprived areas. Although the effect of the mobile vaccination unit may be lower for the most deprived population and for people from Black, Asian, and other ethnic minority groups, the mobile vaccination unit does still appear to have increased uptake in these groups, particularly for younger people. The survival analysis showed similar results overall (Appendix 12).

Discussion

Our study presents much-needed empirical evidence of the effectiveness of mobile vaccination units in promoting COVID-19 vaccination, indicating that they can increase uptake in their targeted neighbourhoods. The effect size estimated in our analysis closely corresponds to the actual number, indicating that a significant proportion of vaccinations conducted in the mobile units were additional. Put simply, our findings suggest that among individuals utilising the mobile vaccination units, there was a minimal number who would have otherwise sought their vaccinations at conventional static centres. This implies that the mobile vaccination units effectively reached individuals who may have faced barriers in accessing conventional static vaccination sites. Our study therefore also lends support to previous studies on other forms of preventative care that mobile units are useful tools in improving geographical accessibility and convenience of services for patients.[12–15]

Within those neighbourhoods, however, the intervention tended to increase uptake most amongst younger people, white people and less socioeconomically deprived areas. However, the targeted neighbourhoods were the most deprived. Our analysis indicated that the intervention was similarly effective in the least deprived and intermediate levels of deprivation *within* these targeted

neighbourhoods. It is only in areas with IMD score of over 53, the lower bound of the most deprived, that the effectiveness declined. However, 53 is at the 95th percentile of the national distribution of IMD scores, representing very deprived areas nationwide. Our findings indicate therefore that the intervention was effective at increasing uptake amongst young people in relatively deprived areas (although not in extremely deprived areas) and across young people from all ethnic groups in these areas.

Our study has limitations. We only had data on individuals who had been registered with the GP at time of our study. The GP registered population is larger than that of the 2021 Census (2.7 million vs. 2.5 million people) due to known data issues (e.g., delays in people updating addresses when move home, different definitions of resident population). Although unregistered people attending for mobile units were encouraged and can register with a GP in their attendance, there may have been people vaccinated who did not wish to be registered, such as undocumented immigrants, homeless populations, travellers, and displaced people. We were unable to estimate the impact of the intervention in these groups. The mobile vaccination unit could have increased uptake due to improved accessibility through the mobile vaccination unit itself and/or the awareness raising and publicity associated with visits of these units. Our analysis cannot distinguish between these effects.

Our analysis covers a relatively short period of follow-up. We are therefore unable to determine whether the observed effect is due to people being vaccinated earlier than they would otherwise have been or if they would have never taken up vaccine without the intervention. We could link approximate but not exact time/date visits of the mobile units. Further research should look to evaluate if mobile units had different effects at different stages of a pandemic (e.g., initial roll out compared to re-opening of society or once most people have been vaccinated by traditional means). We used a measure of average distance to construct the intervention and non-intervention group, which would have made our effect estimate more conservative (see Appendix 11). Although we have accounted for observed differences between places visited by the mobile vaccination units and those not and differences in individual characteristics, it is still possible that unmeasured confounding could bias the results.

Conclusion

Our study has implications for strategies aiming to increase vaccine uptake. By improving geographic accessibility and convenience of services, the mobile vaccination unit likely promoted uptake of the first dose of the COVID-19 vaccine in our study population. The evidence indicating greater effects in less deprived areas and in the White/White British population raises concerns that the intervention could however lead to an increase in inequalities in uptake within targeted areas. It is important to

ensure the mobile vaccination units are effectively targeted to the communities with low uptake and combined with comprehensive engagement and outreach with Black and Asian ethnic groups and with more socioeconomically disadvantaged communities. With successive SARS-CoV-2 variants and the need for multiple vaccine doses to achieve sufficient immunity, rapidly increasing uptake and reducing inequalities in uptake was of critical public health importance. Deployment of mobile units alongside other effective approaches to increase uptake in disadvantaged groups can contribute to this goal.

Transparency statement

The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned (and, if relevant, registered) have been explained.

Author contribution statement

B.B. conceived the original idea, devised the project, the main conceptual ideas and proof outline. X.Z. contributed to the literature review, collected the data, and carried out the data analysis. R.A. conducted the initial literature review. X.Z. drafted the manuscript and designed the figures with support from B.B. and M.G.. J.T., S.K. and P.P. assisted with the data access and commented on the manuscript. R.P. assisted in coding. M.GF and M.G. aided in commenting on the manuscript. I.B. aided in supervising the project and commented on the manuscript. S.B. helped to improve the language and visualisation. All authors provided critical feedback and helped to shape the research manuscript.

Conflicts of interest statement

We have no conflicts of interest to disclose.

Ethics statements

Patient consent for publication

Not required.

Ethics approval

University Research Ethics Committee review is not required by the University of Liverpool for the secondary analysis of data which have been anonymised by an external party and are provided to the research team in a fully anonymised format.

Data sharing statement

The individual-level data is sensitive and could not be shared. But statistical codes are available from https://github.com/civicdatacoop/mobileVaxUnit.

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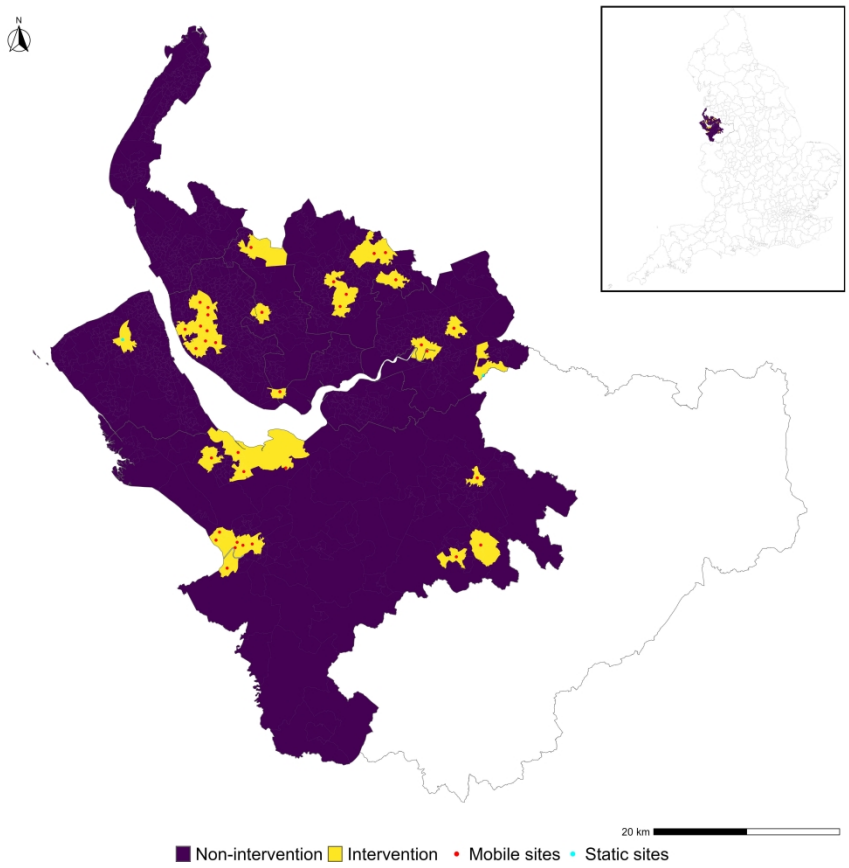
Figure 1. Location of the 35 eligible mobile vaccination units (red dots), the two static pop-up sites (cyan dots), and the non-intervention (purple) and intervention (yellow) areas across Cheshire and Merseyside. The sub-map in the box of the top right shows the location of Cheshire and Merseyside in England.

Figure 2. The trend in the weekly vaccination rate with their 95% confidence intervals in the intervention and synthetic control areas.

Figure 3. Heatmap of the estimated impact of the mobile vaccination units upon weekly number of first dose COVID-19 vaccines administered among all the subgroups based on interaction analysis.



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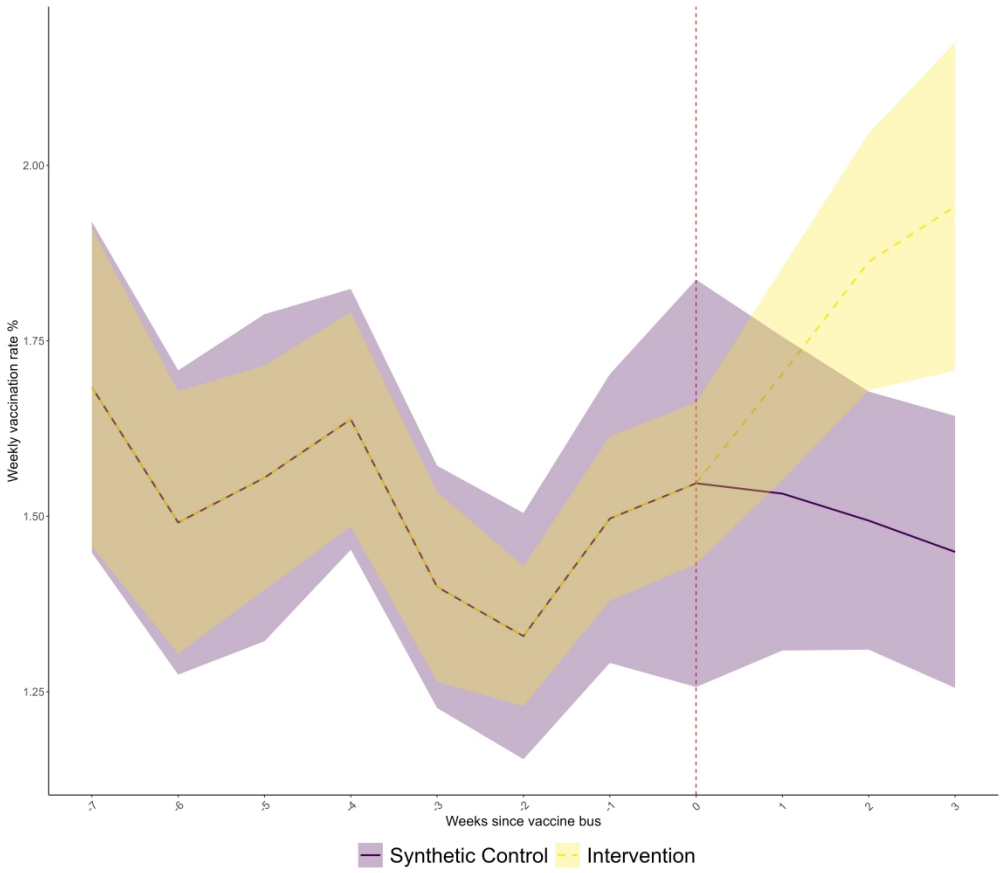

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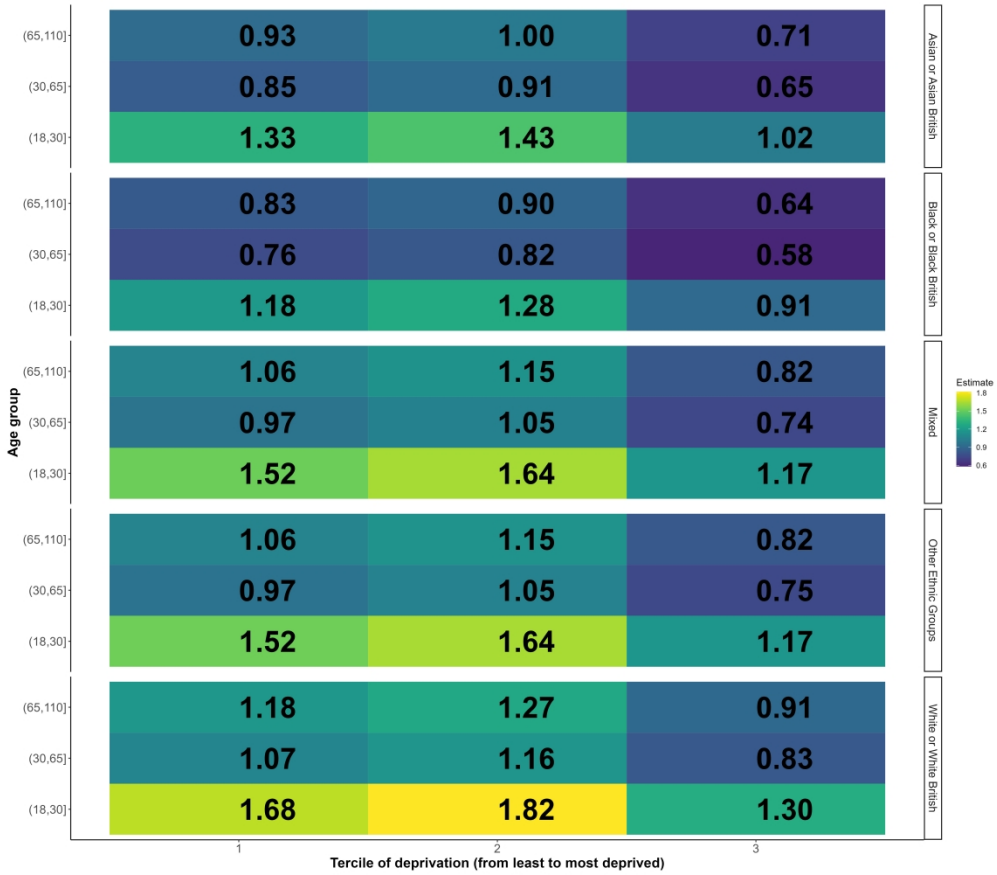

Figure 3. Heatmap of the estimated impact of the mobile vaccination units upon weekly number of first dose COVID-19 vaccines administered among all the subgroups based on interaction analysis.

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Appendices

Appendix 1. Timeline of the age eligibility for the rollout of the COVID-19 vaccine programme for the first dose in England.

Table A1. The availability of vaccine appointments for the first dose of COVID-19 vaccine in England, by date.

Start date	Appointments available for
8 December 2020	Residents in a care home for older adults and their carers; and all aged 80 and over
Procedures set out on 9 and 14 January 2021	Frontline health and social care workers
18 January 2021	All aged 70 and over, and clinically extremely vulnerable individuals
15 February 2021	All aged 65 and over; and those aged 16 to 64 with underlying health conditions which put them at higher risk of serious disease and mortality
1 March 2021	All aged 60 and over
6 March 2021	All aged 56 and over
17 March 2021	All aged 50 and over
13 April 2021	All aged 45 and over
26 April 2021	All aged 44 and over
27 April 2021	All aged 42 and over
30 April 2021	All aged 40 and over
13 May 2021	All aged 38 and over
18 May 2021	All aged 36 and over
20 May 2021	All aged 34 and over
22 May 2021	All aged 32 and over
26 May 2021	All aged 30 and over
8 June 2021	All aged 25 and over
15 June 2021	All aged 23 and over
16 June 2021	All aged 21 and over
18 June 2021	All adults (namely aged 18 and over)

Source: COVID-19 vaccination in the United Kingdom - Wikipedia.

Appendix 2. Crude and age-adjusted accumulated uptake of the COVID-19 vaccine first dose in Cheshire and Merseyside between the 49th week of 2020 (6th to 12th December 2020; the first COVID-19 vaccine was administered in the UK on 8th December 2020) and the 29th week of 2021 (18th to 24th July 2021; the end point of our study is 19th July 2021, three weeks after the last mobile vaccination unit visit on 28th June 2021).

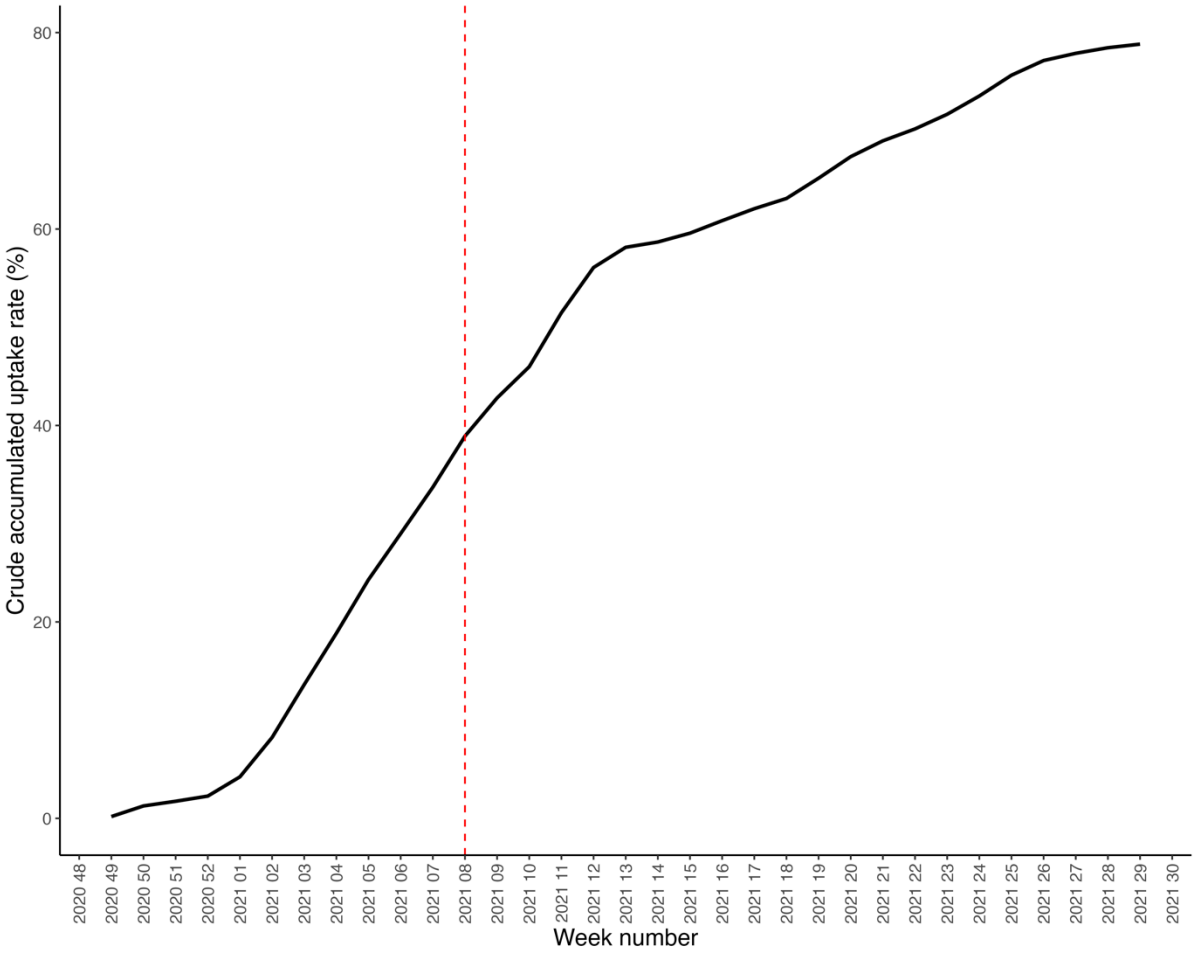


Figure A1. Crude accumulated uptake rate of the first dose COVID-19 vaccine across Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021, the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). After a relatively linear and stable growth between the 1st and 7th week of 2021, Cheshire and Merseyside started to see signs of slowing down in the crude uptake rate since the 8th week of 2021 (21st to 27th February 2021).

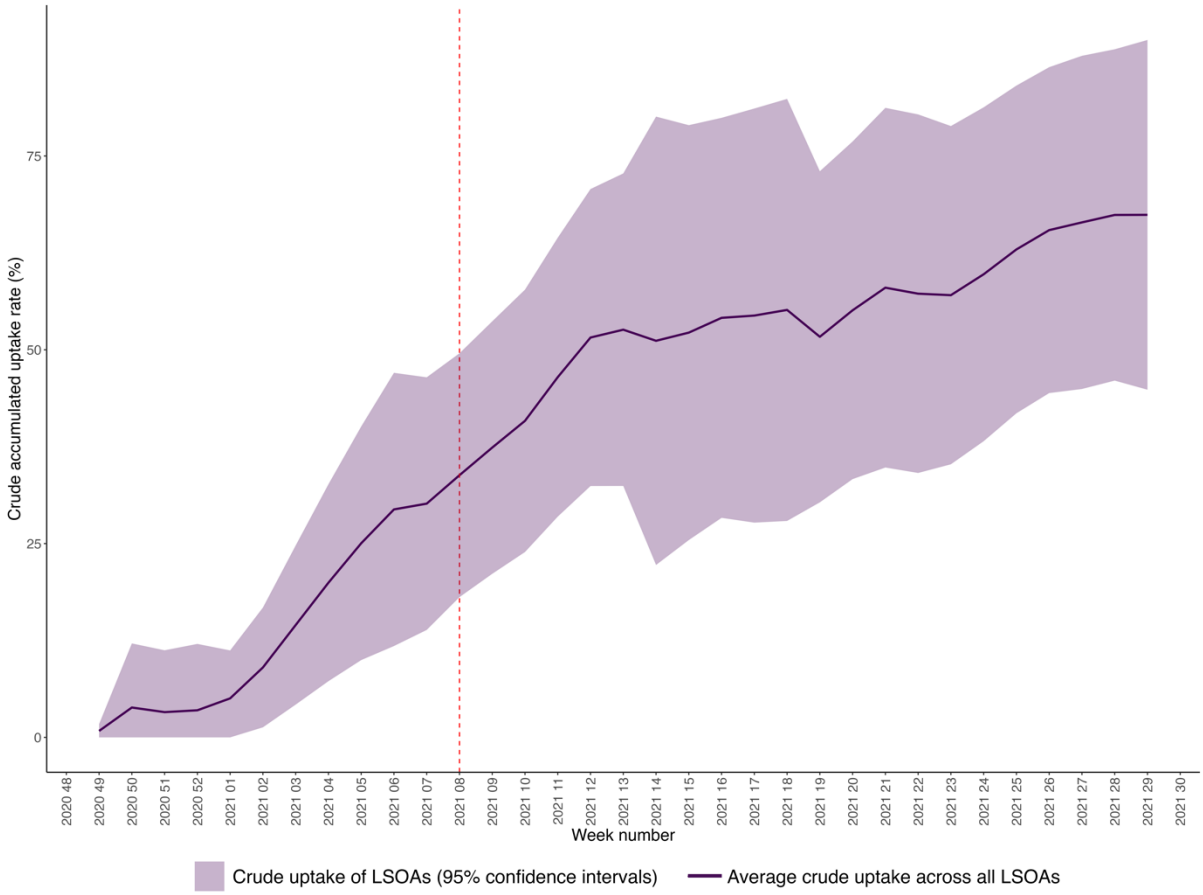
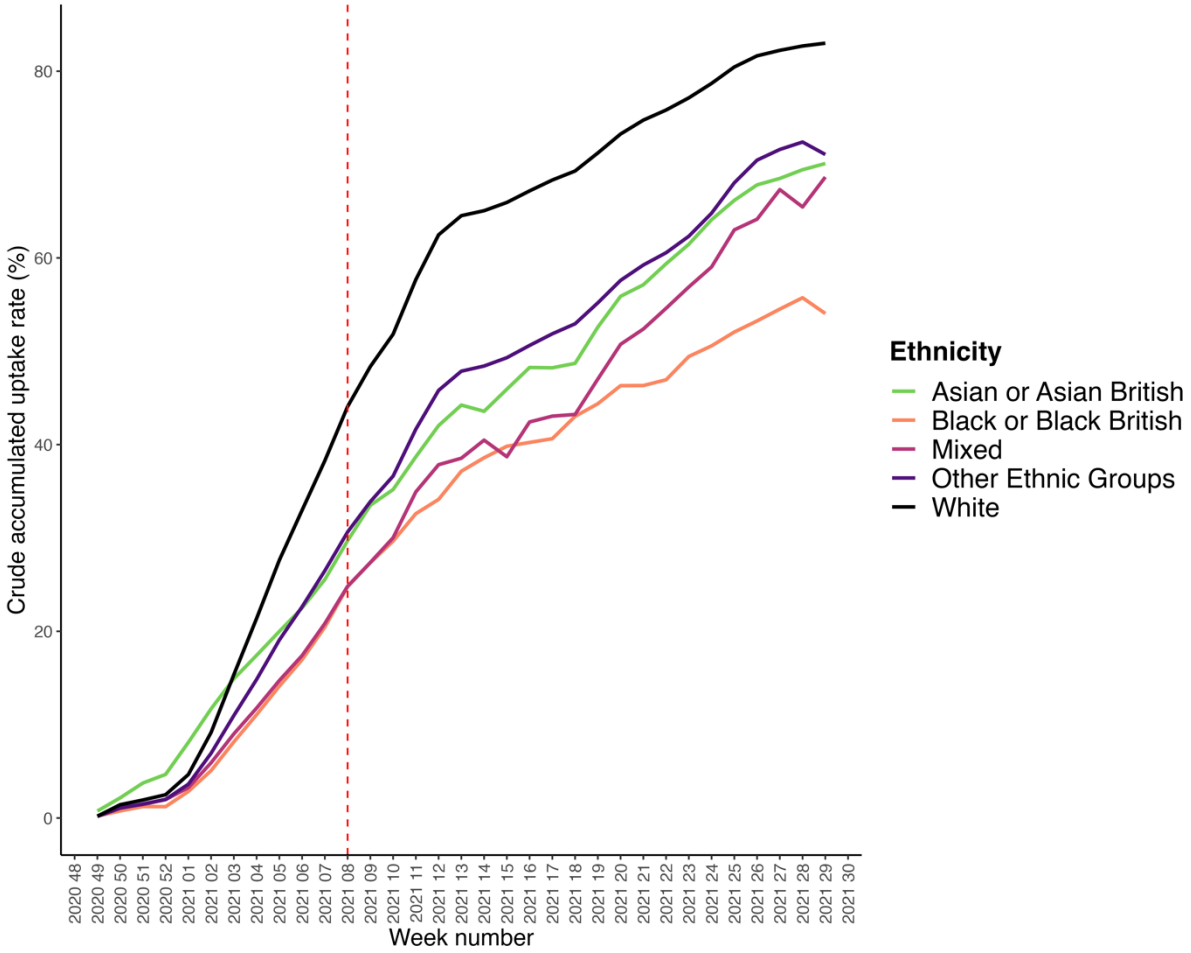
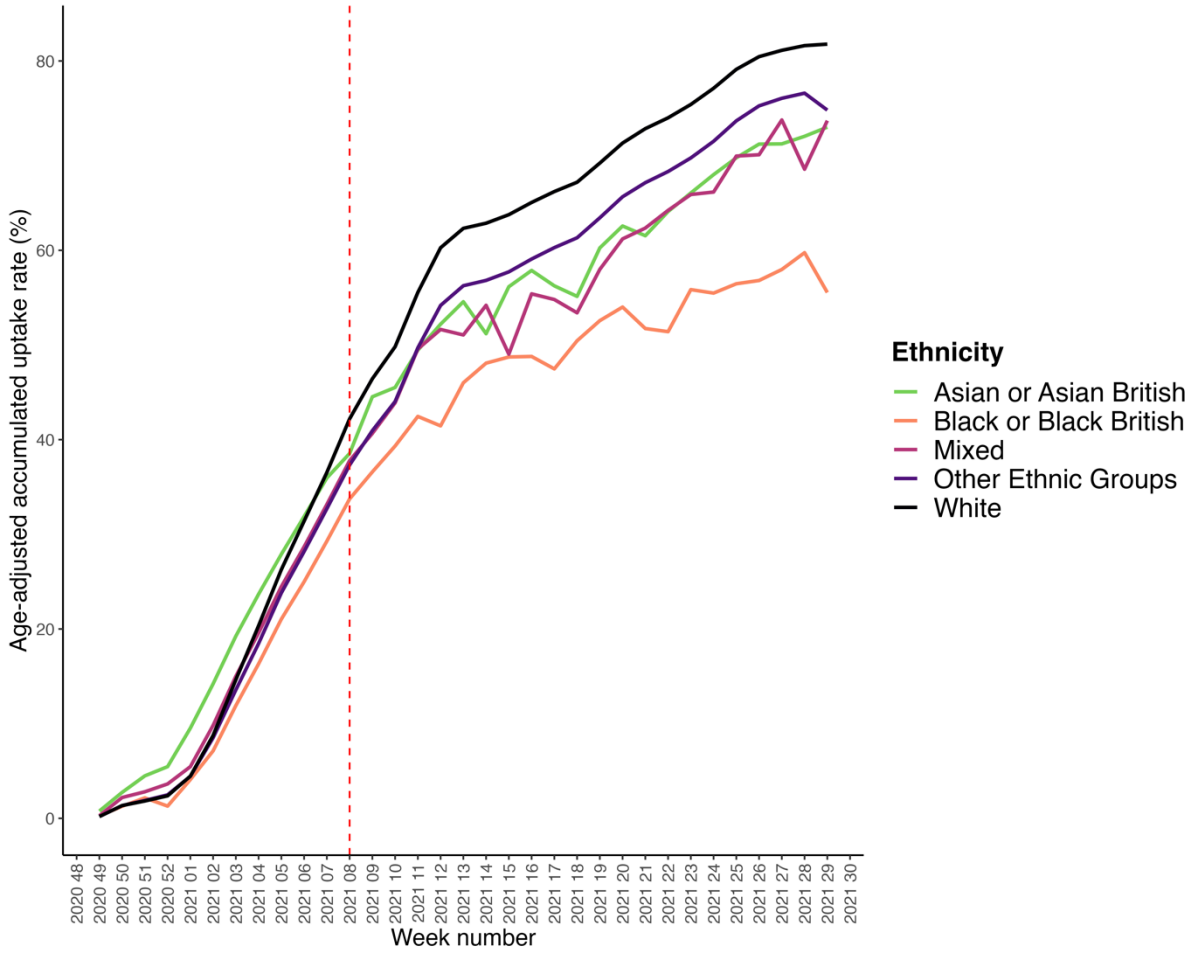


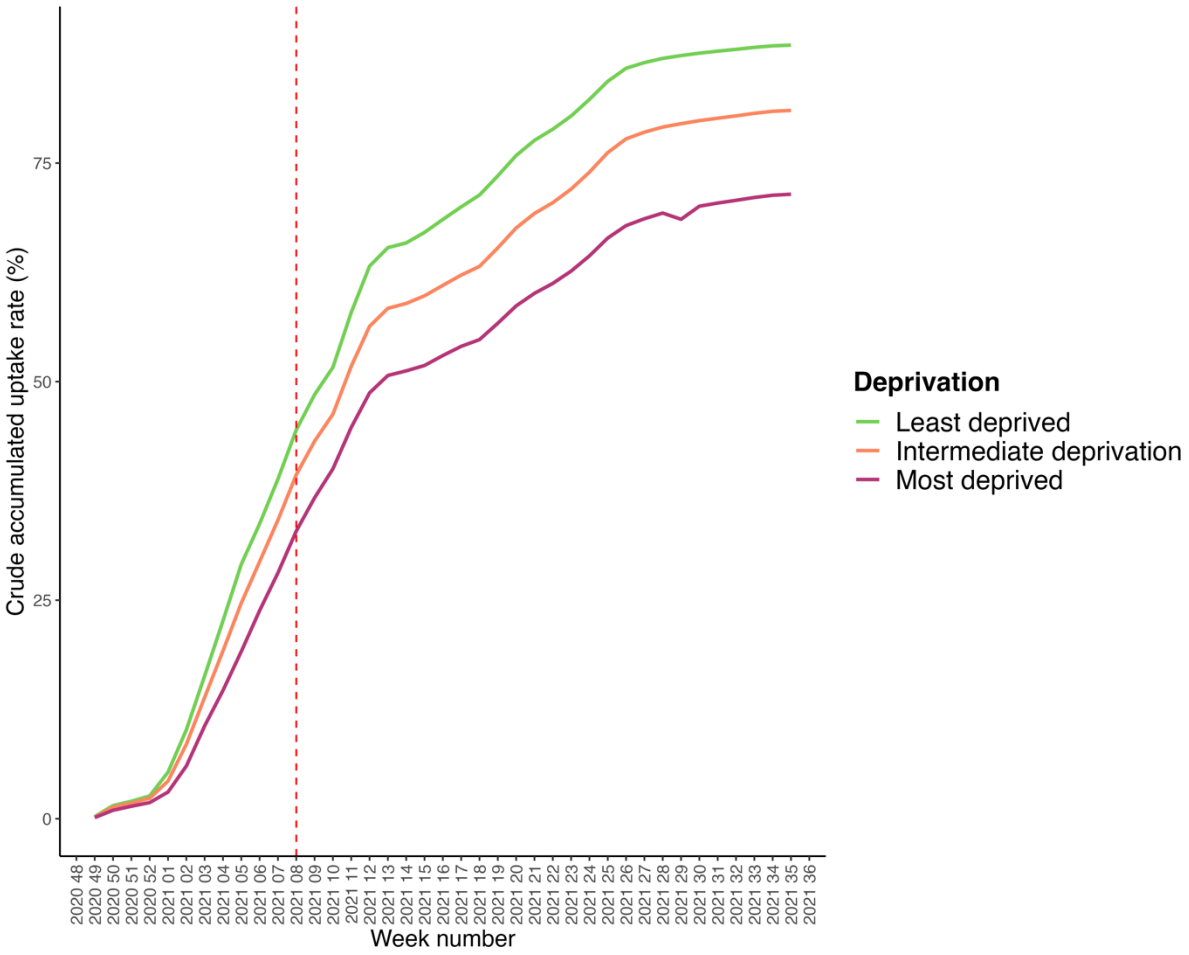
Figure A2. Average crude accumulated uptake rate of the first dose COVID-19 vaccine across all lower layer super-output areas (LSOAs) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021, with its 95% confidence intervals. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), LSOAs of Cheshire and Merseyside had seen expanding variations in their crude accumulated uptake of the first dose COVID-19 vaccine.



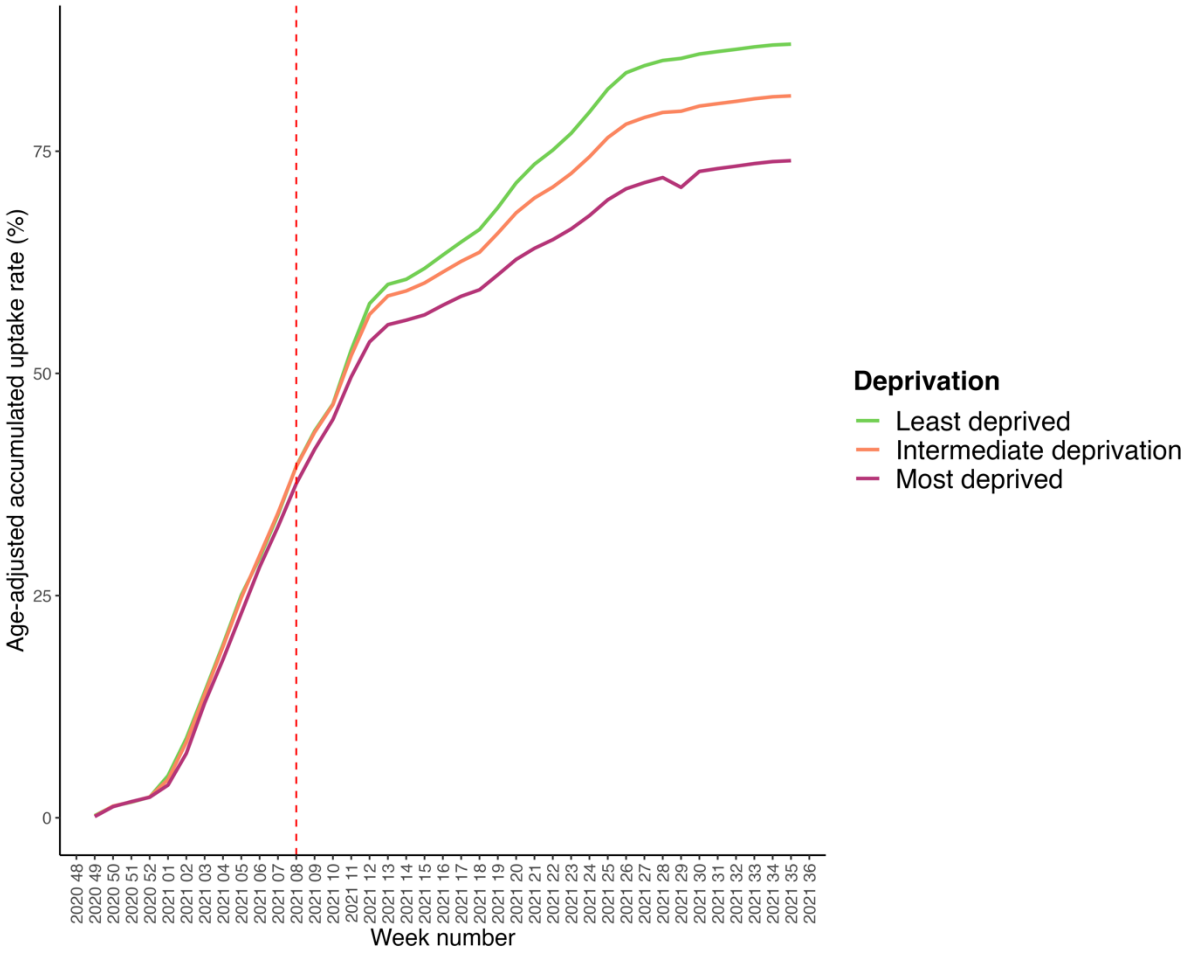
A3. Crude accumulated uptake rate of the first dose COVID-19 vaccine among ethnic groups (White, Asian or Asian British, Black or Black British, Mixed, and Other) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), ethnic groups of Cheshire and Merseyside had seen widening gaps in their crude accumulated uptake of the first dose COVID-19 vaccine.



A4. Age-adjusted accumulated uptake rate of the first dose COVID-19 vaccine among ethnic groups (White, Asian or Asian British, Black or Black British, Mixed, and Other) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). The 8th week of 2021 (21st to 27th February 2021), as a turning point, had become pronounced for widening gaps in age-adjusted accumulated uptake of the first dose COVID-19 vaccine among ethnic groups in Cheshire and Merseyside.



A5. Crude accumulated uptake rate of the first dose COVID-19 vaccine among different socio-economic groups (Least deprived, Intermediate deprivation, and Most deprived) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), different socio-economic groups of Cheshire and Merseyside had seen increasingly growing gaps in their crude accumulated uptake of the first dose COVID-19 vaccine.



A6. Age-adjusted accumulated uptake rate of the first dose COVID-19 vaccine among different socio-economic groups (Least deprived, Intermediate deprivation, and Most deprived) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), different socio-economic groups of Cheshire and Merseyside had seen signs of widening gaps in their age-adjusted accumulated uptake of the first dose COVID-19 vaccine.

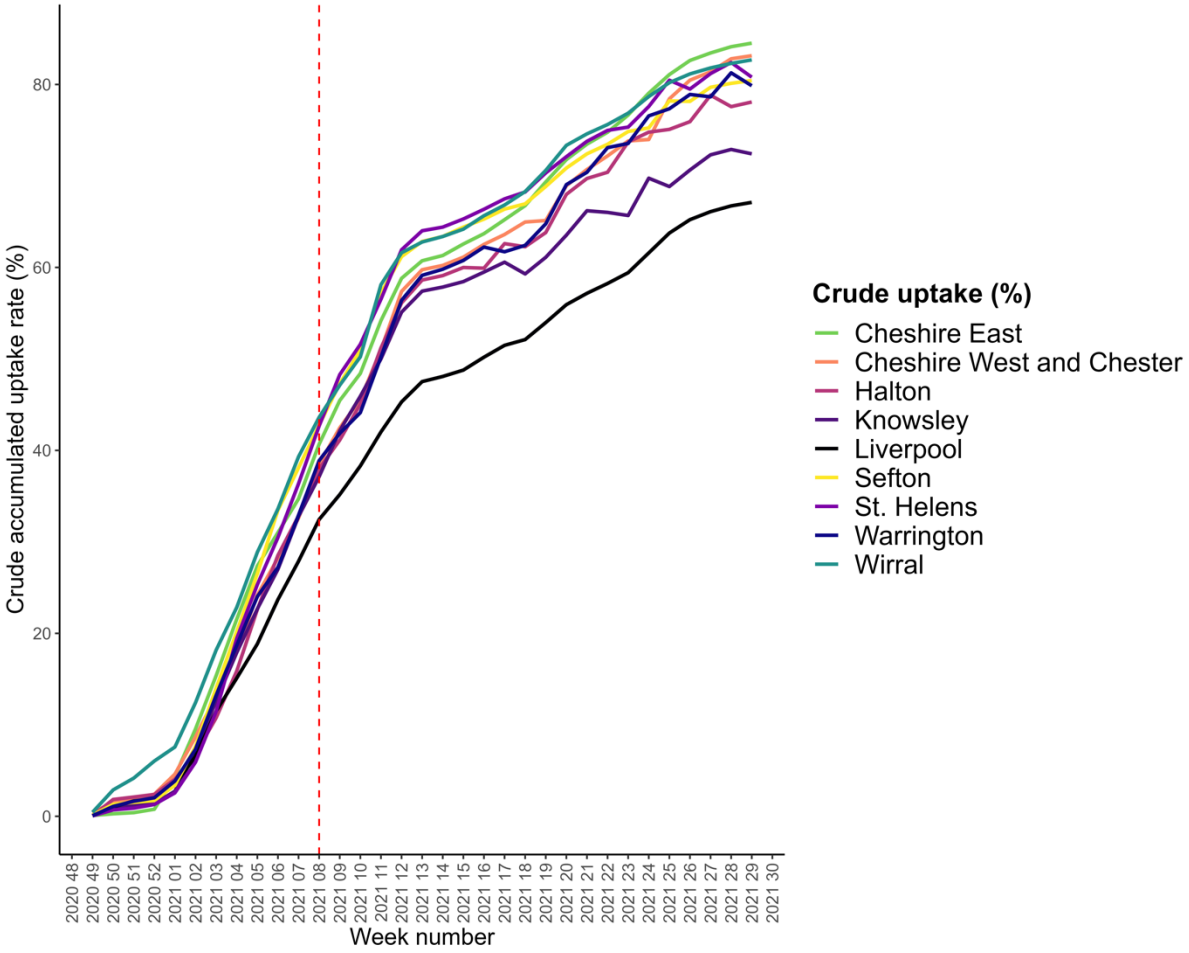


Figure A7. Crude accumulated uptake rate of the first dose COVID-19 vaccine by local authorities in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021, the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021).

Appendix 3. Summary statistics of the intervention and full non-intervention population at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

Whilst Table 1 presents summary statistics for the intervention and non-intervention areas within the eight local authorities that reported data on the deployment (or non-deployment) of the mobile vaccination units and therefore are used to conduct the main analysis, Table A2 below shows the comparison between the intervention and the rest of the Cheshire and Merseyside, including the eight local authorities above and the one local authority with missing data on the intervention that has been excluded from the main analysis.

Table A2. The comparison between the intervention and the rest of Cheshire and Merseyside at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

	Rest of the Cheshire and Merseyside region	Intervention areas
Total population	1829809	338006
% women	50.72	48.92
Population density – people per hectare	34.88	65.11
Mean age	42.72	38.03
% Asian/Asian British	1.20	3.28
% Black/Black British	0.52	2.37
% Mixed people	1.39	1.87
IMD score	25.83	40.38
% households with at least one-bedroom fewer than they need	2.55	4.77
Average travel time by car to the nearest conventional static vaccine site - minutes	4.28	2.83
First dose vaccine uptake among adults (the percentage of adults who have received the first dose of COVID-19 vaccine among the total eligible adult population prior to pre-intervention) (%)	66.15	52.65

Average weekly first dose vaccination rate among adults in the 7 weeks prior to intervention (%)	2.08	1.51
Number of LSOAs	1346	216

Appendix 4. The weekly number of the first dose administered in the intervention and control groups for each of the seven weeks prior to the intervention (the mobile vaccination unit).

Table A3. Weekly number of the first dose administered in the intervention and control groups for each of the seven weeks prior to the intervention (the mobile vaccination unit).

Weeks before the intervention	Weekly number of the first dose administered in the LSOAs being visited by the mobile vaccination units	Weekly number of the first dose administered in the LSOAs in the rest of Cheshire & Merseyside used to construct the synthetic control	Weekly number of the first dose administered in the synthetic control (weighting LSOAs in the rest of Cheshire & Merseyside using synthetic control weights)
7	5692	31995	5692
6	5040	29288	5040
5	5256	31869	5256
4	5537	33022	5537
3	4730	24901	4730
2	4493	21180	4493
1	5059	21685	5059

Appendix 5. Geographical pattern of weights in area-based synthetic control analysis.

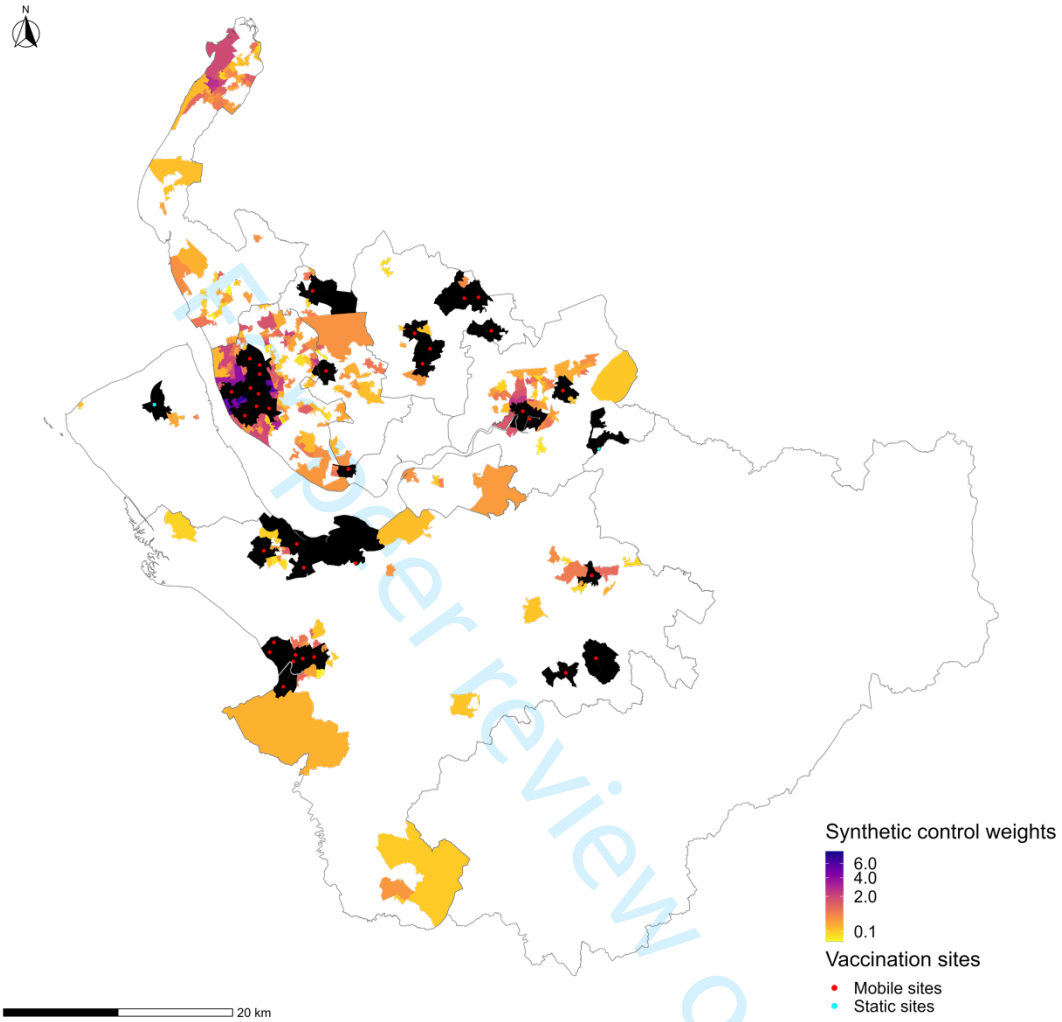


Figure A8. Weighting of areas outside of the catchment of the mobile vaccination units to construct the synthetic control group. Areas within the catchment of the mobile vaccination units are coloured black, whilst locations of the mobile vaccination unit are represented by red (35 mobile sites) and cyan (two static pop-up sites) dots. The white non-intervention areas are those that have been allocated zero weights in constructing the synthetic control, whilst other coloured non-intervention areas are those with non-zero weights in constructing the synthetic control: the darker the colour, the larger the weight.

Appendix 6. Regression output for the interaction model based on adult individuals.

Subgroup analysis by deprivation, ethnicity and age indicates, lower impact of the mobile vaccination unit on vaccination uptake for the most deprived areas compared to more affluent areas, a lower impact for Asian/Asian British, Black/Black British or Other ethnic groups, compared to white British people, and a lower impact on people aged 31-65-year-olds. The sample sizes are quite low for the subgroup analysis (see Appendix 7 below for more details) so the results reported here are only indicative of the overall pattern. Table A4 below shows the effect sizes of the mobile vaccination unit for the subgroups as relative risks. Compared to people not visited by the mobile vaccination units in their neighbourhoods, visits of the mobile vaccination units have increased vaccination rates in the following groups: people aged 18-30 from all socio-economic backgrounds and all ethnic groups except for Black/Black British; White/White British people aged above 30 from least and intermediate deprived areas; people aged 30-65 of mixed and other ethnic groups from the intermediate deprived areas; and people aged above 65 of mixed and other ethnic groups from least and intermediate deprived areas (see Figure 3 in the main text for more details).

Table A4. Regression output with interaction terms based on adult individuals. The table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention.

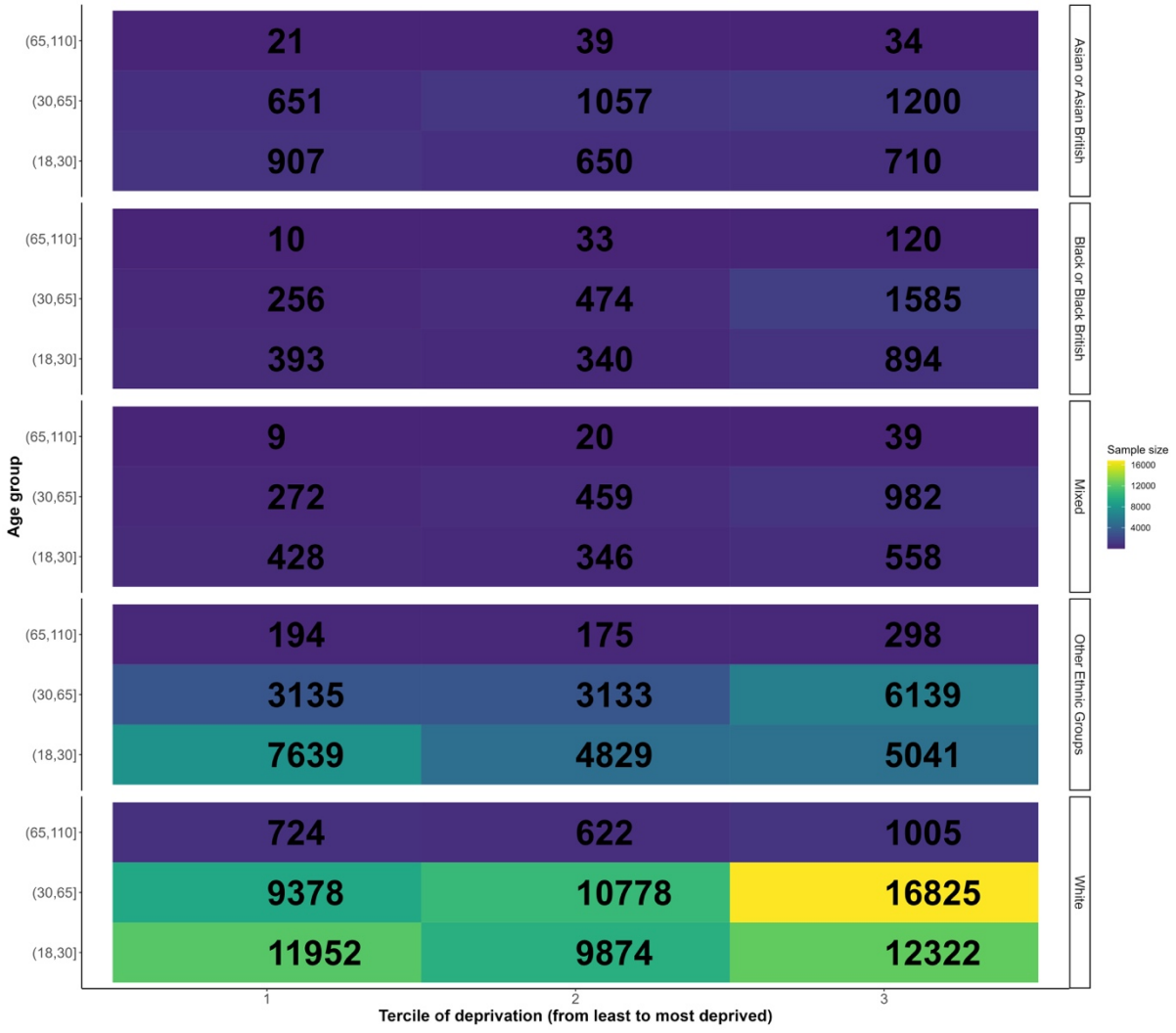
Variables	RR	95% CI		p-value
		LCL	UCL	
Mobile vaccination unit (reference: no mobile vaccination unit)	1.683	1.584	1.789	<0.001
Age group (reference: 18-30 years old)				
(30,65]	1.249	1.187	1.313	<0.001
65+	0.201	0.147	0.275	<0.001
Sex (reference: Women)				
Men	1.013	0.984	1.042	0.380
Ethnicity (reference: White/White British)				
Asian/Asian British	0.919	0.791	1.068	0.271
Black/Black British	0.749	0.605	0.929	0.008
Mixed	0.746	0.608	0.915	0.005
Other ethnic groups	0.799	0.746	0.856	<0.001
IMD tercile (reference: Least deprived)				
Intermediate deprivation	0.786	0.741	0.834	<0.001
Most deprived areas	0.673	0.631	0.718	<0.001
Chronic health conditions (reference: none)	1.098	1.076	1.120	<0.001
Carer (reference: not carer)	0.320	0.273	0.375	<0.001
Social care receiver (reference: not social care receiver)	0.979	0.764	1.255	0.869
Travel time by car to the nearest static vaccine centre (minutes)	1.087	1.082	1.093	<0.001
Interaction between age groups and mobile vaccination unit (reference: 18-30 years old with mobile vaccination unit)				
30-65 years old with mobile vaccination unit	0.638	0.602	0.676	<0.001
65+ years old with mobile vaccination unit	0.700	0.475	1.030	0.070
Interaction between ethnicity and mobile vaccination unit (reference: White/White British with mobile vaccination unit)				
Asian/Asian British with mobile vaccination unit	0.788	0.664	0.935	0.006
Black/Black British with mobile vaccination unit	0.704	0.550	0.901	0.005

Mixed with mobile vaccination unit	0.900	0.712	1.138	0.379
Other ethnic groups with mobile vaccination unit	0.903	0.835	0.976	0.010
Interaction between IMD tercile and mobile vaccination unit (reference: Least deprived with mobile vaccination unit)				
Intermediate deprivation with mobile vaccination unit	1.081	1.010	1.158	0.024
Most deprived areas with mobile vaccination unit	0.770	0.715	0.829	<0.001

Note: The intercept is excluded from the output. We reported the result in three decimal digits specifically here to facilitate the explanation on how to interpret interaction terms.

Appendix 7. Sample size of the sub-groups (with visits of the mobile vaccination units) in the weighted Poisson model including interaction terms between the intervention indicator (mobile vaccination unit) and IMD tercile within Cheshire and Merseyside, ethnic and age groups respectively.

Figure A10. Heatmap of the sample size for each subgroup receiving the visit of the mobile vaccination units based on interaction analysis.



Appendix 8. Sensitivity test – excluding ethnicity from the main model.

Table A5. Results of analysis for adult individuals of all ages, excluding ethnicity.

	RR	95% CI		p-value
		LCL	UCL	
Model 2a. Individual level weighted Poisson regression analysis	1.24	1.21	1.28	<0.001

Results of individual-level analysis presented in Table A5 and Table 2 are almost identical, implying that excluding cases with missing information on ethnicity did not affect the robustness of our results.

Appendix 9. Sensitivity test – excluding the two pop-up sites across C&M.

Table A6. Results of analysis for adult individuals of all ages, excluding the two pop-up sites.

	RR	95% CI		p-value
		LCL	UCL	
Model 2b. Individual level weighted Poisson regression analysis	1.23	1.18	1.29	<0.001

Table A6 of individual-level analysis shows very similar results to those of Table 2, indicating that it is unlikely that the use of the two pop-up sites rather than vaccine buses alone influenced our results overall.

Appendix 10. Sensitivity test – results of the synthetic control method based on different distance thresholds in constructing the synthetic control.

Table A7. Estimated effect of mobile vaccination units on weekly vaccine uptake (the percentage of adults who have received the first dose of the COVID-19 vaccine in a given week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1a uses the 500 meter distance threshold to construct the intervention and non-intervention areas with LSOA level data, accounting for area-based differences between intervention and non-intervention areas, with permuted p-values and confidence intervals. Model 1b, 1c and 1d use the distance threshold of 1, 2 and 3KM respectively, all else equal.

	RR	95% CI		p-value
		LCL	UCL	
Model 1a. LSOA level synthetic control analysis – 500-meter threshold	1.10	-1.04	1.30	0.208
Model 1b. LSOA level synthetic control analysis – 1500-meter threshold	1.15	1.04	1.26	<0.001
Model 1c. LSOA level synthetic control analysis – 2000-meter threshold	1.05	-1.04	1.17	0.280
Model 1d. LSOA level synthetic control analysis – 3000-meter threshold	1.02	-1.12	1.19	0.888

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Appendix 11. Sensitivity test – results of the synthetic control method excluding LSOAs with centroids located between 1 to 1.5 km from the nearest mobile vaccination unit to account for the potential spatial spill over effect.

Table A8. Estimated effect of mobile vaccination units on weekly vaccine uptake (the percentage of adults who have received the first dose of the COVID-19 vaccine in a given week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1e uses the same distance threshold (1 km) as the main model 1 to construct the intervention and non-intervention areas with LSOA level data, but excludes LSOAs with population weighted centroids located between 1 and 1.5km from the nearest mobile vaccination unit to additionally account for the potential spatial spill over effect, with permuted p-values and confidence intervals.

	RR	95% CI		p-value
		LCL	UCL	
Model 1e. LSOA level synthetic control analysis – accounting for potential spatial spill over effect between 1 and 1.5 km	1.24	1.11	1.40	<0.001

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Appendix 12. Sensitivity test – results of survival analyses based on adult individuals.

Using weights calibrated in the synthetic control analysis, we conducted a survival analysis to check the robustness of the synthetic control analysis. In this analysis, we compared the survival probability (the probability of adults to stay unvaccinated) between the synthetic control and intervention groups in the three weeks following the intervention, only including unvaccinated adults at the time of the intervention, a binary categorical variable indicating whether an individual had received the first-dose of the COVID-19 vaccine as the outcome variable, the number of week from the intervention as the time variable, and the variable of the intervention (the mobile bus units). Figure A8 below shows the survival curves of two groups and the risk table. Even without controlling for any individual-level confounders used in the main individual-level analysis, this model estimates 3487 additional vaccinations over three weeks of follow-up period (3487 = (32005-47132) - (29878-48492)), broadly in line with the effect size estimated in the main analysis (n=3723).

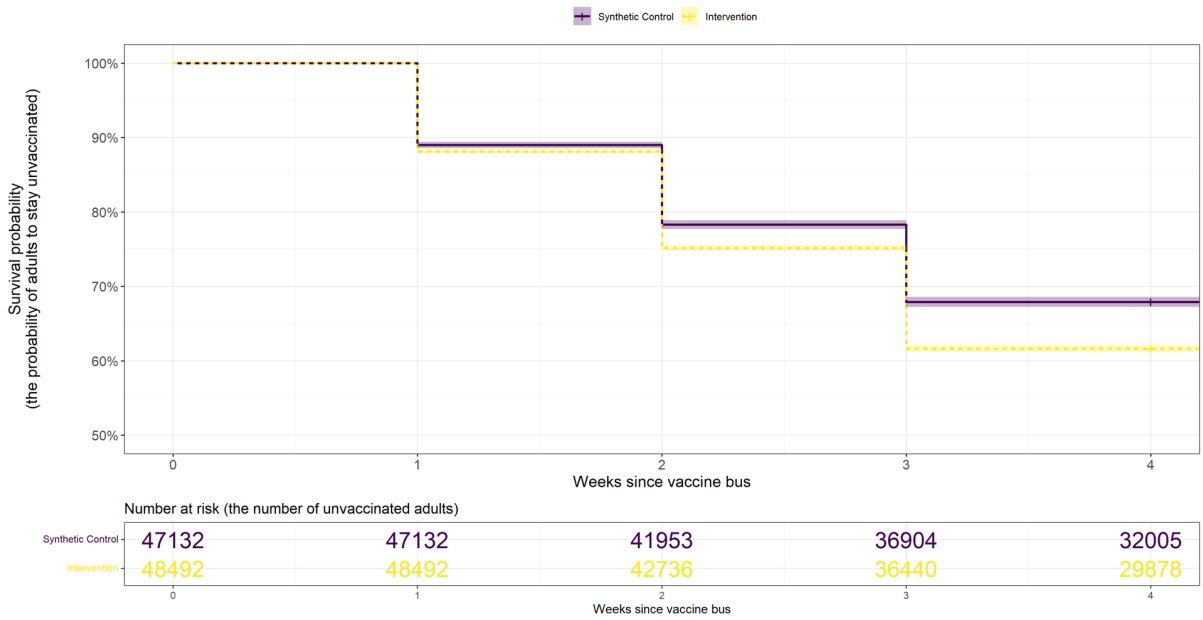


Figure A9. The survival curves of the synthetic control (coloured in purple) and intervention groups (coloured in yellow) with their respective 95% confidence intervals and the risk table, following the same colouring scheme of Figure 2 in the main analysis.

We then used a Cox proportional hazards regression model to replicate the sub-group analysis in Appendix 6. Results are shown in Table A9, similar to Table A4 in the overall trends and patterns.

Table A10. Cox regression output for the interaction model based on adult individuals. The table shows the hazard ratio (HR) indicating the estimated ratio of weekly vaccination rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention.

Variables	HR	95% CI		p-value
		LCL	UCL	
Mobile vaccination unit (reference: no mobile vaccination unit)	1.83	1.72	1.95	<0.001
Age group (reference: 18-30 years old)				
(30,65]	2.16	2.05	2.29	<0.001
65+	1.49	1.08	2.06	0.017
Sex (reference: Women)				
Men	1.07	1.03	1.10	<0.001
Ethnicity (reference: White/White British)				
Asian/Asian British	0.83	0.71	0.98	0.027
Black/Black British	0.90	0.72	1.12	0.344
Mixed	0.77	0.62	0.96	0.021
Other ethnic groups	0.98	0.91	1.05	0.549
IMD tercile (reference: Least deprived)				
Intermediate deprivation	0.92	0.86	0.98	0.008
Most deprived areas	0.94	0.88	1.01	0.090
Chronic health conditions (reference: none)	0.97	0.95	0.99	0.013
Carer (reference: not carer)	0.67	0.56	0.80	<0.001
Social care receiver	1.02	0.79	1.30	0.894
Travel time by car to the nearest static vaccine centre (minutes)	1.04	1.04	1.05	<0.001
Interaction between age groups and mobile vaccination unit (reference: 18-30 years old with mobile vaccination unit)				
30-65 years old with mobile vaccination unit	0.65	0.61	0.69	<0.001
65+ years old with mobile vaccination unit	0.57	0.38	0.85	0.006
Interaction between ethnicity and mobile vaccination unit (reference: White/White British with mobile vaccination unit)				

Asian/Asian British with mobile vaccination unit	0.88	0.73	1.06	0.179
Black/Black British with mobile vaccination unit	0.70	0.54	0.90	0.006
Mixed with mobile vaccination unit	0.98	0.76	1.26	0.879
Other ethnic groups with mobile vaccination unit	0.98	0.91	1.07	0.670
Interaction between IMD tercile and mobile vaccination unit (reference: Least deprived with mobile vaccination unit)				
Intermediate deprivation with mobile vaccination unit	0.91	0.85	0.98	0.013
Most deprived areas with mobile vaccination unit	0.58	0.54	0.63	<0.001

Note: HR is hazard ratio. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Reporting checklist for cross sectional study.

Based on the STROBE cross sectional guidelines.

Instructions to authors

Complete this checklist by entering the page numbers from your manuscript where readers will find each of the items listed below.

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		Reporting Item	Page Number
Title and abstract			1-2
Title	#1a	Indicate the study's design with a commonly used term in the title or the abstract	1
Abstract	#1b	Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			4-5
Background / rationale	#2	Explain the scientific background and rationale for the investigation being reported	4-5
Objectives	#3	State specific objectives, including any prespecified hypotheses	5
Methods			5-9
Study design	#4	Present key elements of study design early in the paper	5-9
Setting	#5	Describe the setting, locations, and relevant dates, including periods of	6-7

		recruitment, exposure, follow-up, and data collection	
Eligibility criteria	#6a	Give the eligibility criteria, and the sources and methods of selection of participants.	7-9
	#7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9
Data sources / measurement	#8	For each variable of interest give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group. Give information separately for for exposed and unexposed groups if applicable.	5-6
Bias	#9	Describe any efforts to address potential sources of bias	8-9
Study size	#10	Explain how the study size was arrived at	9
Quantitative variables	#11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	5-6
Statistical methods	#12a	Describe all statistical methods, including those used to control for confounding	7-9
Statistical methods	#12b	Describe any methods used to examine subgroups and interactions	9
Statistical methods	#12c	Explain how missing data were addressed	9
Statistical methods	#12d	If applicable, describe analytical methods taking account of sampling strategy	
Statistical methods	#12e	Describe any sensitivity analyses	9
Results			9-12
Participants	#13a	Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed. Give information separately for for exposed and unexposed groups if applicable.	
Participants	#13b	Give reasons for non-participation at each stage	
Participants	#13c	Consider use of a flow diagram	

Descriptive data	#14a	Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders. Give information separately for exposed and unexposed groups if applicable.	9-10
Descriptive data	#14b	Indicate number of participants with missing data for each variable of interest	
Outcome data	#15	Report numbers of outcome events or summary measures. Give information separately for exposed and unexposed groups if applicable.	10
Main results	#16a	Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	10-11
Main results	#16b	Report category boundaries when continuous variables were categorized	
Main results	#16c	If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11
Other analyses	#17	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses	11-12
Discussion			12-14
Key results	#18	Summarise key results with reference to study objectives	12-13
Limitations	#19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias.	13
Interpretation	#20	Give a cautious overall interpretation considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence.	13-14
Generalisability	#21	Discuss the generalisability (external validity) of the study results	13-14
Other Information			
Funding	#22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	15

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Evaluating the impact of using mobile vaccination units to increase COVID-19 vaccination uptake in Cheshire and Merseyside, UK: A synthetic control analysis.

Xingna Zhang[1], John Tulloch[2], Shane Knott[3], Rachel Allison[4], Paula Parvulescu[5], Iain Buchan[6], Marta García-Fiñana[7], Roberta Piroddi[8], Mark A. Green[9], Sophie Baird[10], Ben Barr[11]

[1] Tenure Track Fellow, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[2] Tenure Track Fellow, Department of Livestock and One Health in the Institute of Infection, Veterinary and Ecological Science, University of Liverpool, Liverpool, UK

[3] Senior Public Health Practitioner (Healthcare), Liverpool City Council, Liverpool, UK

[4] FY1 Doctor, Russells Hall Hospital, Dudley, UK

[5] Consultant in Public Health Medicine, Liverpool City Council, Liverpool, UK

[6] Chair in Public Health and Clinical Informatics, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[7] Professor of Health Data Science, Department of Health Data Science, University of Liverpool, Liverpool, UK

[8] Research Fellow, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

[9] Reader in Health Geography, Department of Geography & Planning, University of Liverpool, Liverpool, UK

[10] Public Health Registrar, The UK Health Security Agency, UK

[11] Chair in Applied Public Health Research, Department of Public Health, Policy & Systems, University of Liverpool, Liverpool, UK

Corresponding author:

Xingna Zhang

xingna.zhang@liverpool.ac.uk

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ABSTRACT

Objective To evaluate the impact of mobile vaccination units on COVID-19 vaccine uptake of the first dose, the percentage of vaccinated people among the total eligible population. We further investigate whether such an effect differed by deprivation, ethnicity, and age.

Design Synthetic control analysis.

Setting The population registered with General Practices (GPs) in nine local authority areas in Cheshire and Merseyside in Northwest England, UK.

Intervention Mobile vaccination units that visited 37 sites on 54 occasions between 12th April and 28th June 2021. We defined intervention neighbourhoods as having their population weighted centroid located within 1km of mobile vaccination sites (338,006 individuals). A weighted combination of neighbourhoods that had not received the intervention (1,495,582 individuals) was used to construct a synthetic control group.

Outcome The weekly number of first-dose vaccines received among people aged 18 years and over as a proportion of the population.

Results The introduction of a mobile vaccination unit into a neighbourhood increased the number of first vaccinations conducted in the neighbourhood by 25% (95% CI: 21% to 28%) within three weeks after the first visit to a neighbourhood, compared to the synthetic control group. Interaction analyses showed smaller or no effect amongst older age groups, Asian and Black ethnic groups, and the most socioeconomically deprived populations.

Conclusions Mobile vaccination units are effective interventions for increasing vaccination uptake, at least in the short-term. While mobile units can be geographically targeted to reduce inequalities, we found evidence that they may increase inequalities in vaccine uptake within targeted areas, as the intervention was less effective amongst groups that tended to have lower vaccination uptake. Mobile vaccination units should be used in combination with activities to maximise outreach with Black and Asian communities and socioeconomically disadvantaged groups.

Strengths and limitations of this study

- The synthetic control method for microdata offers a rigorous method for identifying control areas that experienced similar levels of COVID-19 vaccine uptake as the intervention areas prior to the introduction of mobile vaccination units, supporting a possible causal interpretation of the finding of increased uptake in areas with mobile vaccination visits following their introduction.
- The use of individual-level data enabled us to construct weighted Poisson regression models to offer robust estimation of the observed effect, with interaction analysis to reveal whether this effect varied by level of deprivation, age groups and ethnicity.
- We were not able to include individuals that had not been registered with the GP at time of our study, which could lead to the underestimation of the effect given that the main vaccination programme was provided through GPs.
- As our analysis covers a relatively short follow-up period, the results may not reflect the sustained impact of the intervention over longer periods of time.
- There may also be other differences between places being visited by the mobile vaccination units and those that were not and differences in individual characteristics, beyond those included in this study, that led to the differences in the observed effect.

Introduction

Vaccination is one of the most effective public health interventions for improving health and saving lives.[1] Following the national rollout of the COVID-19 vaccine program on 8th December 2020 in the UK, relatively high vaccine uptake has helped reduce the risk of hospitalisation and mortality from COVID-19.[2] Nevertheless, vaccine uptake was lower among young people, socioeconomically disadvantaged groups and ethnic minorities for a combination of factors including vaccine eligibility (Appendix 1 presents the timeline for age eligibility of the first dose of the COVID-19 vaccine in England) and hesitancy, health disparities and inequalities, convenience and access, language and cultural barriers, and trust in healthcare systems.[3–6] Some of these groups have also often experienced disproportionately greater levels of infections, hospitalisations and deaths during the pandemic. With successive SARS-CoV-2 variants, additional booster vaccinations were needed to give sufficient protection. Inequalities in uptake of these subsequent doses were greater than with the initial doses,[7] potentially undermining responses to new variants that rely largely on increased uptake of booster vaccinations. The UK government invested £22.5 million to help areas increase uptake amongst hard-to-reach groups in December 2021, as tackling health inequalities is a core government priority.[8] A central part of this strategy was to use mobile vaccination units such as pop-up sites and vaccine buses – "taking the vaccines into the hearts of local communities".[9]

Mobile vaccination units have been used in many countries to increase uptake in disadvantaged communities.[10] These generally involve vaccination clinics based in large vehicles such as buses or temporary pop-up clinics in community settings. As well as bringing vaccines into targeted communities, they usually involve outreach programmes (e.g., leaflet campaigns to advertise vaccination units and explain the benefits of vaccination). The use of mobile vaccination units to increase uptake is based on the premise that geographic accessibility and convenience of vaccination services are potentially important determinants of uptake and that they support uptake from people who have difficulty in accessing existing sites due to information or travel barriers, childcare or healthcare responsibilities, or being excluded from the official healthcare system.[11]

Although former studies found mobile units as useful tools to reduce health inequalities in administering other forms of preventative care such as cancer screening,[12–15] there has been limited research evaluating interventions that aim to increase COVID-19 vaccine uptake. One Randomised Controlled Trial (RCT) shows that provision of information on personal benefit reduces hesitancy,[16] with another RCT indicating that text message reminders lead to small increases in uptake.[17] One study of a community-based strategy in an underserved Latinx population in San Francisco found that mobile units reached their intended recipients, but the study was unable to

estimate the impact on vaccination uptake.[18] Another study found that users of the COVID-19 mobile vaccination units tended to be younger, non-White race, and Hispanic ethnicity compared to the general vaccinated populations in the Greater Boston area, suggesting the potential benefits of mobile vaccination units without estimating the average treatment effect.[19] A few studies investigated the impact of interventions aiming to increase Influenza and pneumococcal vaccination, including one systematic review,[20] five RCTs [21–25] and two cluster RCTs.[26,27] Of these, three were published in the United Kingdom,[21,22,26] three in the United States [20,23,24] and two in Hong Kong.[25,27] They all show that sending out reminders, telephone calls and educational outreach tend to increase uptake. We found no studies that quantified the effect of introducing mobile vaccination units on COVID-19 vaccine uptake.

It also remains largely uncertain how effective mobile vaccination units are at increasing uptake amongst disadvantaged groups, having been deployed to improve vaccine access for those communities.[2,18,19] The lack of existing evidence is concerning, considering their central role in the strategies to reduce vaccine uptake inequalities. We therefore used a synthetic control approach to investigate the impact of mobile vaccination units in the Northwest of England and how this varied by age, socioeconomic status, and ethnicity.

Methods

Data

We utilised anonymised electronic health records (EHR) on all people aged 18 and over, registered with a General Practice (GP) in Cheshire and Merseyside, England, between 22nd February and 19th July 2021.[28] This data included vaccination status, vaccination date, age, sex, ethnicity, chronic health conditions diagnosed in primary care (chronic obstructive pulmonary disease, chronic heart disease, diabetes, chronic kidney disease asthma, cancer, obesity, depression, and stroke/transient ischaemic attack), whether people were in contact with social care, whether they were a paid carer, travel time by car to the nearest conventional static vaccination site requiring booking in advance and the Lower Super Output Areas (LSOA) of residence. LSOAs are small geographical areas of England, with approximately 1500 residents each. Ethnicity was based on information of primary care records. Where unavailable, ethnicity was taken from hospital, community, or social care records if available in these datasets. Ethnicity was categorised in these datasets using the 17 standard Office for National Statistics Categories. These were then re-coded to 5 categories for analysis (White/White British, Asian/Asian British, Black/Black British, Mixed, and Other).

We linked the EHR data to LSOA-level data, including 2019's indices of multiple deprivation (IMD) – a composite measure of deprivation across seven domains (income, employment, education, health, crime, barriers to housing & services, and living environment), an over-crowded housing measure (the proportion of households with at least one-bedroom fewer than they need) based on 2011's Census, and population density using 2019's mid-year population estimates from the Office for National Statistics. The public health teams of the nine local authorities in the Cheshire and Merseyside region were asked to provide a list of locations and dates of mobile vaccination units in their areas between May and November 2021. Six local authorities provided this information and two local authorities reported that they had had no mobile vaccination units. Analysis was therefore limited to these eight local authorities.

Intervention

Six local authorities operated mobile vaccination units, that visited 37 sites on 54 occasions, between 12th April and 28th June 2021. This included 52 visits from vaccine buses and two from two pop-up static clinics (different from conventional static vaccination sites, these two pop-up sites offered walk-in services without the need to book in advance). Six sites were visited more than once during our study period, with repeated visits scheduled either consecutively or at least one week apart. Vaccines were offered typically from 9am to 4.30pm or 5pm on the day of most visits, with four visits operating from 8am to 6pm, 9am to 3pm, 9.15am to 2.30pm and 10am to 2pm respectively. We chose to treat all sites uniformly in our analysis to avoid potentially overemphasising the impact of sites with multiple visits and minimise the potential influence of site-specific factors. This simplifying assumption offers us a more conservative approach and allows us to focus on the overall effect of the intervention rather than site-specific variations, thus enabling clearer interpretation and generalisability of the results. The deployment of the mobile vaccination units also involved outreach programmes to advertise vaccination units and explain the benefits of vaccination for each visit. Units were primarily focused on offering first-dose COVID-19 vaccinations to those that had not received a vaccine at any of the city's existing conventional static vaccination sites and were eligible for vaccination at the time.[29] Vaccines were offered on a drop-in basis with no appointment needed. The number of vaccinations received at these mobile units was unavailable for one local authority (Warrington). The total number of first dose vaccinations for the remaining five local authorities that had deployed the mobile vaccination units was 3824. Sites visited by mobile vaccination units were identified by local public health and health service teams based on their knowledge of vaccine uptake (I.e., the percentage of adults who have received the first dose of the COVID-19 vaccine among the total eligible adult population in our study), practicalities of having space and permissions to locate the vaccination unit, and relationships with local community groups.

We defined intervention neighbourhoods as having their population weighted centroid located within 1km of mobile vaccination sites and identified 216 LSOAs that were either hosts for mobile vaccination units or had population weighted centroids within a 1km radius of mobile vaccination units. We calculated the start time of the intervention as the week a mobile vaccination unit first visited. This left 1112 non-intervention LSOAs within the eight participating local authorities that did not have population weighted centroids within 1km of a mobile unit. We then applied a 'placebo' start time to each of these non-intervention LSOAs, generated uniformly at random in the same weekly proportion as the distribution of intervention start dates for the intervention LSOAs.

Statistical analysis

We aggregated the individual-level data to construct a panel of weekly measures at the LSOA level from seven weeks (22nd February 2021) before the first mobile vaccination unit visit on 12th April 2021 to three weeks (19th July 2021) after the last mobile vaccination unit visit on 28th June 2021. We chose seven weeks as our pre-intervention period after evaluating trends of the accumulated uptake, overall and by ethnic and socio-economic groups, with consideration of the rollout of the vaccine prioritised by age groups (Appendix 1 and 2). A seven-week pre-intervention period allowed us to capture trends for most people eligible for the vaccine and focus on the intervention at a relatively stable stage of the pandemic. We then chose a three-week follow-up period due to the policy change in July 2021 to prioritise administrating the second doses. A three-week period avoided spill-over effect of this prioritisation and allowed us to estimate the effect of repeated visits in some sites and the accompanying outreach programmes. We therefore aimed to investigate the short-term effect of the intervention here. The weekly panel data included LSOA-level measures of total GP registered population size, the proportion of Black/Black British people, the proportion of Asian/Asian British people, the proportion of people of mixed ethnicity, mean age of residents, population density, the proportion of women, the IMD score, the proportion of households living in overcrowded housing, the average travel time by car to the nearest conventional static vaccine site, the cumulative number of first dose administered at the start of the pre-intervention period, and the number of new first dose vaccinations administered per week (Appendix 3 compares these measures between the intervention and the rest of Cheshire and Merseyside).

We apply the synthetic control method for microdata developed by Robbins et al. to estimate the effect of mobile vaccination units on vaccine uptake. Our outcome variable, weekly vaccine uptake, is the percentage of adults who have received the first dose of the COVID-19 vaccine during each week among the total eligible adult population.[30,31] The synthetic control method is a generalisation of difference-in-difference methods.[32] An untreated version of the intervention areas (i.e. a synthetic

control) is created using a weighted combination of areas that were unexposed to the intervention. The intervention effect is estimated by comparing the trend in outcomes in the intervention areas to that in the synthetic control areas following the intervention.[33]

The weights were calculated using the raking method [34] so that the weighted averages for all the variables outlined above in the synthetic control group were the same as for the intervention. This included the cumulative number of first vaccine doses administered prior to the pre-intervention period, the number of first dose vaccines administered in each of the seven weeks prior to the intervention (Appendix 4) and each local area characteristic, outlined above.[30] Appendix 5 presents the geographical distribution of these weights and illustrates how the synthetic control group is constructed. The estimated effect of the mobile vaccination unit on the weekly number of first doses, was calculated as the difference between the intervention and the (weighted) synthetic control cohorts in the weekly number of vaccines received over a three-week period after the intervention. To estimate the sampling distribution of the treatment effect, and the permuted p-values and 95% confidence intervals, we applied a permutation procedure outlined by Robbins et al. by repeating the analysis through 250 placebo permutations randomly allocating non-intervention LSOAs to the intervention group.[31]

As our area-based analysis could be biased by insufficiently accounting for confounders at the individual level, we additionally conducted analysis using individual-level data on all adults registered with the GP and living in the intervention and non-intervention LSOAs (as defined above), who had been unvaccinated before the mobile vaccination unit first visited their neighbourhood. We used a weighted Poisson regression model with robust sandwich variance estimators, which has been shown to be a valid alternative to the logistic regression model for the analysis of binary outcomes,[35,36] to estimate the relative risk of vaccination by comparing the vaccine rates between these two groups in the three weeks following the intervention. Using a weighted Poisson regression model to estimate this effect without considering the differences between the intervention and non-intervention areas on the aggregate level would potentially underestimate standard errors and p-values, as this would not account for complex aspects of the process used to generate the synthetic control weights for LSOAs. We therefore weighted this regression using the synthetic control weights as highlighted above to account for systematic LSOA-level differences, after additionally controlling for the following individual-level potential confounders: age, sex, ethnicity, health conditions (as defined above), whether people were in contact with social care, whether they were paid carers and the travel time by car from each person's address to the nearest conventional static vaccination centre. 18.62% and 0.01% of ethnicity and sex were missing respectively, leaving 233278 records for the main complete case analysis.

To explore whether the mobile vaccination unit effect differed by deprivation, ethnicity, and age, we fitted another weighted Poisson model including interaction terms between the intervention indicator (mobile vaccination unit) and IMD tercile within Cheshire and Merseyside, ethnic group, and age group respectively (see Appendix 6 and 7 for detailed results). Apart from the sensitivity test of excluding ethnicity (Appendix 8) and the two pop-up sites (Appendix 9) from the analysis to assess the potential impact of the missing data and two pop-up static sites on our results respectively, we have additionally conducted a series of sensitivity tests on the dose effect of distance threshold used to construct the intervention and non-intervention areas (Appendix 10), the potential spatial spill-over effect of the intervention (Appendix 11), and survival analyses (Appendix 12) to further check the robustness of our results.

Patient and public involvement

The local authorities delivering the intervention engaged with various community groups in promoting the intervention and identifying intervention sites. Patients and the public were, however, not directly involved in designing this analysis.

Results

Figure 1 shows the intervention (yellow) and the non-intervention areas (purple). The red and cyan dots represent the mobile and pop-up static vaccination sites respectively. The map in Appendix 5 shows the weights that were applied to the non-intervention areas to construct the synthetic control.

Figure 1 is about here

Table 1 presents summary statistics for the intervention and non-intervention areas (see Appendix 3 for the comparison between the intervention and the rest of Cheshire and Merseyside). The average vaccination rate of the first dose was much higher in the non-intervention areas before the introduction of the intervention. On average, residents of the non-intervention areas had to travel slightly longer to get to the nearest conventional static vaccine site. The intervention areas were younger and more deprived, and had a higher proportion of overcrowded households, higher proportions of Asian/Asian British and Black/Black British ethnic minority groups, and higher population density. There were no differences in terms of the proportion of mixed ethnicity. As the matching algorithm achieved an exact match, the *weighted* average of each variable in Table 1 was identical in the synthetic control to those in the intervention areas.

Table 1. The summary statistics for the intervention and non-intervention areas at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

	Non-intervention areas	Intervention areas
Total population	1495582	338006
% women	50.84	48.92
Population density – people per hectare	38.84	65.11
Mean age	42.71	38.03
% Asian/Asian British	1.10	3.28
% Black/Black British	0.52	2.37
% Mixed people	1.48	1.87
IMD score[1]	28.71	40.38
% households with at least one-bedroom fewer than they need	2.69	4.77
Average travel time by car to the nearest conventional static vaccine site - minutes	4.14	2.83
First dose vaccine uptake among adults (the percentage of adults who have received the first dose of COVID-19 vaccine among the total eligible adult population prior to pre-intervention) (%)	69.28	52.65
Average weekly first dose vaccination rate among adults in the 7 weeks prior to intervention (%)	1.85	1.51
Number of LSOAs	1112	216

Note[1]: We primarily used the IMD score in our main model 1 and 2 in the following analysis. We then sorted the IMD score in ascending order and divided it into three equal parts to facilitate our subgroup analysis by level of deprivation.

Figure 2 shows the trend in weekly vaccination rate in the intervention and synthetic control areas, during a 11-week period (seven weeks before and three weeks after the introduction of the mobile vaccination unit). For the pre-intervention period, trends were indistinguishable, as the synthetic control algorithm has achieved an exact match by successfully calibrating the weights. From the time point of the intervention being introduced, weekly vaccination rates increased from 1.5% to 1.9% in the intervention areas. Trends in the matched synthetic control areas that were not visited by a mobile vaccination unit remained fairly flat, with a small decrease in the post-intervention period. From two weeks post intervention, 95% CIs stopped overlapping.

Figure 2 is about here

Table 2 shows the estimated effect of the mobile vaccination units on weekly vaccination rate, the percentage of adults who have received the first dose of the COVID-19 vaccine in each week among the total eligible adult population, using two models based on area-level and individual-level data respectively. The two analyses show similar results. The area-based analysis indicates that vaccination rates in the neighbourhoods visited by mobile vaccination units were 23% higher in the three weeks

after the first visit, compared to what would have been the case without the mobile vaccination units' visits (RR = 1.23, 95% CI: 1.11 to 1.36). The relative risks adjusted for individual-level characteristics is slightly higher than that of the area-based model (RR = 1.25, 95% CI: 1.21 to 1.28). This overall effect size estimates 3723 additional vaccinations over three weeks of follow-up across the study area, similar to the actual number of people vaccinated in the mobile units (n=3824). Sensitivity tests excluding ethnicity and the two pop-up sites showed similar results with those of model 2 (see Appendix 8 and 9 respectively). Whilst sensitivity tests on the distance threshold demonstrated the spatially sensitive nature of our analysis (Appendix 10), our results are relatively robust against the spatial spill-over effect once an appropriate distance threshold was chosen (Appendix 11).

Table 2. Estimated effect of mobile vaccination units on weekly vaccination rate (the percentage of adults who have received the first dose of the COVID-19 vaccine in each week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1 uses LSOA level data, accounting for area-based differences between intervention and non-intervention areas, with permuted p-values and confidence intervals. Whilst model 2 additionally controls for individual differences between intervention and non-intervention groups.

	RR	95% CI		p-value
		LCL	UCL	
Model 1. LSOA level synthetic control analysis	1.23	1.11	1.36	<0.001
Model 2. Individual level weighted Poisson regression analysis	1.25	1.21	1.28	<0.001

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

We used interaction analyses to investigate if the intervention effect was modified by deprivation, ethnicity, and age (see Appendix 6). We found a significant interaction between deprivation and the intervention indicating reduced effectiveness with increased deprivation (p<0.001), a significant interaction with ethnicity indicating reduced effectiveness for Asian/Asian British (p=0.006), Black/Black British (p=0.005) or other ethnic groups (p=0.010), compared to White/White British people, and a significant interaction with age indicating reduced effectiveness in older age groups. The combination of these interaction effects means that in many groups defined by age, ethnicity, and deprivation there was no evidence of effectiveness (see Figure 3).

Figure 3 is about here

Figure 3 shows estimated effect of mobile vaccination units on weekly vaccine uptake for all the subgroups using the combination of the effect in the reference group (18–30–year–olds of white ethnicity living in the least deprived neighbourhoods that were visited by the mobile vaccination unit) and the interaction terms for deprivation, ethnicity, and age group. The relative effect of the intervention for the reference group is shown in the bottom left cell of Figure 3, indicating that the intervention increased vaccine uptake by 68% (RR 1.68) for 18–30–year–olds of white ethnicity living in the least deprived neighbourhoods and having received the intervention relative to people of the same age group, ethnicity, living in neighbourhoods of the same deprivation level but without the intervention. For people of same ethnic and age group but living in intermediately deprived areas, the effect was slightly larger (RR 1.82, 82% increase; calculated as the combination of the effect on the reference group and the interaction term for intermediate deprivation with mobile vaccination units: 1.683*1.081=1.82; see Appendix 6), whilst for those living in the most deprived areas it was lower (RR 1.30, 30% increase; calculated as 1.683*0.770 in the same manner as above). Effects of other subgroups could be interpreted in the same way. Due to the small sample sizes of these 45 subgroups (see Appendix 7), these results should be treated with caution. However, they indicate the likely pattern of effects of the intervention across these groups. Overall, White, 18–30–year–olds living in neighbourhoods of intermediated deprivation appeared to benefit the most from visits of the mobile vaccination unit (Figure 3). Effects were lowest for older age groups in the most deprived areas. Although the effect of the mobile vaccination unit may be lower for the most deprived population and for people from Black, Asian, and other ethnic minority groups, the mobile vaccination unit does still appear to have increased uptake in these groups for younger people, whilst we find no evidence of a positive effect for most older age groups from Black, Asian, and other ethnic minority groups, particularly in deprived areas. The survival analysis showed similar results overall (Appendix 12).

Discussion

Our study presents much-needed empirical evidence of the effectiveness of mobile vaccination units in promoting COVID-19 vaccination, indicating that they can increase uptake in their targeted neighbourhoods. The effect size estimated in our analysis closely corresponds to the actual number, indicating that a significant proportion of vaccinations conducted in the mobile units were additional. Put simply, our findings suggest that among individuals utilising the mobile vaccination units, there was a minimal number who would have otherwise sought their vaccinations at conventional static centres. This implies that the mobile vaccination units effectively reached individuals who may have faced barriers in accessing conventional static vaccination sites. Our study therefore also lends support to previous studies on other forms of preventative care that mobile units are useful tools in improving geographical accessibility and convenience of services for patients.[12–15]

Within those neighbourhoods, however, the intervention tended to increase uptake most amongst younger people, white people and less socioeconomically deprived areas. However, the targeted neighbourhoods were the most deprived. Our analysis indicated that the intervention was similarly effective in the least deprived and intermediate levels of deprivation *within* these targeted neighbourhoods. It is only in areas with IMD score of over 53, the lower bound of the most deprived, that the effectiveness declined. However, 53 is at the 95th percentile of the national distribution of IMD scores, representing very deprived areas nationwide. Our findings indicate therefore that the intervention was effective at increasing uptake amongst young people in relatively deprived areas (although not in extremely deprived areas) and across young people from all ethnic groups in these areas.

Our study has limitations. We only had data on individuals who had been registered with the GP at time of our study. The GP registered population is larger than that of the 2021 Census (2.7 million vs. 2.5 million people) due to known data issues (e.g., delays in people updating addresses when move home, different definitions of resident population). Although unregistered people attending for mobile units were encouraged and can register with a GP in their attendance, there may have been people vaccinated who did not wish to be registered, such as undocumented immigrants, homeless populations, travellers, and displaced people. We were unable to estimate the impact of the intervention in these groups. The mobile vaccination unit could have increased uptake due to improved accessibility through the mobile vaccination unit itself and/or the awareness raising and publicity associated with visits of these units. Our analysis cannot distinguish between these effects.

Our analysis covers a relatively short period of follow-up. We are therefore unable to determine whether the observed effect is due to people being vaccinated earlier than they would otherwise have been or if they would have never taken up vaccine without the intervention. We could link approximate but not exact time/date visits of the mobile units. Further research should look to evaluate if mobile units had different effects at different stages of a pandemic (e.g., initial roll out compared to re-opening of society or once most people have been vaccinated by traditional means). We used a measure of average distance to construct the intervention and non-intervention group, which would have made our effect estimate more conservative (see Appendix 11) and more sensitive to the choice of threshold (Appendix 10). Selecting an appropriate distance threshold is difficult, suggesting the need to evaluate how distance might impact the delivery and impact of mobile interventions. This not only reflects the geographical nature of the intervention but indicates the potential benefit of improving the data quality for the distance measurement in future research. Although we have accounted for observed differences between places visited by the mobile

vaccination units and those not and differences in individual characteristics, it is still possible that unmeasured confounding could bias the results.

Conclusion

Our study has implications for strategies aiming to increase vaccine uptake. By improving geographic accessibility and convenience of services, the mobile vaccination unit likely promoted uptake of the first dose of the COVID-19 vaccine in our study population. The evidence indicating greater effects in less deprived areas and in the White/White British population raises concerns that the intervention could however lead to an increase in inequalities in uptake within targeted areas. It is important to ensure the mobile vaccination units are effectively targeted to the communities with low uptake and combined with comprehensive engagement and outreach with Black and Asian ethnic groups and with more socioeconomically disadvantaged communities. With successive SARS-CoV-2 variants and the need for multiple vaccine doses to achieve sufficient immunity, rapidly increasing uptake and reducing inequalities in uptake was of critical public health importance. Deployment of mobile units alongside other effective approaches to increase uptake in disadvantaged groups can contribute to this goal.

Transparency statement

The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned (and, if relevant, registered) have been explained.

Author contribution statement

B.B. conceived the original idea, devised the project, the main conceptual ideas and proof outline. X.Z. contributed to the literature review, collected the data, and carried out the data analysis. R.A. conducted the initial literature review. X.Z. drafted the manuscript and designed the figures with support from B.B. and M.G.. J.T., S.K. and P.P. assisted with the data access and commented on the manuscript. R.P. assisted in coding. M.GF and M.G. aided in commenting on the manuscript. I.B. aided in supervising the project and commented on the manuscript. S.B. helped to improve the language and visualisation. All authors provided critical feedback and helped to shape the research manuscript.

Conflicts of interest statement

We have no conflicts of interest to disclose.

Ethics statements

Patient consent for publication

Not required.

Ethics approval

University Research Ethics Committee review is not required by the University of Liverpool for the secondary analysis of data which have been anonymised by an external party and are provided to the research team in a fully anonymised format.

Data sharing statement

The individual-level data is sensitive and could not be shared. But statistical codes are available from https://github.com/civicdatacoop/mobileVaxUnit.

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Figure 1. Location of the 35 eligible mobile vaccination units (red dots), the two static pop-up sites (cyan dots), and the non-intervention (purple) and intervention (yellow) areas across Cheshire and Merseyside. The sub-map in the box of the top right shows the location of Cheshire and Merseyside in England.

Figure 2. The trend in the weekly vaccination rate with their 95% confidence intervals in the intervention and synthetic control areas.

Figure 3. Heatmap of the estimated impact of the mobile vaccination units upon weekly number of first dose COVID-19 vaccines administered among all the subgroups based on interaction analysis.

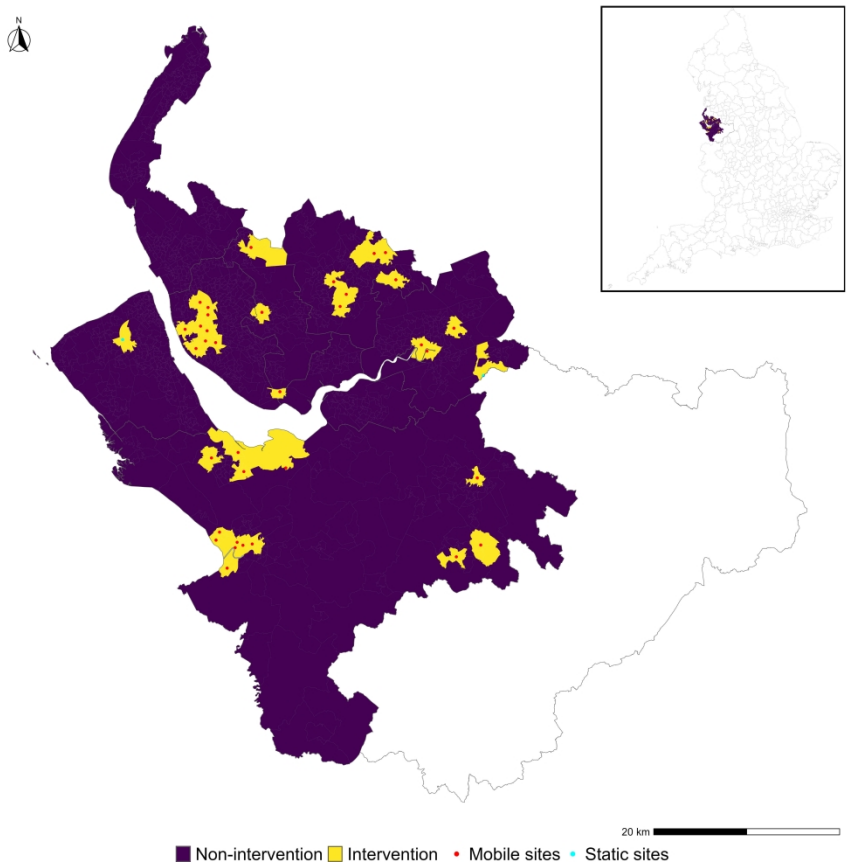

Figure 1. Location of the 35 eligible mobile vaccination units (red dots), the two static pop-up sites (cyan dots), and the non-intervention (purple) and intervention (yellow) areas across Cheshire and Merseyside. The sub-map in the box of the top right shows the location of Cheshire and Merseyside in England

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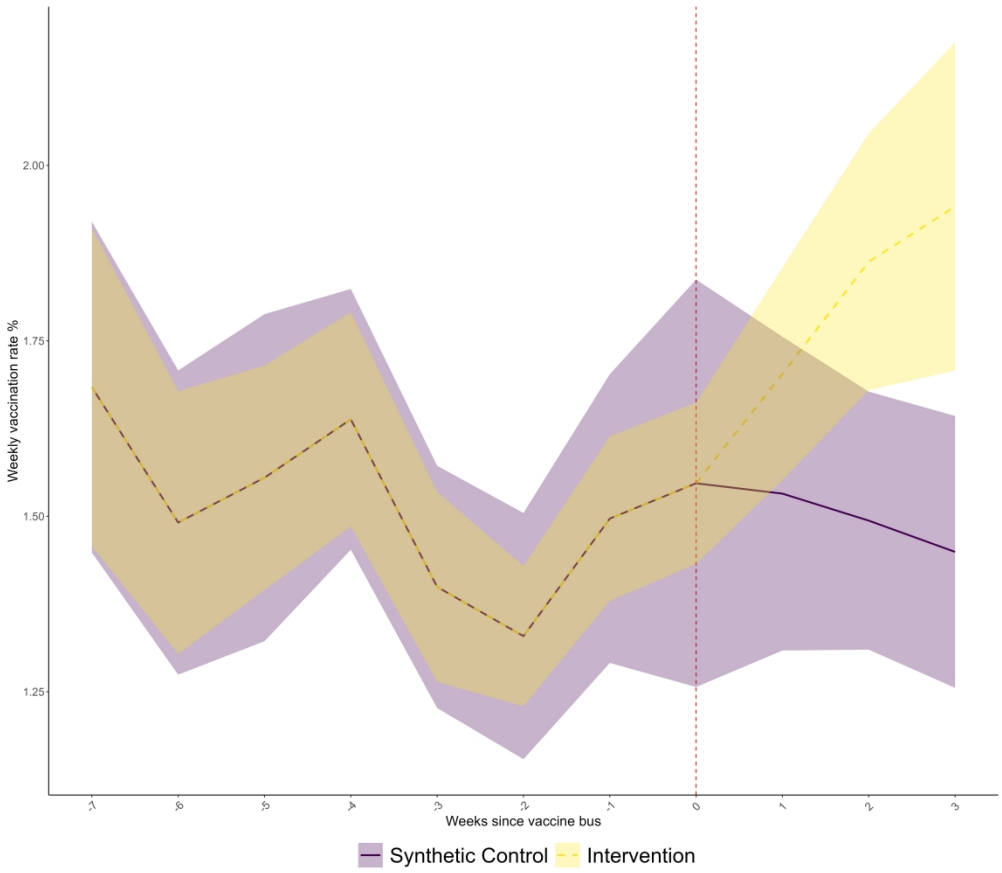

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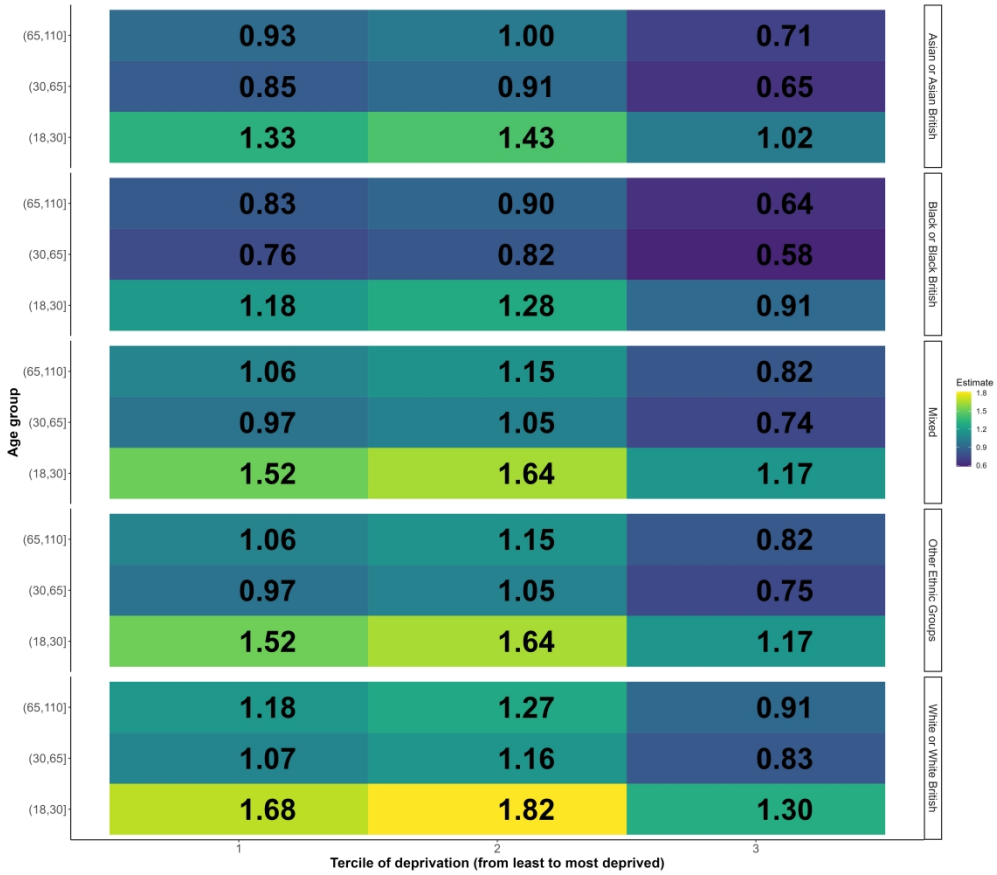

Figure 3. Heatmap of the estimated impact of the mobile vaccination units upon weekly number of first dose COVID-19 vaccines administered among all the subgroups based on interaction analysis.

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Appendices

Appendix 1. Timeline of the age eligibility for the rollout of the COVID-19 vaccine programme for the first dose in England.

Table A1. The availability of vaccine appointments for the first dose of COVID-19 vaccine in England, by date.

Start date	Appointments available for
8 December 2020	Residents in a care home for older adults and their carers; and all aged 80 and over
Procedures set out on 9 and 14 January 2021	Frontline health and social care workers
18 January 2021	All aged 70 and over, and clinically extremely vulnerable individuals
15 February 2021	All aged 65 and over; and those aged 16 to 64 with underlying health conditions which put them at higher risk of serious disease and mortality
1 March 2021	All aged 60 and over
6 March 2021	All aged 56 and over
17 March 2021	All aged 50 and over
13 April 2021	All aged 45 and over
26 April 2021	All aged 44 and over
27 April 2021	All aged 42 and over
30 April 2021	All aged 40 and over
13 May 2021	All aged 38 and over
18 May 2021	All aged 36 and over
20 May 2021	All aged 34 and over
22 May 2021	All aged 32 and over
26 May 2021	All aged 30 and over
8 June 2021	All aged 25 and over
15 June 2021	All aged 23 and over
16 June 2021	All aged 21 and over
18 June 2021	All adults (namely aged 18 and over)

Source: COVID-19 vaccination in the United Kingdom - Wikipedia.

Appendix 2. Crude and age-adjusted accumulated uptake of the COVID-19 vaccine first dose in Cheshire and Merseyside between the 49th week of 2020 (6th to 12th December 2020; the first COVID-19 vaccine was administered in the UK on 8th December 2020) and the 29th week of 2021 (18th to 24th July 2021; the end point of our study is 19th July 2021, three weeks after the last mobile vaccination unit visit on 28th June 2021).

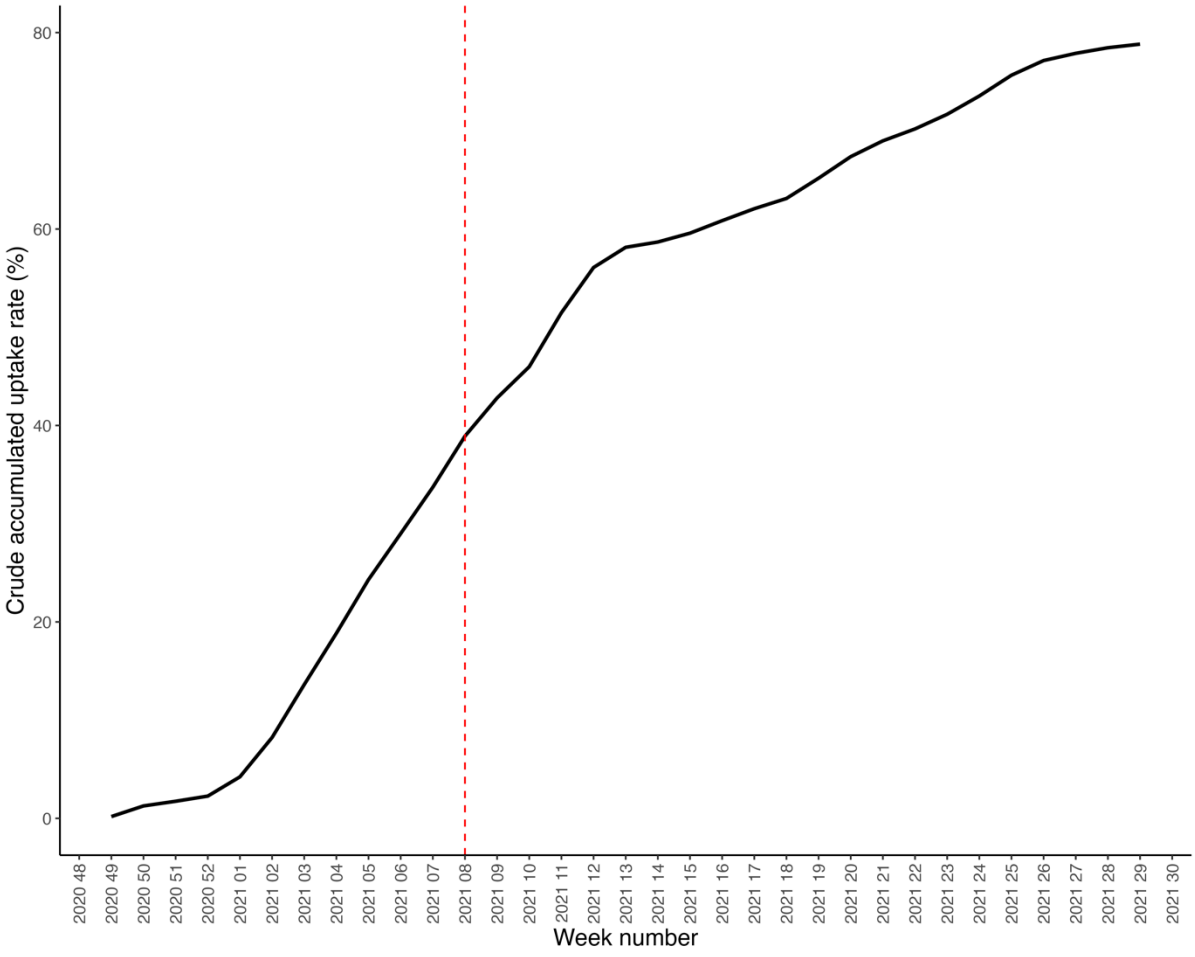


Figure A1. Crude accumulated uptake rate of the first dose COVID-19 vaccine across Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021, the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). After a relatively linear and stable growth between the 1st and 7th week of 2021, Cheshire and Merseyside started to see signs of slowing down in the crude uptake rate since the 8th week of 2021 (21st to 27th February 2021).

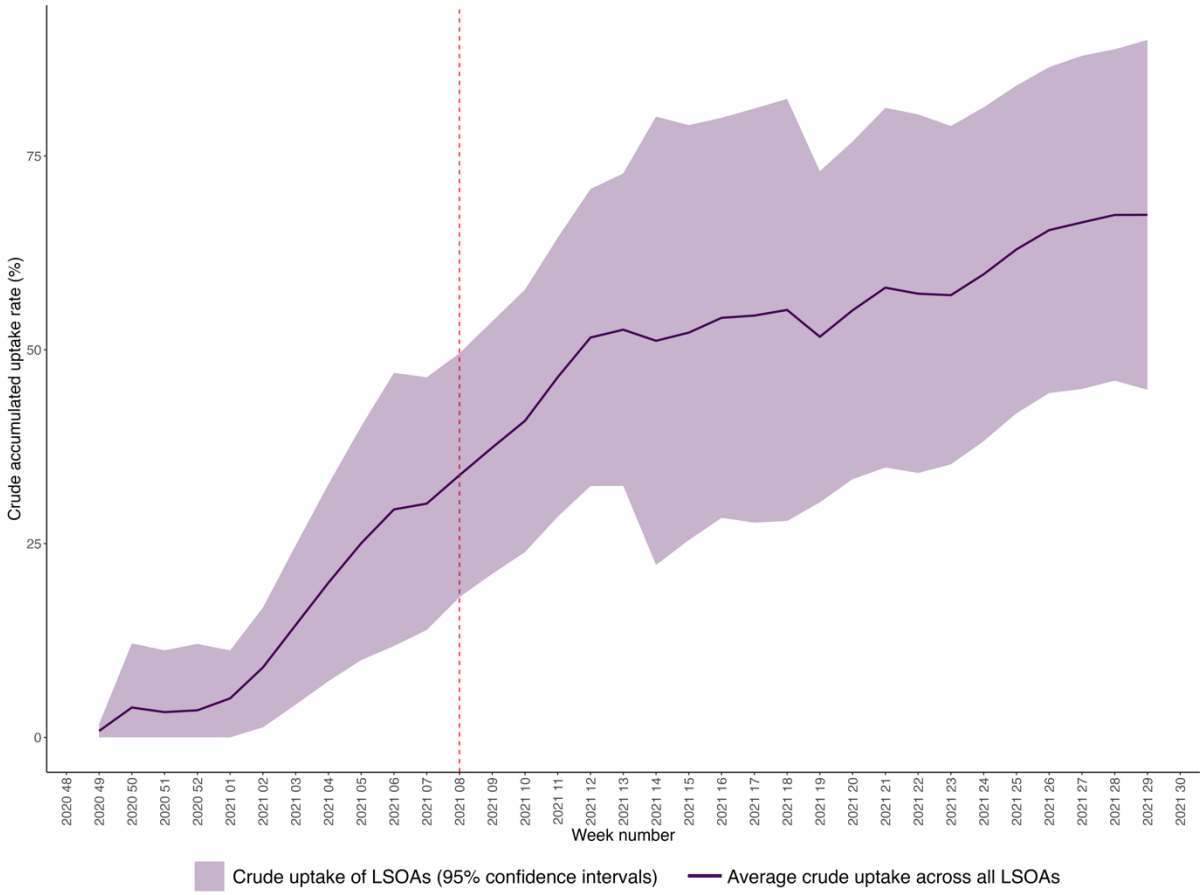
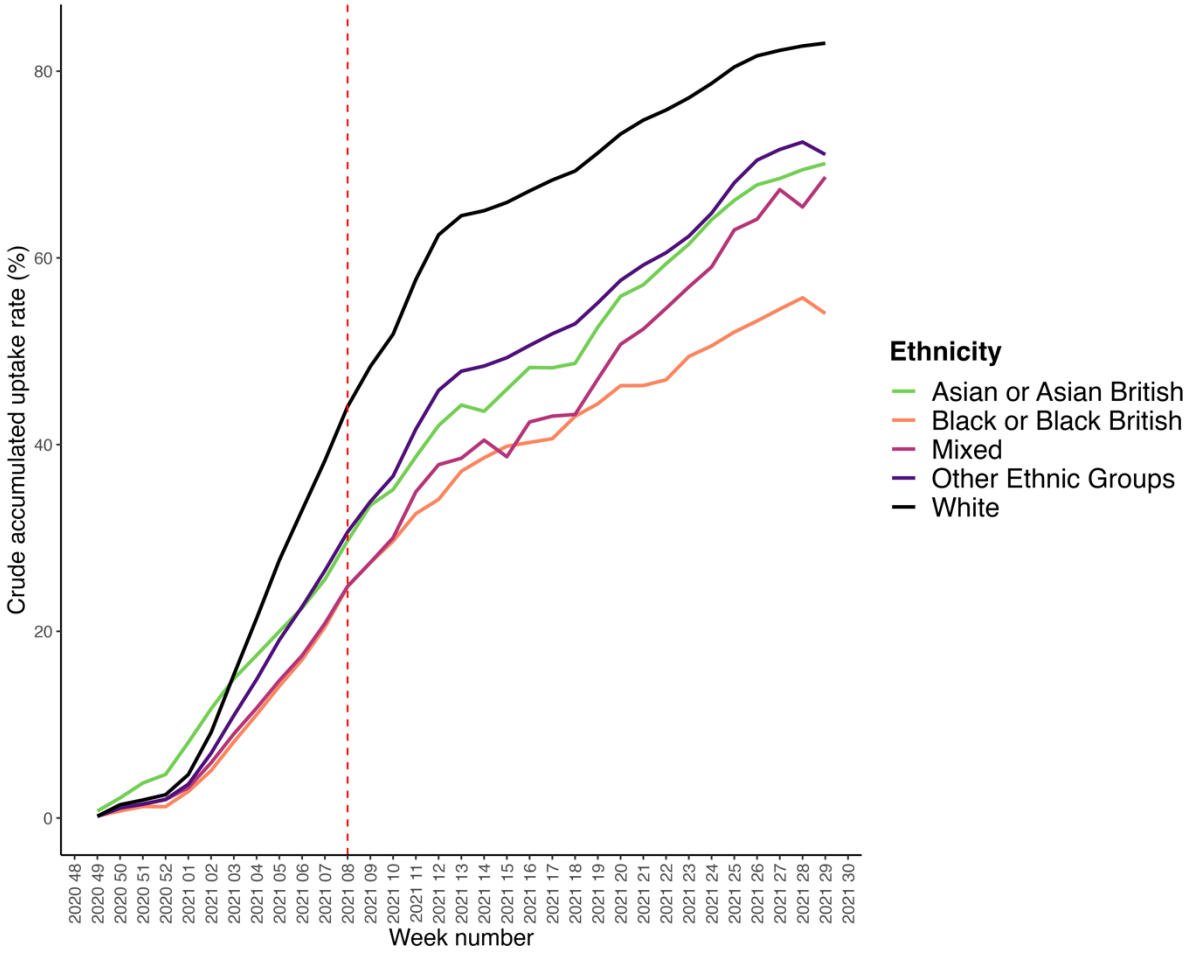
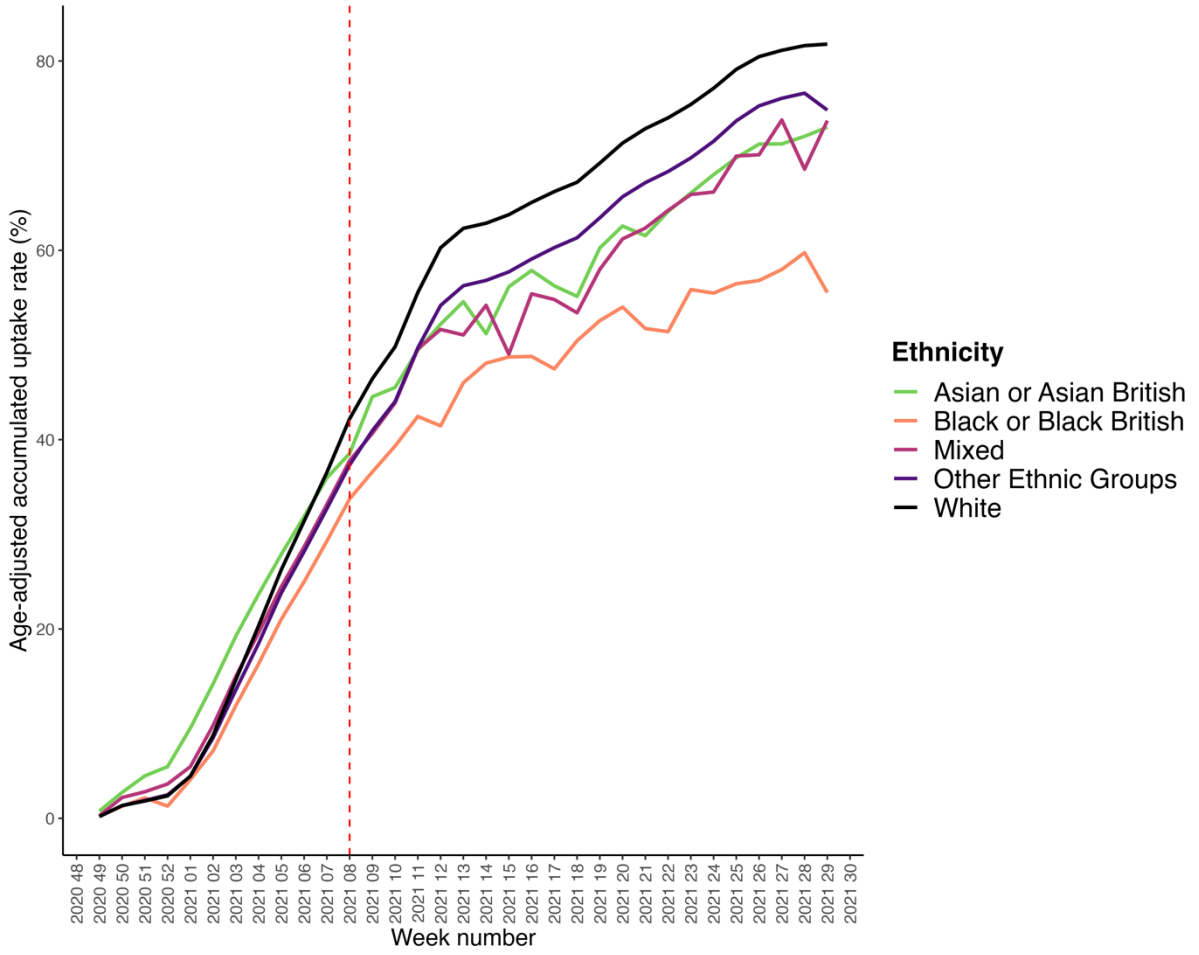


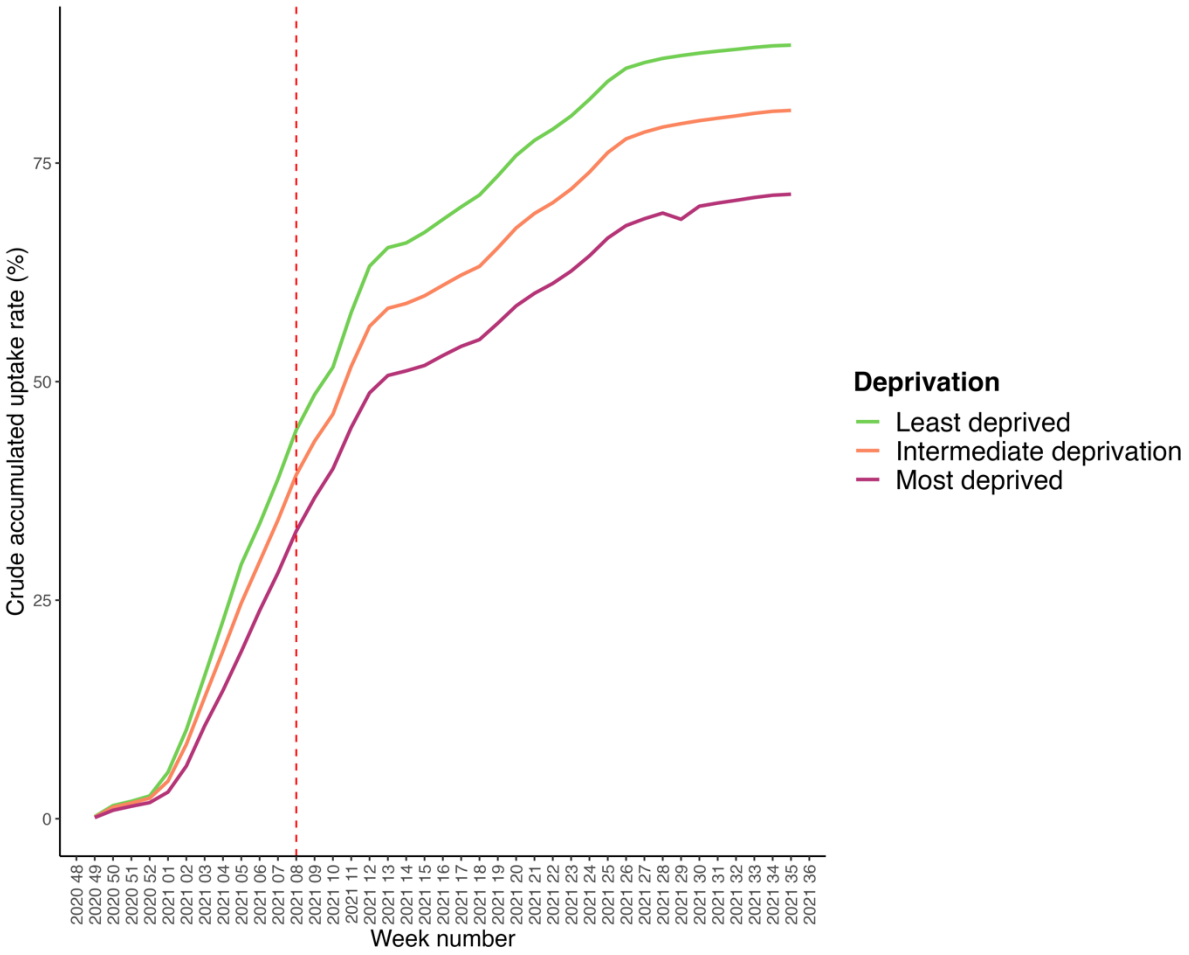
Figure A2. Average crude accumulated uptake rate of the first dose COVID-19 vaccine across all lower layer super-output areas (LSOAs) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021, with its 95% confidence intervals. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), LSOAs of Cheshire and Merseyside had seen expanding variations in their crude accumulated uptake of the first dose COVID-19 vaccine.



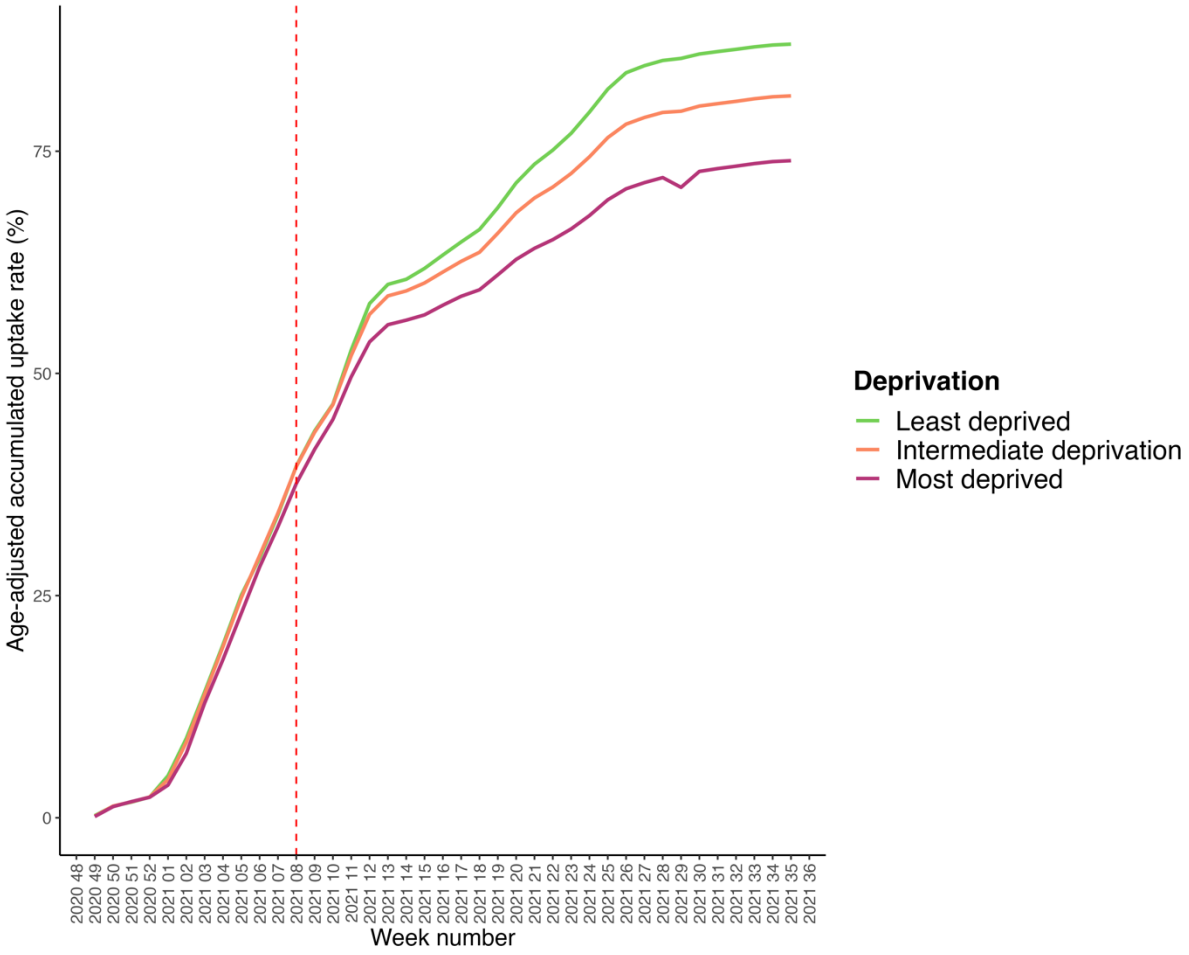
A3. Crude accumulated uptake rate of the first dose COVID-19 vaccine among ethnic groups (White, Asian or Asian British, Black or Black British, Mixed, and Other) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), ethnic groups of Cheshire and Merseyside had seen widening gaps in their crude accumulated uptake of the first dose COVID-19 vaccine.



A4. Age-adjusted accumulated uptake rate of the first dose COVID-19 vaccine among ethnic groups (White, Asian or Asian British, Black or Black British, Mixed, and Other) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). The 8th week of 2021 (21st to 27th February 2021), as a turning point, had become pronounced for widening gaps in age-adjusted accumulated uptake of the first dose COVID-19 vaccine among ethnic groups in Cheshire and Merseyside.



A5. Crude accumulated uptake rate of the first dose COVID-19 vaccine among different socio-economic groups (Least deprived, Intermediate deprivation, and Most deprived) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), different socio-economic groups of Cheshire and Merseyside had seen increasingly growing gaps in their crude accumulated uptake of the first dose COVID-19 vaccine.



A6. Age-adjusted accumulated uptake rate of the first dose COVID-19 vaccine among different socio-economic groups (Least deprived, Intermediate deprivation, and Most deprived) in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021 (within the 8th week of 2021), the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021). Since the 8th week of 2021 (21st to 27th February 2021), different socio-economic groups of Cheshire and Merseyside had seen signs of widening gaps in their age-adjusted accumulated uptake of the first dose COVID-19 vaccine.

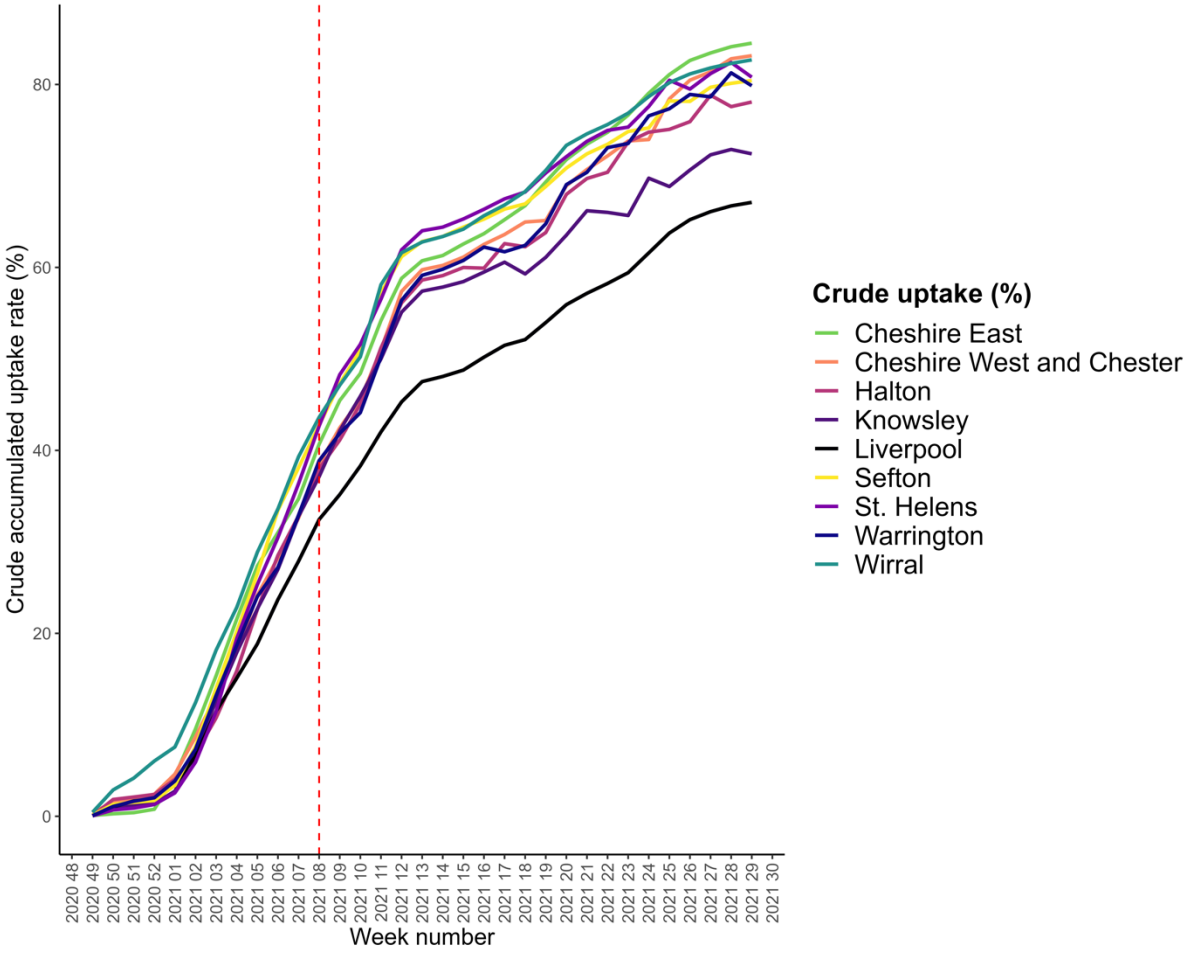


Figure A7. Crude accumulated uptake rate of the first dose COVID-19 vaccine by local authorities in Cheshire and Merseyside between the 49th week of 2020 and the 29th week of 2021. The dashed red vertical line represented the date of 22nd February 2021, the starting point of our study (seven weeks before the first mobile vaccination unit visit on 12th April 2021).

Appendix 3. Summary statistics of the intervention and full non-intervention population at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

Whilst Table 1 presents summary statistics for the intervention and non-intervention areas within the eight local authorities that reported data on the deployment (or non-deployment) of the mobile vaccination units and therefore are used to conduct the main analysis, Table A2 below shows the comparison between the intervention and the rest of the Cheshire and Merseyside, including the eight local authorities above and the one local authority with missing data on the intervention that has been excluded from the main analysis.

Table A2. The comparison between the intervention and the rest of Cheshire and Merseyside at the intervention onset in the 7 weeks prior to the introduction of the mobile vaccination unit.

	Rest of the Cheshire and Merseyside region	Intervention areas
Total population	1829809	338006
% women	50.72	48.92
Population density – people per hectare	34.88	65.11
Mean age	42.72	38.03
% Asian/Asian British	1.20	3.28
% Black/Black British	0.52	2.37
% Mixed people	1.39	1.87
IMD score	25.83	40.38
% households with at least one-bedroom fewer than they need	2.55	4.77
Average travel time by car to the nearest conventional static vaccine site - minutes	4.28	2.83
First dose vaccine uptake among adults (the percentage of adults who have received the first dose of COVID-19 vaccine among the total eligible adult population prior to pre-intervention) (%)	66.15	52.65

Average weekly first dose vaccination rate among adults in the 7 weeks prior to intervention (%)	2.08	1.51
Number of LSOAs	1346	216

Appendix 4. The weekly number of the first dose administered in the intervention and control groups for each of the seven weeks prior to the intervention (the mobile vaccination unit).

Table A3. Weekly number of the first dose administered in the intervention and control groups for each of the seven weeks prior to the intervention (the mobile vaccination unit).

Weeks before the intervention	Weekly number of the first dose administered in the LSOAs being visited by the mobile vaccination units	Weekly number of the first dose administered in the LSOAs in the rest of Cheshire & Merseyside used to construct the synthetic control	Weekly number of the first dose administered in the synthetic control (weighting LSOAs in the rest of Cheshire & Merseyside using synthetic control weights)
7	5692	31995	5692
6	5040	29288	5040
5	5256	31869	5256
4	5537	33022	5537
3	4730	24901	4730
2	4493	21180	4493
1	5059	21685	5059

Appendix 5. Geographical pattern of weights in area-based synthetic control analysis.

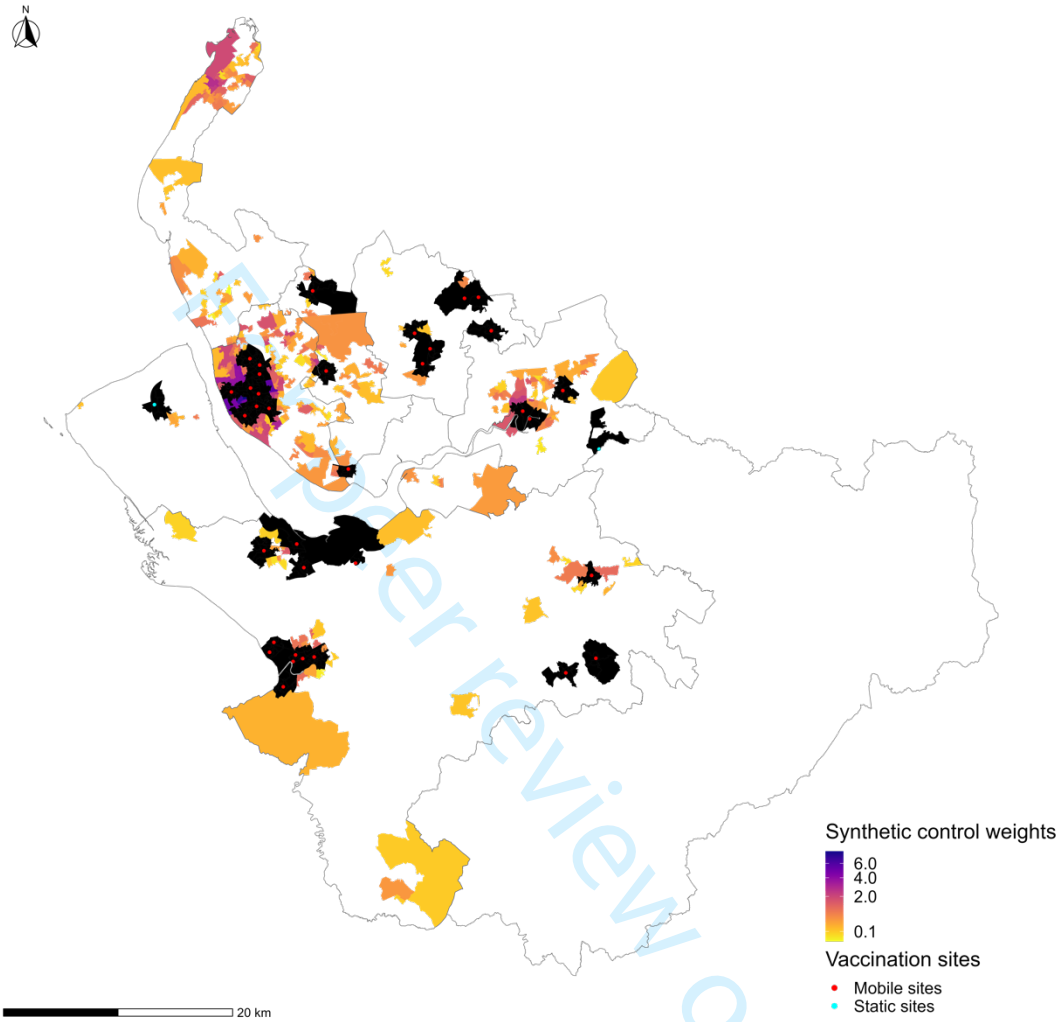


Figure A8. Weighting of areas outside of the catchment of the mobile vaccination units to construct the synthetic control group. Areas within the catchment of the mobile vaccination units are coloured black, whilst locations of the mobile vaccination unit are represented by red (35 mobile sites) and cyan (two static pop-up sites) dots. The white non-intervention areas are those that have been allocated zero weights in constructing the synthetic control, whilst other coloured non-intervention areas are those with non-zero weights in constructing the synthetic control: the darker the colour, the larger the weight.

Appendix 6. Regression output for the interaction model based on adult individuals.

Subgroup analysis by deprivation, ethnicity and age indicates, lower impact of the mobile vaccination unit on vaccination uptake for the most deprived areas compared to more affluent areas, a lower impact for Asian/Asian British, Black/Black British or Other ethnic groups, compared to white British people, and a lower impact on people aged 31-65-year-olds. The sample sizes are quite low for the subgroup analysis (see Appendix 7 below for more details) so the results reported here are only indicative of the overall pattern. Table A4 below shows the effect sizes of the mobile vaccination unit for the subgroups as relative risks. Compared to people not visited by the mobile vaccination units in their neighbourhoods, visits of the mobile vaccination units have increased vaccination rates in the following groups: people aged 18-30 from all socio-economic backgrounds and all ethnic groups except for Black/Black British; White/White British people aged above 30 from least and intermediate deprived areas; people aged 30-65 of mixed and other ethnic groups from the intermediate deprived areas; and people aged above 65 of mixed and other ethnic groups from least and intermediate deprived areas (see Figure 3 in the main text for more details).

Table A4. Regression output with interaction terms based on adult individuals. The table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention.

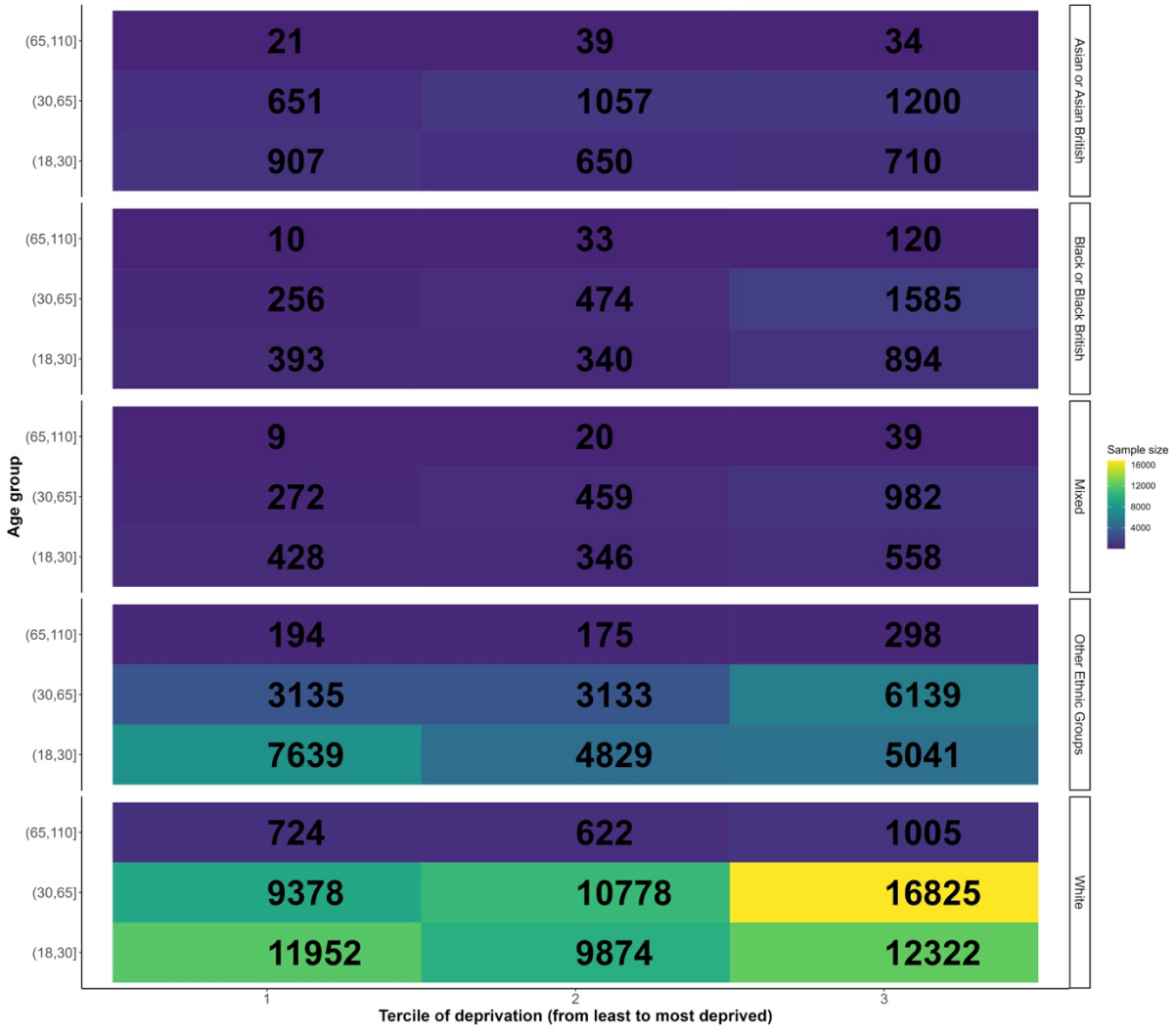
Variables	RR	95% CI		p-value
		LCL	UCL	
Mobile vaccination unit (reference: no mobile vaccination unit)	1.683	1.584	1.789	<0.001
Age group (reference: 18-30 years old)				
(30,65]	1.249	1.187	1.313	<0.001
65+	0.201	0.147	0.275	<0.001
Sex (reference: Women)				
Men	1.013	0.984	1.042	0.380
Ethnicity (reference: White/White British)				
Asian/Asian British	0.919	0.791	1.068	0.271
Black/Black British	0.749	0.605	0.929	0.008
Mixed	0.746	0.608	0.915	0.005
Other ethnic groups	0.799	0.746	0.856	<0.001
IMD tercile (reference: Least deprived)				
Intermediate deprivation	0.786	0.741	0.834	<0.001
Most deprived areas	0.673	0.631	0.718	<0.001
Chronic health conditions (reference: none)	1.098	1.076	1.120	<0.001
Carer (reference: not carer)	0.320	0.273	0.375	<0.001
Social care receiver (reference: not social care receiver)	0.979	0.764	1.255	0.869
Travel time by car to the nearest static vaccine centre (minutes)	1.087	1.082	1.093	<0.001
Interaction between age groups and mobile vaccination unit (reference: 18-30 years old with mobile vaccination unit)				
31-65 years old with mobile vaccination unit	0.638	0.602	0.676	<0.001
65+ years old with mobile vaccination unit	0.700	0.475	1.030	0.070
Interaction between ethnicity and mobile vaccination unit (reference: White/White British with mobile vaccination unit)				
Asian/Asian British with mobile vaccination unit	0.788	0.664	0.935	0.006
Black/Black British with mobile vaccination unit	0.704	0.550	0.901	0.005

Mixed with mobile vaccination unit	0.900	0.712	1.138	0.379
Other ethnic groups with mobile vaccination unit	0.903	0.835	0.976	0.010
Interaction between IMD tercile and mobile vaccination unit (reference: Least deprived with mobile vaccination unit)				
Intermediate deprivation with mobile vaccination unit	1.081	1.010	1.158	0.024
Most deprived areas with mobile vaccination unit	0.770	0.715	0.829	<0.001

Note: The intercept is excluded from the output. We reported the result in three decimal digits specifically here to facilitate the explanation on how to interpret interaction terms.

Appendix 7. Sample size of the sub-groups (with visits of the mobile vaccination units) in the weighted Poisson model including interaction terms between the intervention indicator (mobile vaccination unit) and IMD tercile within Cheshire and Merseyside, ethnic and age groups respectively.

Figure A10. Heatmap of the sample size for each subgroup receiving the visit of the mobile vaccination units based on interaction analysis.



Appendix 8. Sensitivity test – excluding ethnicity from the main model.

Table A5. Results of analysis for adult individuals of all ages, excluding ethnicity.

	RR	95% CI		p-value
		LCL	UCL	
Model 2a. Individual level weighted Poisson regression analysis	1.24	1.21	1.28	<0.001

Results of individual-level analysis presented in Table A5 and Table 2 are almost identical, implying that excluding cases with missing information on ethnicity did not affect the robustness of our results.

Appendix 9. Sensitivity test – excluding the two pop-up sites across C&M.

Table A6. Results of analysis for adult individuals of all ages, excluding the two pop-up sites.

	RR	95% CI		p-value
		LCL	UCL	
Model 2b. Individual level weighted Poisson regression analysis	1.23	1.18	1.29	<0.001

Table A6 of individual-level analysis shows very similar results to those of Table 2, indicating that it is unlikely that the use of the two pop-up sites rather than vaccine buses alone influenced our results overall.

Appendix 10. Sensitivity test – results of the synthetic control method based on different distance thresholds in constructing the synthetic control.

Table A7. Estimated effect of mobile vaccination units on weekly vaccine uptake (the percentage of adults who have received the first dose of the COVID-19 vaccine in a given week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1a uses the 500 meter distance threshold to construct the intervention and non-intervention areas with LSOA level data, accounting for area-based differences between intervention and non-intervention areas, with permuted p-values and confidence intervals. Model 1b, 1c and 1d use the distance threshold of 1, 2 and 3KM respectively, all else equal.

	RR	95% CI		p-value
		LCL	UCL	
Model 1a. LSOA level synthetic control analysis – 500-meter threshold	1.10	-1.04	1.30	0.208
Model 1b. LSOA level synthetic control analysis – 1500-meter threshold	1.15	1.04	1.26	<0.001
Model 1c. LSOA level synthetic control analysis – 2000-meter threshold	1.05	-1.04	1.17	0.280
Model 1d. LSOA level synthetic control analysis – 3000-meter threshold	1.02	-1.12	1.19	0.888

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Appendix 11. Sensitivity test – results of the synthetic control method excluding LSOAs with centroids located between 1 to 1.5 km from the nearest mobile vaccination unit to account for the potential spatial spill over effect.

Table A8. Estimated effect of mobile vaccination units on weekly vaccine uptake (the percentage of adults who have received the first dose of the COVID-19 vaccine in a given week among the total eligible adult population), the table shows the relative risks indicating the estimated ratio of vaccine rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention. Model 1e uses the same distance threshold (1 km) as the main model 1 to construct the intervention and non-intervention areas with LSOA level data, but excludes LSOAs with population weighted centroids located between 1 and 1.5km from the nearest mobile vaccination unit to additionally account for the potential spatial spill over effect, with permuted p-values and confidence intervals.

	RR	95% CI		p-value
		LCL	UCL	
Model 1e. LSOA level synthetic control analysis – accounting for potential spatial spill over effect between 1 and 1.5 km	1.24	1.11	1.40	<0.001

Note: RR is relative risk. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Appendix 12. Sensitivity test – results of survival analyses based on adult individuals.

Using weights calibrated in the synthetic control analysis, we conducted a survival analysis to check the robustness of the synthetic control analysis. In this analysis, we compared the survival probability (the probability of adults to stay unvaccinated) between the synthetic control and intervention groups in the three weeks following the intervention, only including unvaccinated adults at the time of the intervention, a binary categorical variable indicating whether an individual had received the first-dose of the COVID-19 vaccine as the outcome variable, the number of week from the intervention as the time variable, and the variable of the intervention (the mobile bus units). Figure A8 below shows the survival curves of two groups and the risk table. Even without controlling for any individual-level confounders used in the main individual-level analysis, this model estimates 3487 additional vaccinations over three weeks of follow-up period (3487 = (32005-47132) - (29878-48492)), broadly in line with the effect size estimated in the main analysis (n=3723).

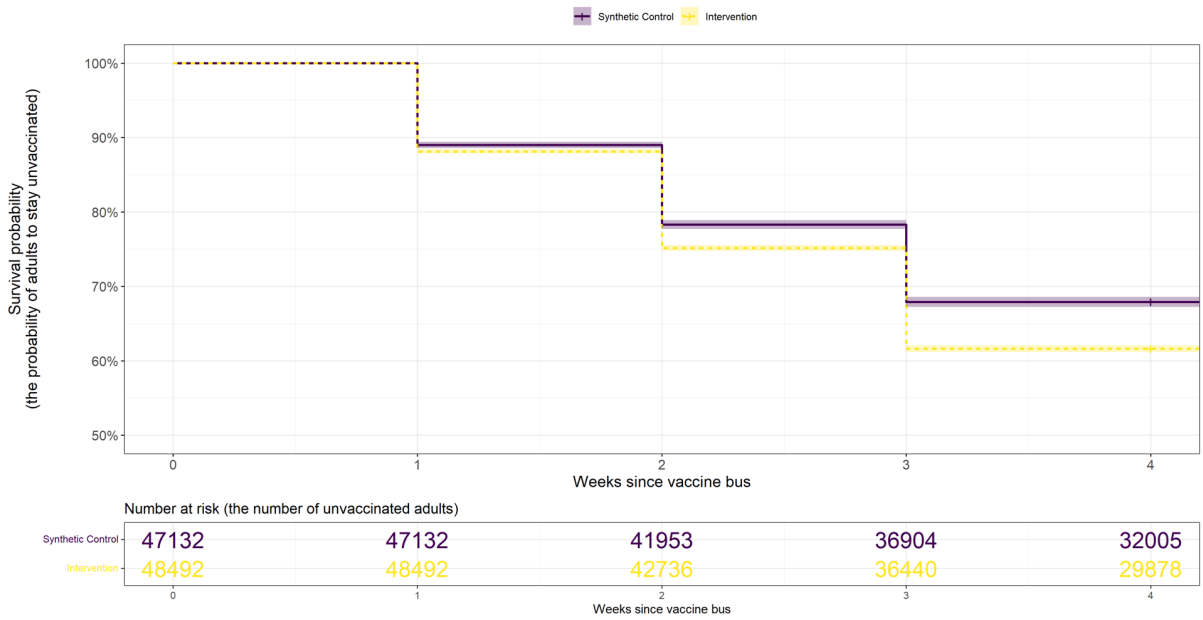


Figure A9. The survival curves of the synthetic control (coloured in purple) and intervention groups (coloured in yellow) with their respective 95% confidence intervals and the risk table, following the same colouring scheme of Figure 2 in the main analysis.

We then used a Cox proportional hazards regression model to replicate the sub-group analysis in Appendix 6. Results are shown in Table A9, similar to Table A4 in the overall trends and patterns.

Table A10. Cox regression output for the interaction model based on adult individuals. The table shows the hazard ratio (HR) indicating the estimated ratio of weekly vaccination rates in the intervention group compared to the synthetic control group in the 3 weeks following intervention.

Variables	HR	95% CI		p-value
		LCL	UCL	
Mobile vaccination unit (reference: no mobile vaccination unit)	1.83	1.72	1.95	<0.001
Age group (reference: 18-30 years old)				
(30,65]	2.16	2.05	2.29	<0.001
65+	1.49	1.08	2.06	0.017
Sex (reference: Women)				
Men	1.07	1.03	1.10	<0.001
Ethnicity (reference: White/White British)				
Asian/Asian British	0.83	0.71	0.98	0.027
Black/Black British	0.90	0.72	1.12	0.344
Mixed	0.77	0.62	0.96	0.021
Other ethnic groups	0.98	0.91	1.05	0.549
IMD tercile (reference: Least deprived)				
Intermediate deprivation	0.92	0.86	0.98	0.008
Most deprived areas	0.94	0.88	1.01	0.090
Chronic health conditions (reference: none)	0.97	0.95	0.99	0.013
Carer (reference: not carer)	0.67	0.56	0.80	<0.001
Social care receiver	1.02	0.79	1.30	0.894
Travel time by car to the nearest static vaccine centre (minutes)	1.04	1.04	1.05	<0.001
Interaction between age groups and mobile vaccination unit (reference: 18-30 years old with mobile vaccination unit)				
31-65 years old with mobile vaccination unit	0.65	0.61	0.69	<0.001
65+ years old with mobile vaccination unit	0.57	0.38	0.85	0.006
Interaction between ethnicity and mobile vaccination unit (reference: White/White British with mobile vaccination unit)				

Asian/Asian British with mobile vaccination unit	0.88	0.73	1.06	0.179
Black/Black British with mobile vaccination unit	0.70	0.54	0.90	0.006
Mixed with mobile vaccination unit	0.98	0.76	1.26	0.879
Other ethnic groups with mobile vaccination unit	0.98	0.91	1.07	0.670
Interaction between IMD tercile and mobile vaccination unit (reference: Least deprived with mobile vaccination unit)				
Intermediate deprivation with mobile vaccination unit	0.91	0.85	0.98	0.013
Most deprived areas with mobile vaccination unit	0.58	0.54	0.63	<0.001

Note: HR is hazard ratio. CI refers to confidence interval. LCL and UCL are the lower and upper confidence interval respectively.

Reporting checklist for cross sectional study.

Based on the STROBE cross sectional guidelines.

Instructions to authors

Complete this checklist by entering the page numbers from your manuscript where readers will find each of the items listed below.

Your article may not currently address all the items on the checklist. Please modify your text to include the missing information. If you are certain that an item does not apply, please write "n/a" and provide a short explanation.

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In your methods section, say that you used the STROBE cross sectionalreporting guidelines, and cite them as:

von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: guidelines for reporting observational studies.

		Reporting Item	Page Number
Title and abstract			1-2
Title	#1a	Indicate the study's design with a commonly used term in the title or the abstract	1
Abstract	#1b	Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			4-5
Background / rationale	#2	Explain the scientific background and rationale for the investigation being reported	4-5
Objectives	#3	State specific objectives, including any prespecified hypotheses	5
Methods			5-9
Study design	#4	Present key elements of study design early in the paper	5-9
Setting	#5	Describe the setting, locations, and relevant dates, including periods of	6-7

		recruitment, exposure, follow-up, and data collection	
Eligibility criteria	#6a	Give the eligibility criteria, and the sources and methods of selection of participants.	7-9
	#7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9
Data sources / measurement	#8	For each variable of interest give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group. Give information separately for for exposed and unexposed groups if applicable.	5-6
Bias	#9	Describe any efforts to address potential sources of bias	8-9
Study size	#10	Explain how the study size was arrived at	9
Quantitative variables	#11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	5-6
Statistical methods	#12a	Describe all statistical methods, including those used to control for confounding	7-9
Statistical methods	#12b	Describe any methods used to examine subgroups and interactions	9
Statistical methods	#12c	Explain how missing data were addressed	9
Statistical methods	#12d	If applicable, describe analytical methods taking account of sampling strategy	
Statistical methods	#12e	Describe any sensitivity analyses	9
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Participants	#13b	Give reasons for non-participation at each stage	
Participants	#13c	Consider use of a flow diagram	
Descriptive data	#14a	Give characteristics of study participants (eg demographic, clinical,	9-10

		social) and information on exposures and potential confounders. Give information separately for exposed and unexposed groups if applicable.	
Descriptive data	#14b	Indicate number of participants with missing data for each variable of interest	8
Outcome data	#15	Report numbers of outcome events or summary measures. Give information separately for exposed and unexposed groups if applicable.	10
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Main results	#16c	If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11
Other analyses	#17	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses	11-12
Discussion			12-14
Key results	#18	Summarise key results with reference to study objectives	12-13
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Interpretation	#20	Give a cautious overall interpretation considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence.	13-14
Generalisability	#21	Discuss the generalisability (external validity) of the study results	13-14
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