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# Assessing the impact of the COVID-19 pandemic on childhood vaccine uptake with integrated administrative data *

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**Abstract**

This study examines the impact of the COVID-19 pandemic on childhood vaccination coverage in New Zealand using population-wide administrative data. For each immunisation event from 6 weeks to 4 years, we compare children who became eligible for immunisation during the pandemic to earlier born cohorts. We find for our affected cohorts that the initial phase of the pandemic had, on average, small or nil effects on timely immunisation at the four infancy events, but a large effect at the 4-year event of -15 percentage points. Nine months after eligibility, catch-up for the affected cohort was largely achieved for the infancy immunisations, but 4-year coverage remained 6 percentage points below pre-pandemic levels. Uptake initially dropped most among children of European ethnicity and of high-earning parents but catch-up quickly surpassed their Māori, Pacific, and lower-earning counterparts for whom sizeable gaps in coverage below pre-pandemic levels remained at the end of our observation period. The pandemic thus widened pre-existing inequalities in immunisation coverage.

*Keywords:* childhood vaccine uptake, immunisation, COVID-19 pandemic

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# 1 Introduction

The COVID-19 pandemic has posed a threat to the uptake of routine childhood immunisations, increasing the risk of outbreaks of vaccine-preventable diseases. Across the globe, the delivery of immunisation programmes was disrupted due to a range of factors including redeployment of healthcare workers to pandemic response activities, reduced vaccine supplies, fear of COVID-19 exposure, travel restrictions, and misinformation (Shet et al., 2022; Causey et al., 2021; Evans and Jombart, 2022; Immunisation Taskforce, 2023). As a consequence of this disruption, current international evidence has predominantly found that the pandemic's initial impact on childhood immunisation uptake was negative with immediate declines in coverage observed around the world (Ota et al., 2021; Lassi et al., 2021). However, evidence is scant on the pandemic's longer-term impact (assessment of the extent of vaccination catch-up after the initial phase of the pandemic) and its impact on inequities in healthcare access (assessment of heterogeneous impacts on coverage among different population groups).

Our research aims to estimate the impact of the pandemic on paediatric vaccination coverage[1] in New Zealand using national immunisation registry data linked to population-wide administrative information. Our analysis compares the vaccination coverage of New Zealand children who became eligible for immunisation during the pandemic with coverage among earlier-born cohorts whose immunisations were due before the pandemic. Our use of linked integrated data at a nationwide level permits estimation of the initial impact and consequent catch-up rate for different vaccination events (between birth and age four) for affected cohorts, as well as a wide range of heterogeneity analyses to ascertain differential impacts on specific population groups. Furthermore, most of the existing literature has focused on particular regions, provinces, or jurisdictions, whereas the linked administrative data used in this study allows analysis across the entire population of children born in New Zealand.

New Zealand's National Immunisation Schedule[2] is a series of publicly-funded vaccines available to New Zealanders from six weeks to 65 years of age and in pregnancy. Immunisations for children under the age of 18 are free. This is in addition to a number of other national policies to remove financial barriers to accessing the health system for children in New Zealand (such as free visits to the doctor for children under 14). The immunisation history of all individuals born in New Zealand since 2005 is recorded in the National Immunisation Register (NIR).[3] The NIR information system thus permits monitoring of the uptake and timeliness of the National Immunisation Schedule.

New Zealand recorded its first case of COVID-19 on 28 February 2020. Earlier that

[1]On-time vaccination coverage is typically defined as the share of children receiving the recommended vaccines for a specific age within a 30-day window of the due date and up-to-date vaccination coverage is typically defined as the share of children receiving all recommended vaccines by a certain milestone age or a specific point in time. A third definition of coverage - cumulative vaccination coverage - tracks the share of children receiving a recommended vaccine from the due date as catch-up of delayed vaccinations occurs.

[2]The immunisation schedule relevant to our population of interest - children aged under five years - is provided in Table A1 in Appendix A.

[3]The NIR is currently being replaced by the newly designed Aotearoa Immunisation Register (AIR) which will provide a more accurate record of immunisation coverage in New Zealand (Te Whatu Ora, 2023).

month, the government had introduced border controls (entry restrictions and quarantine of arriving travellers) and from 21 March 2020 a four-level alert system was adopted with the aim of eliminating COVID-19 which had begun to spread in the community. The highest alert level (Level 4) involved a nationwide lockdown or stay-at-home order in place from 26 March to 27 April 2020 which was one of the most stringent lockdowns in the world (Grimes, 2022; Hale et al., 2021). Under Alert Level 4, domestic travel was severely restricted, gatherings were cancelled, public venues were closed, schools and other educational facilities were closed, and businesses were closed except for essential services such as supermarkets, general practices, and pharmacies. Partial lockdown at Alert Level 3 continued until 13 May 2020, requiring people to stay at home including working and learning from home where possible, restrictions on gatherings, closure of public venues, and adherence to physical distancing.

The combination of border controls, case and contact detection and management, physical distancing, and a high degree of public compliance with these public health measures, meant the elimination strategy was initially successful, with no community transmission detected from early May and zero new cases sustained for over 100 days thereafter (Baker et al., 2020; Summers et al., 2020). This ended with an outbreak in Auckland (New Zealand's most-populous and main gateway city) in August 2020, at which point a regional lockdown at Level 3 was implemented in Auckland. Throughout the remainder of 2020 and most of 2021 there were a series of lockdowns which varied in location and stringency depending on the nature of the outbreak and extent of community transmission at the time. The restrictions associated with these lockdowns has led to New Zealand being viewed as having one of the most stringent COVID-19 policy responses in the world at the beginning of the pandemic (Gibson, 2022). However, after relatively short elimination phases to contain outbreaks, New Zealand returned to less restrictive phases more quickly than other countries (Baker et al., 2023). While lockdowns substantially reduced health service utilisation across both hospital and general practice activity and resulted in delayed seeking of healthcare by patients (Imlach et al., 2022; Ministry of Health, 2020a; G. Wilson et al., 2021), the delivery of immunisation services in primary care (such as routine paediatric vaccinations) was intended to continue as an 'essential service' throughout all alert levels (Ministry of Health, 2021).

This study adds to the growing literature on the impacts of the pandemic on childhood vaccination coverage. International evidence initially relied on proxy information based on number of vaccines doses administered or ordered by physicians in early 2020 to estimate the pandemic's impact - see Aizawa et al. (2021) for Japan, Langdon-Embry et al. (2020), Patel Murthy et al. (2021), and Santoli et al. (2020) for the U.S., McDonald et al. (2020) for England, and Zhong et al. (2021) for Singapore. The handful of retrospective cohort studies analysing vaccine *coverage* (rather than counts) based on immunisation registry data have mostly found negative impacts at the start of the pandemic (for example, Ackerson et al. (2021), Bode et al. (2021), DeSilva et al. (2022), McDonald et al. (2020), and Ji et al. (2022)). Interestingly, a few studies have found *positive* impacts on paediatric immunisation uptake in some countries - see Martínez-Marcos et al. (2023) for Catalonia, Spain; McQuaid et al. (2022) for Scotland; and Yu et al. (2021) for South Korea.

Evidence is also limited on the extent of catch-up in vaccination coverage beyond the initial lockdowns and on the differential impact across population groups to better understand equity implications. On the latter, the evidence that does exist is mixed - Ackerson et al. find that the decline in coverage was larger, and recovery during the ‘reopening period’ of the pandemic was weaker, among Black children in the US compared to non-Black children, whereas DeSilva et al. (2022) find that pre-pandemic racial differences in coverage in the US were mostly preserved (not exacerbated) during 2020.[4]

Our study’s contribution to the literature is three-fold: (i) A detailed assessment of the initial impact of the pandemic, and the extent of vaccination catch-up, in a strict policy response environment (New Zealand’s stringent lockdown policies across 2020 and 2021 present a useful case study for investigating the pandemic’s impact on routine paediatric vaccination uptake); (ii) A population-wide analysis, given much of the prior international literature is focused at the regional level); and (iii) Investigation of heterogeneous impacts by different demographic characteristics due to the ability to link the NIR to other administrative data sources. The remainder of this paper consists of: Section 2 describes the integrated data sources; Section 3 presents descriptive trends in vaccination coverage for different immunisation events between birth and age four; Section 4 details the empirical strategy to analyse the effect of the pandemic on vaccine uptake (both average effects and heterogeneous effects); and Section 5 concludes.

## 2 Data

We use data from the Integrated Data Infrastructure (IDI), a large research database managed by Stats NZ. It holds micro-data from various government agencies, organisations, and surveys with longitudinal information on education, income, health and other life events. Stats NZ links the data so that records from all sources can be assigned to the person they belong to, and de-identifies it before it is made available to researchers (Stats NZ, 2020b).

The IDI includes administrative data from the NIR which we use to measure vaccine uptake. The Ministry of Health also uses the NIR to estimate New Zealand’s immunisation coverage. It provides data on immunisation events such as the date and type of administered vaccines (Ministry of Health, 2020b). Vaccination registries are sometimes considered unreliable due to incomplete recording of vaccinations and inaccurate estimates of population denominators (Cutts et al., 2016). However, Chisholm et al. (2021) recently assessed the data quality of the NIR with the help of information from parent-held immunisation records. They found high data accuracy compared with international equivalents, especially for vaccines covered by the National Immunisation Schedule. Advantages of using administrative over survey data for research on vaccine uptake include the large sample size that allows assessments of smaller subsets of the population and that results may be less prone to biases often associated with survey data, such as information bias, selection bias, and sampling

[4] Except at the 18 month milestone where DeSilva et al. (2022) find that the disparity in coverage between Black and other children increased during the pandemic.

error (Chisholm et al., 2021). In our analysis, we focus on the proportion of children in the population of interest who received a vaccination by a given date. We do not distinguish between those who actively declined a vaccination (which is recorded in the NIR), those who missed or postponed a vaccination for unknown reasons, or those whose parents chose to opt-off the NIR.

Our population of interest is constructed using data on births registered in New Zealand from the Department of Internal Affairs (DIA). We restrict the analysis to children living in New Zealand and exclude those who have died or moved overseas, using information on deaths and international travel. We also use the birth register to link children to their parents to examine families' characteristics.[5]

Information on child and parental characteristics come from various data sources. Child sex, ethnicity, and place of residence is derived from the IDI central tables collated by Stats NZ. Regarding ethnicity, we allocated each child to a single ethnic group using the Ministry of Health (2017) prioritisation for level 1 codes (priority order: Māori, Pacific Peoples, Asian, Middle Eastern/Latin American/African, Other Ethnicity, European). For regional classifications, we used the sixteen regions (regional councils and unitary authorities) in NZ and aggregate some less-populated regions to the areas Gisborne/Hawke's Bay and Tasman/Nelson/Marlborough/West Coast.

Inland Revenue provides income tax data. For each child, we identify the main earner of the family by using the maximum of mother's and father's earnings (income from salaries and wages) in the calendar year before birth. We then characterise family earnings as low (below the 33rd percentile), medium, or high (above the 66th percentile).

Information on parents' education comes from the 2018 census, which we use to indicate if any of a child's parents has a bachelor's degree or higher. Information on whether a child has an overseas-born parent comes from the administrative population census, which itself combines data from the census, birth registrations, visa applications and border movements (Stats NZ, 2021).

We use the New Zealand Deprivation Index 2018 (NZDep2018) to measure the level of socioeconomic deprivation of the area in which the children live. NZDep2018 combines information from the 2018 census to provide a deprivation score for each Statistical Area 1 (small geographical areas with approximately 100 to 200 people) in New Zealand. Based on this score, a deprivation scale divides all areas into 10 groups from least (1) to most (10) deprived (Atkinson et al., 2020). We use this scale to distinguish areas with low (levels 1-3), medium (4-7), and high (8-10) deprivation.

[5]We do not have information on the actual caregivers, and therefore implicitly assume that the biological parents are a good proxy for the socioeconomic status of a child's family. Additionally, in separate analyses we use the level of socioeconomic deprivation of a child's neighbourhood as a proxy for their socioeconomic status.

## 3 Trends in childhood vaccine uptake

Figure 1 presents a first overview of childhood vaccinations over time. It shows the raw number of vaccines administered to children under the age of 5 years by month. The depicted vaccines are MMR (measles, mumps, rubella), 6-in-1 (diphtheria, tetanus, acellular pertussis, polio, hepatitis B, *Haemophilus influenzae* type b), PCV (pneumococcal conjugate vaccine), RV (rotavirus), VV (varicella (chickenpox) vaccine), Hib (*Haemophilus influenzae* type b), and DTaP-IPV (diphtheria, tetanus, acellular pertussis, polio). It reveals a number of notable differences in vaccine uptake over the years 2015 to 2021.

First, changes in the National Immunisation Schedule have large effects on uptake. For example, the increase in varicella vaccinations in 2017 is attributable to the introduction of the vaccine at age 15 months for all children born in April 2016 or later. Previously, only high-risk individuals were eligible for varicella (Ministry of Health, 2020b). Second, there are large spikes in MMR uptake in 2019, when New Zealand experienced a large measles outbreak with 2185 notified cases. During the outbreak, some regions started vaccinating children at an earlier age, and the Ministry of Health encouraged all unvaccinated people under 50 years of age to get vaccinated (G. Sonder and Ryan, 2020). These developments highlight that a simple comparison of vaccination behaviour over time is challenging because children may face substantially different environments when growing up, and as such policy context is highly relevant.

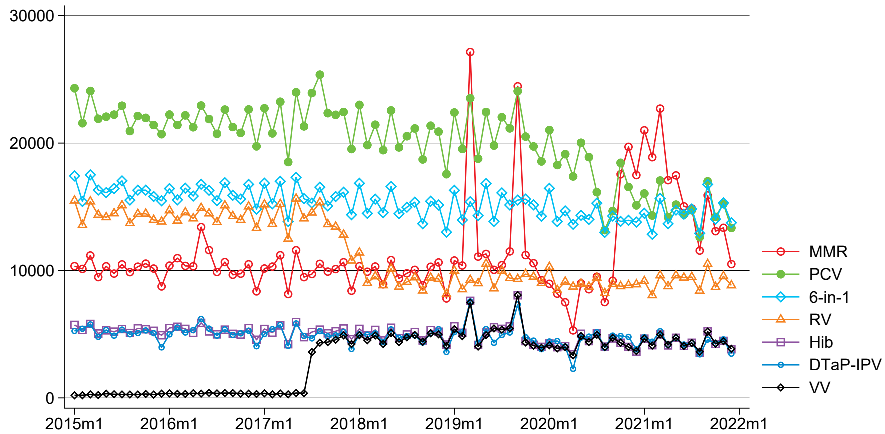


**Figure 1:** Number of vaccines administered to children under the age of 5 years over time

Third, there is also substantial variation in uptake during the COVID-19 pandemic in 2020 and 2021. Figure 1 shows a visible dip in uptake of several vaccines in April 2020 after imposition of the level 4 lockdown on 26 March, especially for MMR and DTaP-IPV. There is also a gradual decline of PCV uptake in 2020 and 2021, however, this coincides with removal of PCV at the 3 month immunisation event. At the same time, MMR uptake starts to increase in late 2020, which could also be related to changes in the immunisation schedule; in October 2020, the recommended age for the two MMR doses changed from 15 and 48 months to 12 and 15 months (Ministry of Health, 2020b).

To get a clearer idea of the effect of the pandemic on (on-time) vaccine uptake, we restrict the analysis to specific immunisation events according to the immunisation schedule. For example, Figure 2 examines the first event at 6 weeks of age. For each calendar month, we select children who turn 2 months old and depict the share of those children who receive the vaccines scheduled at the 6 week event.[6] It shows that the three scheduled vaccines (6-in-1, PCV, RV) move largely in parallel over time, indicating that decisions to receive individual vaccines are highly correlated. However, uptake of RV is approximately 2 percentage points (pp) lower throughout the observed time period.[7] Figure 2 also shows the share of children who are fully immunised, that is, received all three recommended vaccines. This share very closely matches the share of children with RV, suggesting that almost all children who received RV also received the 6-in-1 and PCV vaccines.

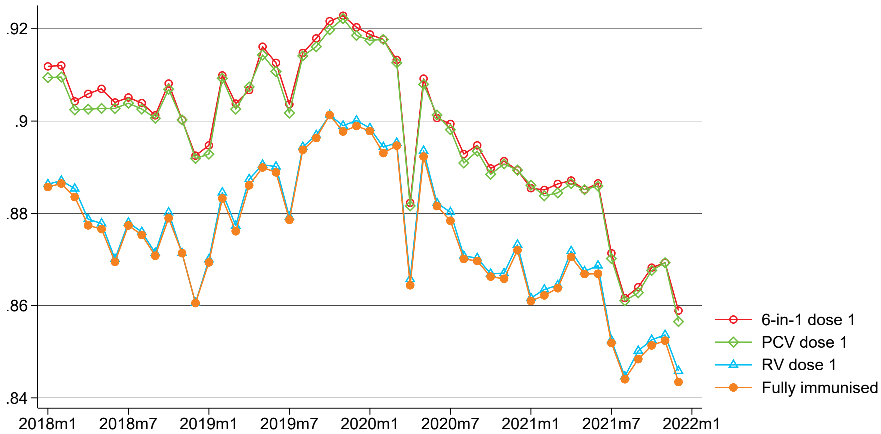


**Figure 2:** Share of 2-month-old children receiving their 6 week immunisations over time

With respect to the COVID-19 pandemic, Figure 2 shows a drop in uptake from March to April 2020 by about 3 pp, coinciding with the first lockdown period. It also indicates a gradual decline in vaccine uptake over time, with more than 90 % of 2-month-old children being fully immunised on time in October 2019 to less than 85 % in December 2021.

Figure 3 summarises the share of fully immunised children for all analysed immunisation events. As above, we select children who reach a specific age in each calendar month and assess if they receive all recommended vaccines up to that age to determine their vaccination status[8]. Therefore, Figure 3 is based on a different population cohort at each time point. It shows that the share of children immunised on time is lower for later immunisations. At the beginning of the analysis period in 2018, around 80-90 % of children receive the scheduled vaccines in the first year of life within one month of becoming eligible. This share drops to

[6]Note that the IDI only has information on birth month but not the exact birth date.

[7]It is unclear why the uptake of RV is slightly lower than for the 6-in-1 and the PCV vaccines. Parents may have different views about the benefits and risks of vaccination, as rotavirus vaccine was only introduced in 2014. In addition, there are specific contraindications which exclude some children from vaccination (Ministry of Health, 2020b).

[8]For this analysis, we keep the required vaccinations for each immunisation event constant, and label children as fully vaccinated if they have received the following vaccinations: 1 dose of 6-in-1, 1 dose of RV, 1 dose of PCV for the 6 week event. 2 doses of 6-in-1, 2 doses of RV, 1 dose of PCV for the 3 month event. 3 doses of 6-in-1, 2 doses of RV, 2 doses of PCV for the 5 month event. 3 doses of 6-in-1, 2 doses of RV, 3 doses of PCV, 1 dose of MMR, 1 dose of Hib, 1 dose of VV for the 15 month event. 3 doses of 6-in-1, 3 doses of PCV, 2 doses of MMR, 1 dose of Hib, 1 dose of DTaP-IPV for the 4 year event.

below 70 % at the 15 month event, and to below 60 % at the 4 year event.

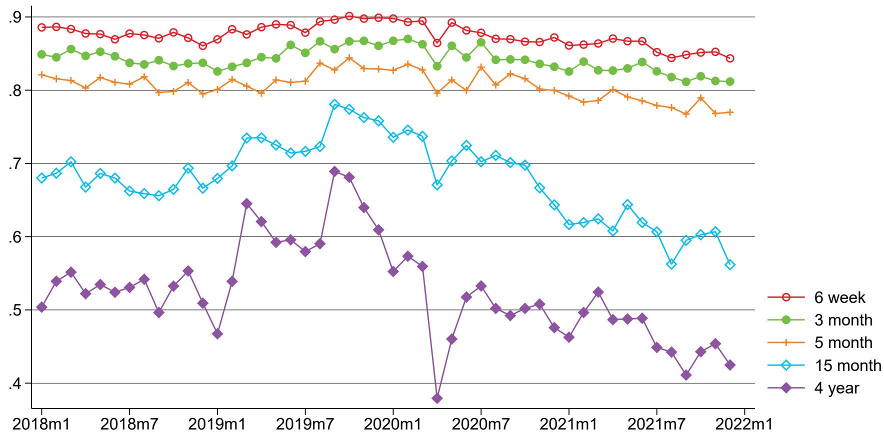


**Figure 3:** Share of fully immunised children within one month of becoming eligible for different immunisation events over time

Before assessing the trajectories in vaccine uptake during and post the COVID-19 pandemic, it is worth noting differences in trends before the pandemic for the 6 week, 3 and 5 month vaccines, relative to the 15 month and 4 year vaccines. For the first three immunisation events, there is not much variation pre-pandemic; whereas for the later ages, there is greater volatility in uptake, with some evidence of a declining trend in the last few months of 2019. Nevertheless, the average vaccine uptake for both the 15 month and 4 year events at the start of 2020 was similar to the comparable incidence rate at the start of 2018.

Once the pandemic hit, we see a visible drop in vaccine uptake for all events. The drop is more pronounced among older children. For the 4 year event, the share of fully immunised children declines from 56 % in March 2020 to 38 % in April 2020. Uptake bounces back in the subsequent few months, but over the entire course of 2020 and 2021, Figure 3 indicates a steady downward trend in on-time vaccinations for all immunisation events (particularly among older children again). Similar declines in childhood immunisations over the course of the pandemic have been documented at 6 months and 2 years (Immunisation Taskforce, 2023).

# 4 Effects of the pandemic

## 4.1 Empirical strategy

To analyse the effect of the pandemic on vaccine uptake, we focus on children who become eligible for immunisation during the pandemic. Section 3 above reveals large drops in immunisations in the first months of the pandemic, when the country went into a national lockdown. For each immunisation event, we therefore analyse the vaccination status of children who reach the age at which immunisation is recommended in March, April, or May 2020. For example, for the 4 year immunisation event, the cohort of affected children consists of children born in March to May 2016. We contrast vaccine uptake of affected children with a cohort of unaffected children born one year earlier. For the 4 year event, this group consists of children born in March to May 2015. Table 1 provides and overview of the selected cohorts by immunisation event.

**Table 1:** Birth months of selected children

| Immunisation event | Affected cohort | Unaffected cohort |
|---|---|---|
| 4 year | March - May 2016 | March - May 2015 |
| 15 month | Dec 2018 - Feb 2019 | Dec 2017 - Feb 2018 |
| 5 month | Oct - Dec 2019 | Oct - Dec 2018 |
| 3 month | Dec 2019 - Feb 2020 | Dec 2018 - Feb 2019 |
| 6 week | Jan - March 2020 | Jan - March 2019 |

Notes: This table shows the birth months of children in the affected and unaffected cohorts used to estimate the effects of the pandemic on vaccine uptake.

We compare vaccination status between these groups at each month as children grow older, to precisely analyse gaps in uptake and potential catch-up over time. To do so, we estimate the following linear probability model:

$$v_i = \alpha + \beta A_i + \gamma X_i + \epsilon_i, \tag{1}$$

where $v_i$ is a dummy variable indicating if child $i$ has received the recommended vaccines, $A_i$ is a dummy variable indicating if the child belongs to the group of affected children, and $X_i$ is a vector of control variables. For the recommended vaccines, we follow the relevant immunisation schedule (provided in Table A1 in Appendix A) and consider children to be fully vaccinated if they have received the recommended vaccines for the respective immunisation event. We estimate equation 1 at nine different points in time for each immunisation event, depending on the age of the children. For the 4 year immunisation event, for example, we follow children at each month from age 49 months to 57 months.[9] In baseline regressions, control variables include child's sex and dummy variables for the calendar month of birth. In sensitivity checks, we additionally control for region of residence, child's ethnicity, family earnings level, parental marital status, and overseas-born parents.

Coefficient $\beta$ provides an estimate of the effect of the pandemic on vaccine uptake. The underlying assumption is that the group of affected children would have behaved similarly to the earlier-born cohort in the absence of the COVID-19 pandemic. Any differences in uptake can then be attributed to the pandemic. Similar strategies have been used, for example, to analyse effects of measles outbreaks (Schober, 2020) and influenza pandemics (Fletcher, 2018; Almond and Mazumder, 2005).

Figure 4 illustrates the empirical approach. It shows the share of fully immunised children for the 4 year event over age. At 49 months, one month after becoming eligible for immunisation, 46 % of the affected cohort of children have received the recommended vaccines. This compares to 61 % of the earlier-born unaffected children. Assuming that these children constitute an appropriate counterfactual for vaccination status, the difference of 15 pp in uptake represents the impact of the pandemic. Naturally, the share of fully immunised

[9] Note that at 58 months, children in the unaffected group born in May 2015 experience the start of the pandemic, which complicates the interpretation of any remaining differences.

children increases in both groups over time. Although it increases faster among children affected by the pandemic, there is still a 6 pp difference at 57 months of age. Estimating these differences by means of regression equation 1 allows us to make statements about their statistical significance and add control variables.

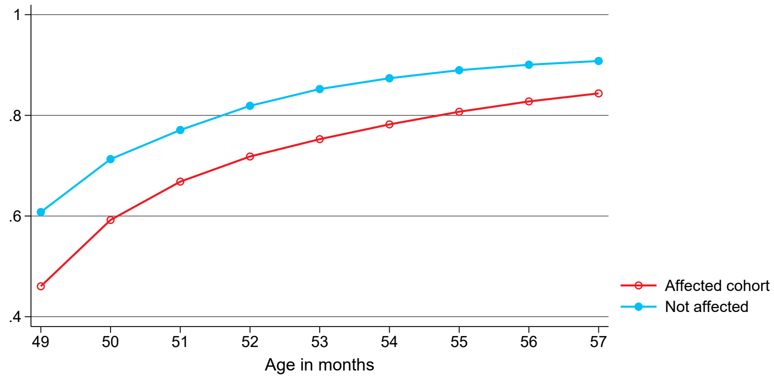


**Figure 4:** Share of fully immunised children after 4 year immunisation event, comparing affected and unaffected cohorts

While we cannot directly test the assumption that children affected by the pandemic would have behaved similar to those who were born earlier, we can compare their characteristics to assess any observable differences between cohorts. Table 2 shows that child and parental characteristics are very similar in both groups at the 4 year immunisation event. Observable differences are either statistically insignificant or small. The affected cohort has a slightly larger share of Asian children and has parents with somewhat higher earnings and lower benefit dependency.[10] We control for background characteristics in sensitivity checks below to test if these differences affect our estimates.

Tables A2, A3, A4, and A5 in Appendix A compare characteristics of affected and unaffected children for the remaining immunisation events (6 weeks, 3, 5, 15 month events). Overall, we find similar distributions of characteristics between groups which support the identifying assumption. The similarity is also plausible because we always compare children who are only born one year apart, and, at the population level, it can be expected that the characteristics of children born in New Zealand change only slowly over time.

## 4.2 Average effects

Figure 5 summarises the results of estimating equation 1 for different immunisation events, Table 3 Panel A shows the corresponding regression output at two time periods—1 month and 9 months after children become eligible for immunisation. The pandemic had large effects on timely vaccination at the 4 year event. It led to a 15 percentage point (pp) reduction in the share of fully immunised children 1 month after they became eligible (at 49 months of age). The affected group of children managed to partially catch-up during the course of the

[10]The differences in the share of Asian children between cohorts are consistent with general population trends in New Zealand in recent years, where there has been a disproportionate increase in the Asian population (Stats NZ, 2020a).

**Table 2:** Characteristics of affected and unaffected children at 4 year immunisation event

| | (1)<br>Affected | (2)<br>Unaffected | (3)<br>Difference | (4)<br>p-value |
|---|---|---|---|---|
| Female | 0.48 | 0.48 | 0.00 | 0.853 |
| European | 0.44 | 0.45 | 0.02 | 0.005 |
| Māori | 0.30 | 0.30 | 0.00 | 0.758 |
| Pacific People | 0.09 | 0.09 | 0.00 | 0.628 |
| Asian | 0.15 | 0.13 | -0.02 | 0.000 |
| Information on mother | 0.99 | 0.99 | 0.00 | 0.488 |
| Information on father | 0.94 | 0.94 | -0.00 | 0.280 |
| Characteristics of parents | | | | |
| Born overseas | 0.36 | 0.35 | -0.01 | 0.032 |
| Married | 0.52 | 0.51 | -0.01 | 0.174 |
| Benefit receipt | 0.25 | 0.27 | 0.01 | 0.014 |
| Bachelor's degree or higher | 0.40 | 0.39 | -0.02 | 0.013 |
| Low earnings | 0.36 | 0.38 | 0.02 | 0.000 |
| Medium earnings | 0.33 | 0.33 | 0.00 | 0.647 |
| High earnings | 0.31 | 0.29 | -0.02 | 0.000 |
| Region of residence | | | | |
| Northland Region | 0.04 | 0.04 | 0.00 | 0.852 |
| Auckland Region | 0.33 | 0.33 | 0.00 | 0.630 |
| Waikato Region | 0.11 | 0.11 | -0.00 | 0.381 |
| Bay of Plenty Region | 0.07 | 0.07 | -0.01 | 0.043 |
| Taranaki Region | 0.03 | 0.03 | 0.00 | 0.309 |
| Manawatu-Wanganui Region | 0.05 | 0.05 | 0.00 | 0.778 |
| Wellington Region | 0.10 | 0.10 | -0.00 | 0.462 |
| Canterbury Region | 0.12 | 0.12 | 0.00 | 0.224 |
| Otago Region | 0.04 | 0.04 | 0.00 | 0.199 |
| Southland Region | 0.02 | 0.02 | 0.00 | 0.466 |
| Gisborne/Hawke's Bay | 0.05 | 0.05 | -0.00 | 0.496 |
| Tasman/Nelson/Marlborough/West Coast | 0.03 | 0.03 | -0.00 | 0.589 |
| Area deprivation level | | | | |
| Low deprivation | 0.23 | 0.23 | 0.00 | 0.926 |
| Medium deprivation | 0.36 | 0.36 | 0.00 | 0.517 |
| High deprivation | 0.41 | 0.40 | -0.00 | 0.476 |

Notes: This table compares average characteristics of children affected (Column 1) and unaffected (2) by the COVID-19 pandemic. Column 3 shows the difference between groups, Column 4 shows the p-value testing the equality of the two means. The number of observations is 12,618 for parents' education level and 13,164 for all other characteristics.

pandemic, however, 9 months after eligibility (at 57 months of age) uptake was still 6 pp lower.

Effects on earlier immunisation events (the four infancy events from 6 weeks to 15 months) are smaller. At the 15 month event, the pandemic led to a 3 pp reduction in uptake 1 month after eligibility, and there is no statistically significant effect 9 months after eligibility. At the 5 month event, there is a 1 pp difference at the start and at the end of the observed period, while there are no statistically significant effects at the 3 month and 6 week events. The larger effects at later immunisation events in the regression results are consistent with the analysis on vaccination trends in Section 3, showing the biggest drop in timely vaccine uptake at the 4 year event around the start of the pandemic.

Table 3 also shows that the results are robust to the inclusion of additional control variables to allow for observable differences in characteristics between the affected and the earlier-born cohort of children. In Panel B, we include covariates for region of residence, child's ethnicity, family earnings level, parental marital status, and overseas-born parents. The results are very similar compared to the baseline effects, suggesting that the estimates of the effect of the pandemic are not driven by differences in characteristics between the groups.

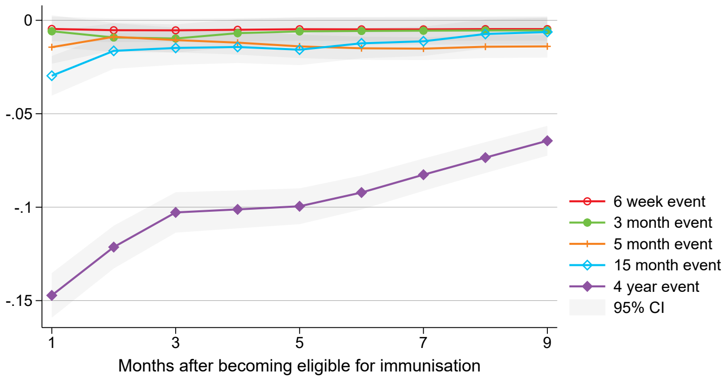


**Figure 5:** Effect of the COVID-19 pandemic on childhood vaccine uptake at different immunisation events

**Table 3:** Effect of the COVID-19 pandemic on childhood vaccine uptake

| | 1 month after eligibility | | | 9 months after eligibility | | | N |
|---|---|---|---|---|---|---|---|
| | Mean (1) | Estimate (2) | S.E. (3) | Mean (4) | Estimate (5) | S.E. (6) | (7) |
| *Panel A: Baseline specification* | | | | | | | |
| 6 week event | 0.92 | −0.00 | (0.003) | 0.93 | −0.00 | (0.003) | 27504 |
| 3 month event | 0.85 | −0.01 | (0.004) | 0.89 | −0.01 | (0.004) | 27039 |
| 5 month event | 0.84 | $-0.01^{**}$ | (0.005) | 0.94 | $-0.01^{***}$ | (0.003) | 27567 |
| 15 month event | 0.75 | $-0.03^{***}$ | (0.005) | 0.89 | −0.01 | (0.004) | 26478 |
| 4 year event | 0.61 | $-0.15^{***}$ | (0.006) | 0.91 | $-0.06^{***}$ | (0.004) | 26139 |
| *Panel B: Additional control variables* | | | | | | | |
| 6 week event | 0.92 | −0.01 | (0.004) | 0.93 | −0.00 | (0.004) | 17409 |
| 3 month event | 0.85 | $-0.01^{*}$ | (0.004) | 0.89 | $-0.01^{*}$ | (0.004) | 25998 |
| 5 month event | 0.84 | $-0.02^{***}$ | (0.004) | 0.94 | $-0.02^{***}$ | (0.003) | 26496 |
| 15 month event | 0.75 | $-0.03^{***}$ | (0.005) | 0.89 | $-0.01^{*}$ | (0.004) | 25515 |
| 4 year event | 0.61 | $-0.15^{***}$ | (0.006) | 0.91 | $-0.07^{***}$ | (0.004) | 25473 |

Notes: This table summarises the average effects of the pandemic on vaccine uptake. Each estimate represents the results from a separate regression for different immunisation events 1 and 9 months after children become eligible. Columns 1 and 4 show the mean of the unaffected cohort, columns 2 and 5 the point estimate, columns 3 and 6 robust standard error, and column 7 the number of children in the regression. Panel A includes controls for child's calendar month of birth and sex, Panel B adds control variables for region of residence, child's ethnicity, family earnings level, parental marital status, and overseas-born parents. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

Our estimates of pandemic-induced declines in childhood vaccination uptake for our affected cohort of between zero and 15 pp are broadly in line with results from other retrospective cohort studies in high-income countries. These studies have found that on-time and/or up-to-date routine immunisation coverage among children aged under 5 years declined in the early months of the pandemic (up to May 2020, capturing lockdowns in many countries) relative to pre-pandemic levels by between 3 and 18 pp in US jurisdictions (Ackerson et al., 2021; Bode et al., 2021; Bramer et al., 2020; DeSilva et al., 2022), between 6 and 8 pp in the Netherlands (Middeldorp et al., 2021), between 0.5 and 1.9 pp in England (McQuaid et al., 2022), between 4 and 7 pp in Alberta, Canada (MacDonald et al., 2022), and between 1.7 and 14.7 pp in Ontario, Canada (Ji et al., 2022).

Our finding that uptake for the affected cohort recovered to within 1 pp of pre-pandemic levels for most immunisation events (except the 4 year event which only partially recovered to 6 pp below pre-pandemic levels) is also broadly similar to experiences in other countries. From June 2020, vaccination coverage partially recovered in Ontario, Canada and Southern California, US to be 4 to 9 pp below pre-pandemic levels by the end of follow-up (Ji et al., 2022; Ackerson et al., 2021) and nearly completely recovered in the Netherlands and Alberta, Canada to 1 to 2 pp below pre-pandemic levels (Middeldorp et al., 2021; MacDonald et al., 2022).

Our finding that pandemic-induced declines in coverage were larger among older children (notably at the 4 year event) than among infants in our affected cohort is also borne out in the literature; studies have generally found that declines were smallest (or no decline was observed) among very young infants, were somewhat larger among children aged between 6 months and 2 years, and were largest among older children aged over 2 years (Ackerson et al., 2021; Bramer et al., 2020; Ji et al., 2022; Kujawski et al., 2022; MacDonald et al., 2022).

### 4.3 Child characteristics

In this and the following sections, we analyse potential heterogeneous effects of the pandemic on vaccine uptake, by estimating equation 1 separately for sub-samples of the affected cohort with different characteristics. We focus on the 4 year event in the main text, because Section 4.2 revealed the largest effects for this immunisation event. Results for the remaining events are briefly summarised, and detailed estimation output is provided in Appendix A.

Figure 6 shows the effect of the pandemic on the affected cohort for the 4 year immunisations when we split the sample by ethnicity, Table 4 shows the corresponding estimation output at age 49 and 57 months. The pandemic reduced timely vaccination among all ethnic groups. The share of fully immunised children at 49 months of age decreased between 12 and 18 pp. Interestingly, there are stark differences in catch-up behaviour during the following months. Vaccine uptake among European and Asian children almost converges to their earlier-born counterparts, with a 2 and 4 pp lower uptake by age 57 months. In contrast, the pandemic had a prolonged effect on Māori and Pacific children, whose vaccine uptake at age 57 months was still 12 and 11 pp lower compared to pre-pandemic levels.

The larger effects among Māori and Pacific children is alarming given that these children already had lower immunisation rates before the pandemic. Table 4 also reports mean uptake of unaffected children by ethnicity. It suggests that before the pandemic, the share of fully immunised children at age 57 months was 13 pp (Māori) and 6 pp (Pacific peoples) lower compared to Asian children, who had the highest immunisation rates. This is consistent with data reported by the Ministry of Health, which estimates that the share of fully immunised

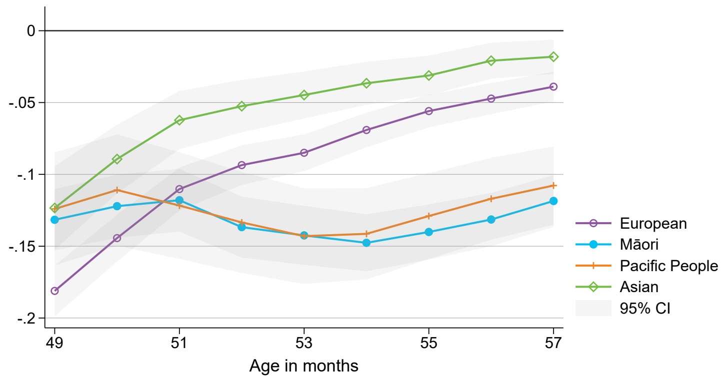


**Figure 6:** Effect of the COVID-19 pandemic on the 4 year immunisation event by ethnicity

children at 5 years was 86.7 % and 91.1 % for Māori and Pacific children in the first quarter of 2020, compared to 93.8 % for Asian children (Ministry of Health, 2022). The COVID-19 pandemic has therefore led to a widening of existing inequalities.

In the US, there is conflicting evidence on whether ethnic inequalities widened as a result of the pandemic. Ackerson et al. (2021) find that the decline in coverage was larger, and recovery in coverage during the 'reopening period' of the pandemic weaker, among Black children in the US compared to non-Black children, but DeSilva et al. (2022) find that pre-pandemic Black vs. non-Black gaps in coverage were mostly preserved (not exacerbated) during the pandemic.

We also find large effect heterogeneity with respect to the birth order of children. Table 4 shows that there are large decreases in timely uptake of 14 to 17 pp for all children at the beginning of the pandemic at age 49 months. While first- and second-born children catch-up to a large extent over the following months, reducing the gap compared to earlier-born cohorts to 5 pp, uptake among third- and fourth-born children is still 9 and 14 pp lower. Past studies in other countries have also documented that birth order affects childhood vaccinations and have linked birth order differences in vaccination behaviour to parental resource constraints (Pruckner et al., 2021; Lin et al., 2022). In contrast, we find no marked differences between male and female children. Ji et al. (2022) also found no sex differences in the impact of the pandemic on coverage among Canadian children.

Tables A6, A7, A8, and A9 in Appendix A summarise the results for the remaining immunisation events. Consistent with the average effects discussed in Section 4.2, we find generally smaller effects at the onset of the pandemic, and only small or statistically insignificant differences 9 months later. There are notable differences. For Māori and Pacific children, we tend to see more persistent effects. For example, uptake of the 5 month immunisations among Māori children by age 14 months is still 5 pp below pre-pandemic levels.

## 4.4 Parents' socioeconomic status

Figure 7 displays the effect of the pandemic on the 4 year immunisation event by parental earnings, Table 5 provides the corresponding estimation output at age 49 and 57 months. We find similar and large decreases in uptake at the onset of the pandemic for all earnings

**Table 4:** Child characteristics and vaccine uptake at the 4 year immunisation event

| | 49 months | | | 57 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Ethnicity* | | | | | | | |
| European | 0.67 | $-0.18^{***}$ | (0.01) | 0.93 | $-0.04^{***}$ | (0.01) | 11610 |
| Māori | 0.45 | $-0.13^{***}$ | (0.01) | 0.84 | $-0.12^{***}$ | (0.01) | 7818 |
| Pacific People | 0.55 | $-0.12^{***}$ | (0.02) | 0.91 | $-0.11^{***}$ | (0.01) | 2454 |
| Asian | 0.78 | $-0.12^{***}$ | (0.01) | 0.97 | $-0.02^{**}$ | (0.01) | 3594 |
| *Panel B: Sex* | | | | | | | |
| Male | 0.61 | $-0.15^{***}$ | (0.01) | 0.91 | $-0.07^{***}$ | (0.01) | 13494 |
| Female | 0.61 | $-0.15^{***}$ | (0.01) | 0.90 | $-0.06^{***}$ | (0.01) | 12648 |
| *Panel C: Birth order* | | | | | | | |
| First born | 0.63 | $-0.15^{***}$ | (0.01) | 0.91 | $-0.05^{***}$ | (0.01) | 13563 |
| Second born | 0.63 | $-0.16^{***}$ | (0.01) | 0.92 | $-0.05^{***}$ | (0.01) | 7965 |
| Third born | 0.54 | $-0.14^{***}$ | (0.02) | 0.90 | $-0.09^{***}$ | (0.01) | 3012 |
| Fourth born | 0.47 | $-0.17^{***}$ | (0.03) | 0.88 | $-0.14^{***}$ | (0.03) | 945 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 4 year immunisation event at age 49 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 57 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

groups, but children in the affected cohort whose parents have high and medium earnings tend to catch-up faster and to a greater extent in the following months. At the end of the observation period (at age 57 months), vaccine uptake of children from families with low earnings is still 10 pp lower than pre-pandemic levels. There are similar differences when we stratify children by parents' education level. Children with degree-qualified parents catch-up faster. By age 57 months, uptake among these children had recovered to 3 pp below pre-pandemic levels, but uptake among children whose parents do not have a degree was 9 pp below pre-pandemic levels.

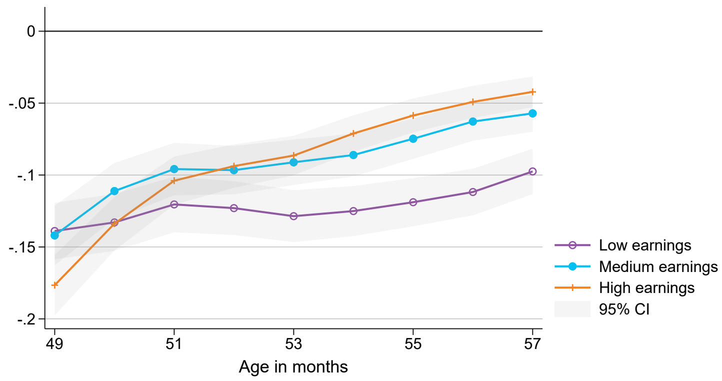


**Figure 7:** Effect of the COVID-19 pandemic on the 4 year immunisation event by parents' earnings

An interesting finding is that the initial decrease is somewhat larger for families with high earnings and a high education level. Faster changes in vaccination behaviour connected to higher education have also been documented for the controversy linking the MMR vaccine to the development of autism (Anderberg et al., 2011) and measles outbreaks (Schober, 2020). A potential explanation is that parents with more education more quickly absorb and respond to new health-related information (Anderberg et al., 2011). In contrast, Ji et al. (2022) found the impact of the pandemic on coverage among Canadian children did not differ by neighbourhood income or neighbourhood socioeconomic deprivation.

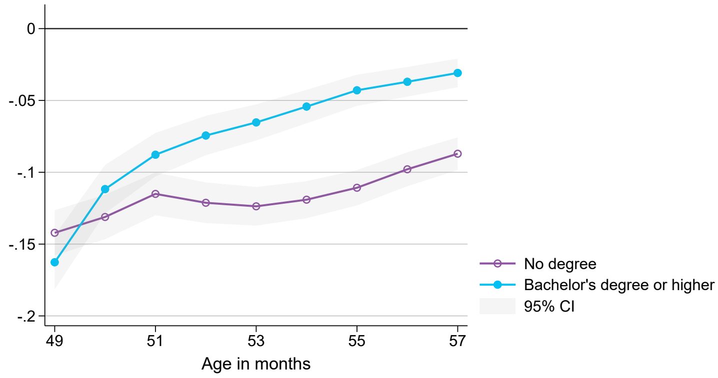


**Figure 8:** Effect of the COVID-19 pandemic on the 4 year immunisation event by parents' education level

We also find differences in the impact of the pandemic for further indicators of socioeconomic status (SES). Children in the affected cohort whose parents receive benefit payments did not seem to catch-up in terms of their vaccine uptake. At both the start and the end of the observation period, their vaccine uptake was 13 pp below pre-pandemic levels. We also find longer-lasting effects for children with unmarried parents, whose uptake at age 57 months is still 10 pp below pre-pandemic levels (compared to 4 pp lower for married). It is likely that parents in the unmarried group are more often sole parents. The differential impact may therefore be related to parental resources (including time) or other underlying differences. Regarding the birth place of the parents, we find somewhat larger effects for children whose parents were born in NZ compared to children who have at least one overseas-born parent.

Tables A10, A11, A12, and A13 in Appendix A summarise the results for the remaining immunisation events. Again, we find similar patterns related to socioeconomic status, but many estimates are statistically insignificant or small compared to the 4 year event. Children whose parents have low earnings, a low education level, or receive benefit payments tended to be more strongly impacted by the COVID-19 pandemic. However, across all analysed groups, the impacts for this affected cohort are smaller than 5 pp at the end of the observation period.

### 4.5 Place of residence

Figure 9 summarises the effects of the pandemic on the 4 year immunisation event by region of residence, Table A14 in Appendix A provides the corresponding estimation output. We find larger effects at 49 months compared to 57 months across the country, meaning there was catch-up in vaccine uptake in all regions. For Southland, Tasman/Nelson/Marlborough/West Coast, Taranaki, and Manawatu-Wanganui there is no statistically significant difference compared to pre-pandemic levels at age 57 months, the end of the observation period. In contrast,

**Table 5:** Parental characteristics and vaccine uptake at the 4 year immunisation event

| | 49 months | | | 57 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Earnings* | | | | | | | |
| Low earnings | 0.51 | $-0.14^{***}$ | (0.01) | 0.85 | $-0.10^{***}$ | (0.01) | 9594 |
| Medium earnings | 0.63 | $-0.14^{***}$ | (0.01) | 0.93 | $-0.06^{***}$ | (0.01) | 8637 |
| High earnings | 0.71 | $-0.18^{***}$ | (0.01) | 0.96 | $-0.04^{***}$ | (0.01) | 7908 |
| *Panel B: Benefit receipt* | | | | | | | |
| No benefit receipt | 0.67 | $-0.16^{***}$ | (0.01) | 0.94 | $-0.04^{***}$ | (0.00) | 19311 |
| Benefit receipt | 0.44 | $-0.13^{***}$ | (0.01) | 0.83 | $-0.13^{***}$ | (0.01) | 6831 |
| *Panel C: Education level* | | | | | | | |
| No degree | 0.56 | $-0.14^{***}$ | (0.01) | 0.89 | $-0.09^{***}$ | (0.01) | 15147 |
| Bachelor's degree or higher | 0.70 | $-0.16^{***}$ | (0.01) | 0.95 | $-0.03^{***}$ | (0.01) | 9906 |
| *Panel D: Marital status* | | | | | | | |
| Unmarried parents | 0.53 | $-0.14^{***}$ | (0.01) | 0.87 | $-0.10^{***}$ | (0.01) | 12786 |
| Married parents | 0.69 | $-0.15^{***}$ | (0.01) | 0.94 | $-0.04^{***}$ | (0.00) | 13353 |
| *Panel E: Birth place* | | | | | | | |
| Born in NZ | 0.57 | $-0.16^{***}$ | (0.01) | 0.89 | $-0.08^{***}$ | (0.01) | 16869 |
| Born overseas | 0.68 | $-0.13^{***}$ | (0.01) | 0.94 | $-0.04^{***}$ | (0.01) | 9270 |

Notes: This table summarises the heterogeneous effects of the COVID-19 pandemic on the 4 year immunisation event at age 49 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 57 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

large gaps remain in Waikato (13 pp), Gisborne/Hawke's Bay (11 pp) and Northland (9 pp).

This heterogeneity could be related to differences in underlying characteristics of the populations. For example, the Māori population are over-represented in the Waikato, Gisborne, Hawke's Bay, and Northland regions (relative to the total population) where catch-up was relatively poor (Stats NZ, n.d.). Alternatively, regional differences could be due to experiences during the first year of the pandemic. After a phase with no cases in the community, new cases in Auckland meant the city moved to a stricter lockdown with additional travel restrictions compared to the rest of the country (Cumming, 2022). This could have a different effect on the behaviour of people or health care providers living near or far from Auckland. Another noticeable finding is that even before the pandemic, there were large differences in vaccine uptake between regions. At age 57 months, the share of fully immunised children in the unaffected cohort in Northland was 78 % compared to 94 % in Canterbury and Otago.

When we stratify by level of area deprivation, we find similar patterns to when we measure socioeconomic status at the family level. While there are large effects at the beginning of the pandemic among all children, catch-up lags among those living in high deprivation areas; their uptake is still 10 pp below pre-pandemic levels, compared to effects of 4 pp for children living in low and medium deprivation areas.

Tables A10, A11, A12, and A13 include estimation results for the remaining immunisation events. Again, we find generally smaller effects, and often no statistically significant

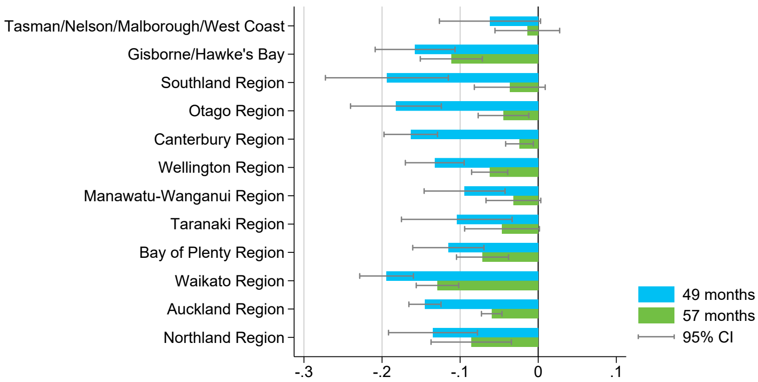


**Figure 9:** Effect of the COVID-19 pandemic on the 4 year immunisation event by region

differences at the end of the observation period. The largest remaining difference of 7 pp is observed in Taranaki at the 5 month event, however, for all other immunisation events in this region, uptake is not significantly different compared to pre-pandemic levels.

# 5 Conclusion

This study examined the impact of the pandemic on paediatric vaccination coverage in New Zealand by comparing New Zealand children who became eligible for immunisation during the pandemic to earlier born cohorts. We found for our affected cohorts that the initial phase of the pandemic had, on average, small or nil effects on timely immunisation at the four infancy events (6 weeks, 3 months, 5 months, and 15 months) with declines in coverage of between zero and 3 pp compared to pre-pandemic levels, but a large effect at the 4 year event of -15 pp. Nine months after eligibility, catch-up for the affected cohort was largely achieved for the infancy immunisations, but 4 year coverage remained 6 pp below pre-pandemic levels. The larger effect at 4 years may be related to flexible guidance issued by the Ministry of Health in late March 2020 that during the lockdowns the infancy immunisations should not be delayed, but that the 4-year immunisation event "potentially could be delayed for a short time, if necessary due to practice circumstances" (Ministry of Health and IMAC, 2020).

For the infancy immunisations, the initial impact of the pandemic tended to be greater on children of Māori ethnicity and of beneficiary parents, and their catch-up did not match that of their European, Asian, and non-beneficiary counterparts. There was little or no variation in impact by child's sex, birth order, birth place, region of residence, neighbourhood deprivation, parents' earnings, and parents' marital status.

In contrast, for the 4 year event, timely uptake initially dropped most among children of European ethnicity and of high-earning parents but catch-up quickly surpassed their Māori, Pacific, and lower-earning counterparts for whom sizeable gaps in coverage below pre-pandemic levels remained at the end of our observation period. Across all other child and parental characteristics, initial impacts on 4 year coverage were fairly even, but catch-up lagged among children born in New Zealand and with third or fourth birth order, children living in Waikato, Gisborne/Hawke's Bay, Northland, and in high deprivation neighbourhoods, and those whose parents were unmarried, receiving benefits, and lacking degree qualifications. Overall, the impact of the pandemic on immunisation coverage was small and negative among our affected cohorts of infants, large and negative among our affected cohort of 4 year olds, and resulted in a widening of pre-existing inequalities with respect to ethnicity and socioeconomic status.

It was outside the scope of our analysis to identify the underlying reasons that drove the pandemic-induced declines in routine childhood vaccine uptake found here (both on average and heterogeneously across groups), but other studies in New Zealand have addressed this topic. Using data from a survey of New Zealand general practice healthcare professionals conducted in mid-2020, G. Wilson et al. (2021) found that respondents' patients had minimised their symptoms and avoided seeking healthcare due to concerns that healthcare services were overwhelmed with responding to the pandemic and to fear of being exposed to COVID-19. Using data from a survey of adults who had contact with primary care services during New Zealand's initial lockdown, Imlach et al. (2022) found that 55 % of respondents had delayed seeking healthcare and that the main reasons for this were not wishing to unnecessarily burden the health system which was perceived to be stretched, fear of being infected with COVID-19, and that some services were postponed or not available. Some respondents felt government advice about accessing healthcare services conflicted with general stay-at-home advice which created confusion about what services were available. Both studies recommend that in future pandemics or other crises the healthcare system responds with unambiguous, up-to-date, widely-disseminated messaging to the public that primary care services remain open for business with clear communication of any changes in service delivery. In a forthcoming companion qualitative study to this one (Charania et al., forthcoming), we report findings from a qualitative study exploring the perceptions of Māori and Pacific caregivers and healthcare professionals on the impact of the pandemic on routine childhood vaccinations in New Zealand. We found that the pandemic amplified logistical barriers to Māori and Pacific caregivers' ability and motivation to get their children vaccinated, especially uncertainty about whether routine childhood vaccinations were classified as an 'essential service' and operating as usual during the lockdowns, difficulty in booking appointments with general practices, and fear of contracting COVID-19. Similar issues were identified in a survey of parents whose children were due for routine vaccinations during the lockdown in England in 2020 (Bell et al., 2021).

There is little empirical information on why the pandemic led to a widening of immunity gaps by ethnicity and socioeconomic status in New Zealand. However, it is known that Māori and Pacific peoples both in New Zealand and in the Pacific region have historically borne the heaviest burden of previous pandemics such as the 2009 H1N1 influenza pandemic and the 2019-2020 measles outbreak in New Zealand (Wilson et al., 2012; Turner, 2019). These past experiences may have made the Māori and Pacific populations more risk-averse with respect to COVID-19 exposure and hence more hesitant to get their children routinely vaccinated during the initial lockdown. Furthermore, Māori and Pacific peoples made up 84 % of cases in the August 2020 COVID-19 outbreak (Sonder et al., 2023) and their risk of hospitalisation for COVID-19 over the first seven months of the pandemic was 2.5 to 3.0 times greater than for other New Zealanders (Steyn et al., 2023), which may have had negative impacts on vaccination catch-up among Māori and Pacific children. Alternatively, lower access to the internet, digital devices, and other forms of digital exclusion may have reduced Māori and Pacific peoples' exposure to public health communications from government and primary care practices including the message that routine immunisation services remained available during lockdowns (Ioane et al., 2021).

Ethnic disparities in vaccine uptake and other health outcomes have been an ongoing policy concern in New Zealand. This was also noted by the Immunisation Taskforce, which was commissioned in 2022 by Te Whatu Ora (Health New Zealand) to provide evidence-based advice on how to improve immunisation coverage. The Taskforce's initial report provided a number of recommendations to achieve equity in childhood immunisation rates across all population groups and increase access to immunisation services. Key recommendations included expanding and diversifying the vaccinator workforce (to include more health practitioners outside of primary care and Māori and Pacific providers who have contact with children and can engage in opportunistic vaccination), improving enrolment into health services after birth for more effective pre-calls and recalls for vaccination, and making outreach services (which target children who miss immunisations at the scheduled times) more proactive rather than waiting for immunisations to be missed before children are recalled (Immunisation Taskforce, 2023). In addition to improvements for future generations of children, an important task is to provide catch-up immunisations to those cohorts who missed immunisation in the past in order to address risks to individual and population health.

## References

Ackerson, Bradley K, Lina S Sy, Sungching C Glenn, Lei Qian, Claire H Park, Robert J Riewerts, and Steven J Jacobsen (2021). “Pediatric Vaccination During the COVID-19 Pandemic”. In: *Pediatrics* 148.1.

Aizawa, Yuta, Tomohiro Katsuta, Hiroshi Sakiyama, Keiko Tanaka-Taya, Hiroyuki Moriuchi, and Akihiko Saitoh (2021). “Changes in childhood vaccination during the coronavirus disease 2019 pandemic in Japan”. In: *Vaccine* 39.29, pp. 4006–4012.

Almond, Douglas and Bhashkar Mazumder (2005). “The 1918 influenza pandemic and subsequent health outcomes: An analysis of SIPP data”. In: *American Economic Review* 95.2, pp. 258–262.

Anderberg, Dan, Arnaud Chevalier, and Jonathan Wadsworth (2011). “Anatomy of a health scare: education, income and the MMR controversy in the UK”. In: *Journal of Health Economics* 30.3, pp. 515–530.

Atkinson, June, Peter Crampton, and Clare Salmond (2020). *NZDep2018 Index of Deprivation.* Final Research Report. Wellington: University of Otago.

Baker, Michael G, Amanda Kvalsvig, Michael J Plank, Jemma L Geoghegan, Teresa Wall, Collin Tukuitonga, Jennifer Summers, Julie Bennett, John Kerr, Nikki Turner, et al. (2023). “Continued mitigation needed to minimise the high health burden from COVID-19 in Aotearoa New Zealand”. In: *The New Zealand Medical Journal (Online)* 136.1583, pp. 67–91.

Baker, Michael G, Nick Wilson, and Andrew Anglemyer (2020). “Successful Elimination of Covid-19 Transmission in New Zealand”. In: *New England Journal of Medicine* 383.8, e56.

Bell, Sadie, Richard Clarke, Pauline Paterson, and Sandra Mounier-Jack (2021). “Parents’ and guardians’ views and experiences of accessing routine childhood vaccinations during the coronavirus (COVID-19) pandemic: A mixed methods study in England”. In: *PLOS ONE* 15.12, e0244049.

Bode, Sara M., Charitha Gowda, Melissa Mangini, and Alex R Kemper (2021). “COVID-19 and Primary Measles Vaccination Rates in a Large Primary Care Network”. In: *Pediatrics* 147.1.

Bramer, Cristi A, Lynsey M Kimmins, Robert Swanson, Jeremy Kuo, Patricia Vranesich, Lisa A Jacques-Carroll, and Angela K Shen (2020). “Decline in child vaccination coverage during the COVID-19 pandemic — Michigan Care Improvement Registry, May 2016-May 2020”. In: *American Journal of Transplantation* 20.7, pp. 1930–1931.

Causey, Kate, Nancy Fullman, Reed J D Sorensen, Natalie C Galles, Peng Zheng, Aleksandr Aravkin, M Carolina Danovaro-Holliday, Ramon Martinez-Piedra, Samir V Sodha, Martha Patricia Velandia-González, Marta Gacic-Dobo, Emma Castro, Jiawei He, Megan Schipp, Amanda Deen, Simon I Hay, Stephen S Lim, and Jonathan F Mosser (2021). “Estimating global and regional disruptions to routine childhood vaccine coverage during the COVID-19 pandemic in 2020: a modelling study”. In: *The Lancet* 398.10299, pp. 522–534.

Chisholm, Hannah, Janine Paynter, Esther Willing, Nikki Turner, and Anna S Howe (2021). "Does the National Immunisation Register stack up? Quantifying accuracy when compared to parent-held health record books". In: *The New Zealand Medical Journal* 134.1541, pp. 22–32.

Cumming, Jacqueline (2022). "Going hard and early: Aotearoa New Zealand's response to Covid-19". In: *Health Economics, Policy and Law* 17.1, pp. 107–119.

Cutts, Felicity T, Pierre Claquin, M Carolina Danovaro-Holliday, and Dale A Rhoda (2016). "Monitoring vaccination coverage: defining the role of surveys". In: *Vaccine* 34.35, pp. 4103–4109.

DeSilva, Malini B, Jacob Haapala, Gabriela Vazquez-Benitez, Matthew F Daley, James D Nordin, Nicola P Klein, Michelle L Henninger, Joshua T B Williams, Simon J Hambidge, Michael L Jackson, James G Donahue, Lei Qian, Megan C Lindley, Julianne Gee, Eric S Weintraub, and Elyse O Kharbanda (2022). "Association of the COVID-19 Pandemic With Routine Childhood Vaccination Rates and Proportion Up to Date With Vaccinations Across 8 US Health Systems in the Vaccine Safety Datalink". In: *JAMA Pediatrics* 176.1, pp. 68–77.

Evans, Beth and Thibaut Jombart (2022). "Worldwide routine immunisation coverage regressed during the first year of the COVID-19 pandemic". In: *Vaccine* 40.26, pp. 3531–3535.

Fletcher, Jason M (2018). "The effects of in utero exposure to the 1918 influenza pandemic on family formation". In: *Economics & Human Biology* 30, pp. 59–68.

Gibson, John (2022). "Government mandated lockdowns do not reduce Covid-19 deaths: implications for evaluating the stringent New Zealand response". In: *New Zealand Economic Papers* 56.1, pp. 17–28.

Grimes, Arthur (2022). "Measuring Pandemic and Lockdown Impacts on Wellbeing". In: *Review of Income and Wealth* 68.2, pp. 409–427.

Hale, Thomas, Noam Angrist, Rafael Goldszmidt, Beatriz Kira, Anna Petherick, Toby Phillips, Samuel Webster, Emily Cameron-Blake, Laura Hallas, Saptarshi Majumdar, and Helen Tatlow (2021). "A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker)". In: *Nature Human Behaviour* 5.4, pp. 529–538.

Imlach, Fiona, Eileen McKinlay, Jonathan Kennedy, Megan Pledger, Lesley Middleton, Jacqueline Cumming, and Karen McBride-Henry (2022). "Seeking Healthcare During Lockdown: Challenges, Opportunities and Lessons for the Future". In: *International Journal of Health Policy and Management* 11.8. 2322-5939, pp. 1316–1324.

Immunisation Taskforce (2023). *Initial Priorities for the National Immunisation Programme in Aotearoa*. Report. Te Whatu Ora - Health New Zealand. URL: https://www.tewhatuora.govt.nz/publications/initial-priorities-for-the-national-immunisation-programme-in-aotearoa/.

Ioane, Julia, Teuila Percival, Winnie Laban, and Ian Lambie (2021). "All-of-community by all-of-government: reaching Pacific people in Aotearoa New Zealand during the COVID-19 pandemic". In: *New Zealand Medical Journal* 134.1533, pp. 96–103.

Ji, Catherine, Pierre-Philippe Piché-Renaud, Jemisha Apajee, Ellen Stephenson, Milena Forte, Jeremy N. Friedman, Michelle Science, Stanley Zlotkin, Shaun K. Morris, and Karen Tu (2022). "Impact of the COVID-19 pandemic on routine immunization coverage in children under 2 years old in Ontario, Canada: A retrospective cohort study". In: *Vaccine* 40.12, pp. 1790–1798.

Kujawski, Stephanie A., Lixia Yao, H. Echo Wang, Cristina Carias, and Ya-Ting Chen (2022). "Impact of the COVID-19 pandemic on pediatric and adolescent vaccinations and well child visits in the United States: A database analysis". In: *Vaccine* 40.5, pp. 706–713.

Langdon-Embry, Marisa, Vikki Papadouka, Iris Cheng, Mohammed Almashhadani, Alexandra Ternier, and Jane R Zucker (2020). "Rebound in Routine Childhood Vaccine Administration Following Decline During the COVID-19 Pandemic — New York City, March 1–June 27, 2020". In: *Morbidity and Mortality Weekly Report* 69.30, pp. 999–1001.

Lassi, Zohra S, Rabia Naseem, Rehana A Salam, Faareha Siddiqui, and Jai K Das (2021). "The Impact of the COVID-19 Pandemic on Immunization Campaigns and Programs: A Systematic Review". In: *International Journal of Environmental Research and Public Health* 18.3, p. 988.

Lin, Allison, Duy Pham, Hannah Rosenthal, and Ruth Milanaik (2022). "Birth Order and Up-to-Date Vaccination Status". In: *Pediatrics* 150.4.

MacDonald, Shannon E, Yuba Raj Paudel, Marilou Kiely, Ellen Rafferty, Manish Sadarangani, Joan L Robinson, S Michelle Driedger, and Lawrence W Svenson (2022). "Impact of the COVID-19 pandemic on vaccine coverage for early childhood vaccines in Alberta, Canada: a population-based retrospective cohort study". In: *BMJ Open* 12.1, e055968.

Martínez-Marcos, Montse, Edurne Zabaleta-del-Olmo, Esperanza-Luisa Gómez-Durán, Anna Reñé-Reñé, and Carmen Cabezas-Peña (2023). "Impact of the COVID-19 lockdown on routine childhood vaccination coverage rates in Catalonia (Spain): a public health register–based study". In: *Public Health* 218, pp. 68–74.

McDonald, Helen I, Elise Tessier, Joanne M White, Matthew Woodruff, Charlotte Knowles, Chris Bates, John Parry, Jemma L Walker, J Anthony Scott, Liam Smeeth, Joanne Yarwood, Mary Ramsay, and Michael Edelstein (2020). "Early impact of the coronavirus disease (COVID-19) pandemic and physical distancing measures on routine childhood vaccinations in England, January to April 2020". In: *Eurosurveillance* 25.19, p. 2000848.

McQuaid, Fiona, Rachel Mulholland, Yuma Sangpang Rai, Utkarsh Agrawal, Helen Bedford, J. Claire Cameron, Cheryl Gibbons, Partho Roy, Aziz Sheikh, Ting Shi, Colin R. Simpson, Judith Tait, Elise Tessier, Steve Turner, Jaime Villacampa Ortega, Joanne White, and Rachael Wood (2022). "Uptake of infant and preschool immunisations in Scotland and England during the COVID-19 pandemic: An observational study of routinely collected data". In: *PLOS Medicine* 19.2, e1003916.

Middeldorp, Marit, Alies van Lier, Nicoline van der Maas, Irene Veldhuijzen, Wieke Freudenburg, Nina M van Sorge, Elisabeth A M Sanders, Mirjam J Knol, and Hester E de Melker (2021). "Short term impact of the COVID-19 pandemic on incidence of vaccine preventable diseases and participation in routine infant vaccinations in the Netherlands in the period March-September 2020". In: *Vaccine* 39.7, pp. 1039–1043.

Ministry of Health (2017). *HISO 10001:2017 Ethnicity Data Protocols*. Wellington: Ministry of Health.

— (2020a). *COVID-19 disruptions to hospital and general practice activity*. Report. Ministry of Health. URL: https://www.health.govt.nz/publication/covid-19-disruptions-hospital-and-general-practice-activity.

— (2020b). *Immunisation Handbook 2020*. Wellington: Ministry of Health.

— (2021). *COVID-19 Community Response Framework v3.0*. Web Page.

— (2022). *National and regional immunisation data*. Ministry of Health. URL: https://www.health.govt.nz/our-work/preventative-health-wellness/immunisation/immunisation-coverage/national-and-regional-immunisation-data.

Ministry of Health and IMAC (2020). *Keep calm and keep vaccinating!* Media release from the New Zealand Ministry of Health and the Immunisation Advisory Centre (IMAC). URL: https://www.nzdoctor.co.nz/article/undoctored/keep-calm-and-keep-vaccinating.

Ota, Martin O C, Selim Badur, Luis Romano-Mazzotti, and Leonard R Friedland (2021). "Impact of COVID-19 pandemic on routine immunization". In: *Annals of Medicine* 53.1, pp. 2286–2297.

Patel Murthy, Bhavini, Elizabeth Zell, Karen Kirtland, Nkenge Jones-Jack, LaTreace Harris, Carrie Sprague, Jessica Schultz, Quan Le, Cristi A Bramer, Sydney Kuramoto, Iris Cheng, Mary Woinarowicz, Steve Robison, Ashley McHugh, Stephanie Schauer, and Lynn Gibbs-Scharf (2021). "Impact of the COVID-19 Pandemic on Administration of Selected Routine Childhood and Adolescent Vaccinations — 10 U.S. Jurisdictions, March–September 2020". In: *Morbidity and Mortality Weekly Report* 70.23.

Pruckner, Gerald J, Nicole Schneeweis, Thomas Schober, and Martina Zweimüller (2021). "Birth order, parental health investment, and health in childhood". In: *Journal of Health Economics* 76, p. 102426.

Santoli, Jeanne M., Megan C. Lindley, Malini B. DeSilva, Elyse O. Kharbanda, Matthew F. Daley, Lisa Galloway, Julianne Gee, Mick Glover, Ben Herring, Yoonjae Kang, Paul Lucas, Cameron Noblit, Jeanne Tropper, Tara Vogt, and Eric Weintraub (2020). "Effects of the COVID-19 Pandemic on Routine Pediatric Vaccine Ordering and Administration — United States, 2020". In: *Morbidity and Mortality Weekly Report* 69.19, pp. 591–593.

Schober, Thomas (2020). "Effects of a measles outbreak on vaccination uptake". In: *Economics and Human Biology* 38.

Shet, Anita, Kelly Carr, M. Carolina Danovaro-Holliday, Samir V. Sodha, Christine Prosperi, Joshua Wunderlich, Chizoba Wonodi, Heidi W. Reynolds, Imran Mirza, Marta Gacic-Dobo, Katherine L. O'Brien, and Ann Lindstrand (2022). "Impact of the SARS-CoV-2 pandemic on routine immunisation services: evidence of disruption and recovery from 170 countries and territories". In: *The Lancet Global Health* 10.2, e186–e194.

Sonder, Gerard and Suitafa Debbie Ryan (2020). *Health Sector Response to the 2019 Measles Outbreaks*. Wellington: Ministry of Health.

Sonder, Corina Grey, Andrew Anglemyer, Collin Tukuitonga, Philip C Hill, Andrew Sporle, and Debbie Ryan (2023). "The August 2020 COVID-19 outbreak in Aotearoa, New Zealand: Delayed contact tracing for Pacific people contributes to widening health disparities". In: *IJID Regions* 6, pp. 177–183.

Stats NZ (2020a). *Ethnic group summaries reveal New Zealand's multicultural make-up*. URL: https://www.stats.govt.nz/news/ethnic-group-summaries-reveal-new-zealands-multicultural-make-up/.

— (2020b). *Integrated Data Infrastructure*. URL: https://www.stats.govt.nz/integrated-data/integrated-data-infrastructure/.

— (2021). *Experimental administrative population census: Data sources and methods*. URL: https://www.stats.govt.nz/research/experimental-administrative-population-census-data-sources-and-methods/.

— (n.d.). *Māori ethnic group*. URL: https://www.stats.govt.nz/tools/2018-census-ethnic-group-summaries/m%C4%81ori.

Steyn, Nicholas, Rachelle N. Binny, Kate Hannah, Shaun C. Hendy, Alex James, Audrey Lustig, Kannan Ridings, Michael J. Plank, and Andrew Sporle (2023). "Māori and Pacific people in New Zealand have a higher risk of hospitalisation for COVID-19". In: *New Zealand Medical Journal* 134.1538, pp. 28–43.

Summers, Jennifer, Hao-Yuan Cheng, Hsien-Ho Lin, Lucy Telfar Barnard, Amanda Kvalsvig, Nick Wilson, and Michael G Baker (2020). "Potential lessons from the Taiwan and New Zealand health responses to the COVID-19 pandemic". In: *The Lancet Regional Health - Western Pacific* 4, p. 100044.

Te Whatu Ora (2023). *The Aotearoa Immunisation Register (AIR)*. Te Whatu Ora - Health New Zealand. URL: https://www.tewhatuora.govt.nz/our-health-system/digital-health/the-aotearoa-immunisation-register-air/.

Turner, Nikki (2019). "A measles epidemic in New Zealand: Why did this occur and how can we prevent it occurring again?" In: *New Zealand Medical Journal* 132.1504, pp. 8–12.

Wilson, Lucy Telfar Barnard, Jennifer A Summers, G D Shanks, and Michael G Baker (2012). "Differential Mortality Rates by Ethnicity in 3 Influenza Pandemics Over a Century, New Zealand". In: *Emerging Infectious Diseases* 18.1, pp. 71–77.

Wilson, Geraldine, Zoe Windner, Susan Bidwell, Anthony Dowell, Les Toop, Ruth Savage, and Ben Hudson (2021). "Navigating the health system during COVID-19: primary care perspectives on delayed patient care". In: *The New Zealand Medical Journal* 134.

Yu, Jeong Hee, Hang jin Jeong, Seon Ju Kim, Jae Young Lee, Young June Choe, Eun Hwa Choi, and En Hi Cho (2021). "Sustained Vaccination Coverage during the Coronavirus Disease 2019 Epidemic in the Republic of Korea". In: *Vaccines* 9.1, p. 2.

Zhong, Youjia, Hannah Eleanor Clapham, Ramkumar Aishworiya, Ying Xian Chua, Jancy Mathews, Mabel Ong, Jingji Wang, Belinda Murugasu, Wen Chin Chiang, Bee Wah Lee, and Hui-Lin Chin (2021). "Childhood vaccinations: Hidden impact of COVID-19 on children in Singapore". In: *Vaccine* 39.5, pp. 780–785.

# A Additional tables and figures

**Table A1:** Vaccines for children under 5 years on New Zealand's National Immunisation Schedule (April 2018 to September 2020)

| | DTaP-IPV-HepB/Hib | PCV10 | RV1 | MMR | Hib-PRP | VV | DTaP-IPV |
|---|---|---|---|---|---|---|---|
| 6 weeks | • | • | • | | | | |
| 3 months | • | • | • | | | | |
| 5 months | • | • | | | | | |
| 15 months | | • | | • | • | • | |
| 4 years | | | | • | | | • |

Notes: DTaP-IPV-HepB/Hib = Diphtheria, tetanus, acellular pertussis, inactivated polio, hepatitis B and *Haemophilus influenzae* type b vaccine, PCV10 = 10-valent pneumococcal conjugate vaccine, RV1 = Rotavirus vaccine, Hib-PRP = *Haemophilus influenzae* type b polyribosylribitol phosphate vaccine, MMR = Measles, mumps and rubella vaccine, VV = Varicella vaccine, DTaP-IPV = diphtheria, tetanus, acellular pertussis and inactivated polio vaccine.

**Table A2:** Characteristics of affected and unaffected children at 15 month immunisation event

| | (1) Affected | (2) Unaffected | (3) Difference | (4) p-value |
|---|---|---|---|---|
| Female | 0.48 | 0.49 | 0.00 | 0.459 |
| European | 0.40 | 0.41 | 0.02 | 0.010 |
| Māori | 0.30 | 0.30 | 0.00 | 0.705 |
| Pacific People | 0.10 | 0.10 | 0.00 | 0.945 |
| Asian | 0.17 | 0.15 | -0.02 | 0.001 |
| Information on mother | 0.99 | 0.99 | 0.00 | 0.012 |
| Information on father | 0.94 | 0.94 | 0.00 | 0.396 |
| Characteristics of parents | | | | |
| Born overseas | 0.39 | 0.38 | -0.02 | 0.010 |
| Married | 0.50 | 0.51 | 0.01 | 0.126 |
| Benefit receipt | 0.24 | 0.25 | 0.00 | 0.365 |
| Bachelor's degree or higher | 0.42 | 0.42 | -0.00 | 0.866 |
| Low earnings | 0.33 | 0.35 | 0.01 | 0.013 |
| Medium earnings | 0.33 | 0.32 | -0.01 | 0.095 |
| High earnings | 0.34 | 0.34 | -0.00 | 0.410 |
| Region of residence | | | | |
| Northland Region | 0.04 | 0.04 | 0.00 | 0.289 |
| Auckland Region | 0.34 | 0.34 | -0.00 | 0.709 |
| Waikato Region | 0.11 | 0.11 | -0.00 | 0.335 |
| Bay of Plenty Region | 0.07 | 0.07 | 0.00 | 0.727 |
| Taranaki Region | 0.03 | 0.03 | -0.00 | 0.543 |
| Manawatu-Wanganui Region | 0.05 | 0.06 | 0.00 | 0.349 |
| Wellington Region | 0.10 | 0.10 | -0.00 | 0.451 |
| Canterbury Region | 0.12 | 0.12 | -0.00 | 0.905 |
| Otago Region | 0.04 | 0.04 | 0.00 | 0.061 |
| Southland Region | 0.02 | 0.02 | 0.00 | 0.767 |
| Gisborne/Hawke's Bay | 0.05 | 0.05 | -0.00 | 0.799 |
| Tasman/Nelson/Marlborough/West Coast | 0.03 | 0.03 | 0.00 | 0.717 |
| Area deprivation level | | | | |
| Low deprivation | 0.22 | 0.22 | 0.00 | 0.373 |
| Medium deprivation | 0.37 | 0.36 | -0.00 | 0.493 |
| High deprivation | 0.42 | 0.42 | -0.00 | 0.940 |

Notes: This table compares average characteristics of children affected (Column 1) and unaffected (2) by the pandemic. Column 3 shows the difference between groups, Column 4 shows the p-value testing the equality of the two means. The number of observations is 12,165 for parents' education level and 13,308 for all other characteristics.

**Table A3:** Characteristics of affected and unaffected children at 5 month immunisation event

| | (1) Affected | (2) Unaffected | (3) Difference | (4) p-value |
|---|---|---|---|---|
| Female | 0.49 | 0.49 | -0.00 | 0.457 |
| European | 0.39 | 0.41 | 0.02 | 0.001 |
| Māori | 0.29 | 0.30 | 0.01 | 0.047 |
| Pacific People | 0.09 | 0.09 | -0.01 | 0.087 |
| Asian | 0.19 | 0.17 | -0.02 | 0.000 |
| Information on mother | 0.99 | 0.99 | -0.00 | 0.380 |
| Information on father | 0.93 | 0.94 | 0.00 | 0.165 |
| Characteristics of parents | | | | |
| Born overseas | 0.42 | 0.39 | -0.03 | 0.000 |
| Married | 0.53 | 0.51 | -0.01 | 0.079 |
| Benefit receipt | 0.21 | 0.22 | 0.02 | 0.000 |
| Bachelor's degree or higher | 0.44 | 0.43 | -0.01 | 0.092 |
| Low earnings | 0.33 | 0.35 | 0.03 | 0.000 |
| Medium earnings | 0.33 | 0.33 | -0.01 | 0.186 |
| High earnings | 0.34 | 0.32 | -0.02 | 0.002 |
| Region of residence | | | | |
| Northland Region | 0.04 | 0.04 | -0.00 | 0.141 |
| Auckland Region | 0.35 | 0.34 | -0.01 | 0.037 |
| Waikato Region | 0.11 | 0.11 | 0.00 | 0.456 |
| Bay of Plenty Region | 0.07 | 0.07 | 0.00 | 0.507 |
| Taranaki Region | 0.02 | 0.03 | 0.00 | 0.012 |
| Manawatu-Wanganui Region | 0.05 | 0.05 | -0.00 | 0.658 |
| Wellington Region | 0.10 | 0.10 | 0.01 | 0.012 |
| Canterbury Region | 0.12 | 0.12 | -0.00 | 0.473 |
| Otago Region | 0.04 | 0.04 | -0.01 | 0.013 |
| Southland Region | 0.02 | 0.02 | 0.00 | 0.369 |
| Gisborne/Hawke's Bay | 0.04 | 0.05 | 0.01 | 0.013 |
| Tasman/Nelson/Marlborough/West Coast | 0.03 | 0.03 | -0.00 | 0.649 |
| Area deprivation level | | | | |
| Low deprivation | 0.21 | 0.21 | -0.00 | 0.483 |
| Medium deprivation | 0.36 | 0.37 | 0.00 | 0.459 |
| High deprivation | 0.43 | 0.42 | -0.00 | 0.888 |

Notes: This table compares average characteristics of children affected (Column 1) and unaffected (2) by the pandemic. Column 3 shows the difference between groups, Column 4 shows the p-value testing the equality of the two means. The number of observations is 12,369 for parents' education level and 13,536 for all other characteristics.

**Table A4:** Characteristics of affected and unaffected children at 3 month immunisation event

| | (1) Affected | (2) Unaffected | (3) Difference | (4) p-value |
|---|---|---|---|---|
| Female | 0.49 | 0.48 | -0.01 | 0.059 |
| European | 0.38 | 0.40 | 0.01 | 0.064 |
| Māori | 0.29 | 0.30 | 0.01 | 0.215 |
| Pacific People | 0.10 | 0.10 | -0.00 | 0.681 |
| Asian | 0.19 | 0.17 | -0.02 | 0.000 |
| Information on mother | 0.99 | 0.99 | 0.00 | 0.641 |
| Information on father | 0.93 | 0.94 | 0.00 | 0.326 |
| Characteristics of parents | | | | |
| Born overseas | 0.42 | 0.40 | -0.02 | 0.000 |
| Married | 0.52 | 0.50 | -0.02 | 0.000 |
| Benefit receipt | 0.22 | 0.24 | 0.02 | 0.000 |
| Bachelor's degree or higher | 0.43 | 0.42 | -0.00 | 0.530 |
| Low earnings | 0.32 | 0.33 | 0.01 | 0.023 |
| Medium earnings | 0.33 | 0.33 | -0.00 | 0.522 |
| High earnings | 0.35 | 0.34 | -0.01 | 0.108 |
| Region of residence | | | | |
| Northland Region | 0.04 | 0.04 | -0.01 | 0.013 |
| Auckland Region | 0.35 | 0.34 | -0.01 | 0.062 |
| Waikato Region | 0.11 | 0.11 | 0.00 | 0.477 |
| Bay of Plenty Region | 0.07 | 0.07 | -0.00 | 0.831 |
| Taranaki Region | 0.02 | 0.03 | 0.00 | 0.047 |
| Manawatu-Wanganui Region | 0.05 | 0.05 | -0.00 | 0.593 |
| Wellington Region | 0.10 | 0.10 | 0.01 | 0.124 |
| Canterbury Region | 0.12 | 0.12 | 0.00 | 0.431 |
| Otago Region | 0.04 | 0.04 | -0.00 | 0.343 |
| Southland Region | 0.02 | 0.02 | 0.00 | 0.800 |
| Gisborne/Hawke's Bay | 0.05 | 0.05 | 0.01 | 0.027 |
| Tasman/Nelson/Marlborough/West Coast | 0.03 | 0.03 | 0.00 | 0.822 |
| Area deprivation level | | | | |
| Low deprivation | 0.20 | 0.21 | 0.00 | 0.468 |
| Medium deprivation | 0.36 | 0.37 | 0.01 | 0.140 |
| High deprivation | 0.44 | 0.42 | -0.01 | 0.043 |

Notes: This table compares average characteristics of children affected (Column 1) and unaffected (2) by the pandemic. Column 3 shows the difference between groups, Column 4 shows the p-value testing the equality of the two means. The number of observations is 12,273 for parents' education level and 13,449 for all other characteristics.

**Table A5:** Characteristics of affected and unaffected children at 6 week immunisation event

| | (1) Affected | (2) Unaffected | (3) Difference | (4) p-value |
|---|---|---|---|---|
| Female | 0.49 | 0.48 | -0.01 | 0.246 |
| European | 0.39 | 0.40 | 0.01 | 0.045 |
| Māori | 0.29 | 0.29 | 0.00 | 0.408 |
| Pacific People | 0.10 | 0.10 | 0.00 | 0.754 |
| Asian | 0.18 | 0.17 | -0.02 | 0.000 |
| Information on mother | 0.99 | 0.99 | 0.00 | 0.105 |
| Information on father | 0.94 | 0.94 | 0.00 | 0.376 |
| Characteristics of parents | | | | |
| Born overseas | 0.41 | 0.40 | -0.01 | 0.013 |
| Married | 0.52 | 0.50 | -0.02 | 0.002 |
| Benefit receipt | 0.22 | 0.24 | 0.01 | 0.009 |
| Bachelor's degree or higher | 0.43 | 0.43 | -0.00 | 0.919 |
| Low earnings | 0.31 | 0.32 | 0.01 | 0.026 |
| Medium earnings | 0.33 | 0.33 | -0.00 | 0.556 |
| High earnings | 0.36 | 0.36 | -0.01 | 0.117 |
| Region of residence | | | | |
| Northland Region | 0.03 | 0.02 | -0.00 | 0.017 |
| Auckland Region | 0.23 | 0.23 | -0.01 | 0.071 |
| Waikato Region | 0.07 | 0.07 | 0.00 | 0.565 |
| Bay of Plenty Region | 0.04 | 0.04 | -0.00 | 0.342 |
| Taranaki Region | 0.01 | 0.02 | 0.00 | 0.067 |
| Manawatu-Wanganui Region | 0.03 | 0.03 | -0.00 | 0.918 |
| Wellington Region | 0.07 | 0.07 | -0.00 | 0.578 |
| Canterbury Region | 0.08 | 0.08 | 0.00 | 0.760 |
| Otago Region | 0.02 | 0.02 | -0.00 | 0.577 |
| Southland Region | 0.01 | 0.01 | -0.00 | 0.993 |
| Gisborne/Hawke's Bay | 0.03 | 0.03 | 0.00 | 0.200 |
| Tasman/Nelson/Marlborough/West Coast | 0.02 | 0.02 | 0.00 | 0.564 |
| Area deprivation level | | | | |
| Low deprivation | 0.14 | 0.14 | -0.00 | 0.787 |
| Medium deprivation | 0.24 | 0.24 | 0.00 | 0.479 |
| High deprivation | 0.62 | 0.62 | -0.00 | 0.666 |

Notes: This table compares average characteristics of children affected (Column 1) and unaffected (2) by the pandemic. Column 3 shows the difference between groups, Column 4 shows the p-value testing the equality of the two means. The number of observations is 12,570 for parents' education level and 13,797 for all other characteristics.

**Table A6:** Child characteristics and vaccine uptake at the 15 month immunisation event

| | 16 months | | | 24 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Ethnicity* | | | | | | | |
| European | 0.81 | $-0.04^{***}$ | (0.01) | 0.89 | 0.01 | (0.01) | 10686 |
| Māori | 0.59 | $-0.04^{***}$ | (0.01) | 0.83 | $-0.03^{***}$ | (0.01) | 7974 |
| Pacific People | 0.69 | $-0.00$ | (0.02) | 0.91 | $-0.02^{*}$ | (0.01) | 2577 |
| Asian | 0.91 | $-0.03^{**}$ | (0.01) | 0.97 | 0.00 | (0.01) | 4290 |
| *Panel B: Sex* | | | | | | | |
| Male | 0.75 | $-0.03^{***}$ | (0.01) | 0.89 | $-0.01$ | (0.01) | 13692 |
| Female | 0.75 | $-0.03^{***}$ | (0.01) | 0.89 | $-0.00$ | (0.01) | 12786 |
| *Panel C: Birth order* | | | | | | | |
| First born | 0.78 | $-0.03^{***}$ | (0.01) | 0.90 | $-0.00$ | (0.01) | 13683 |
| Second born | 0.77 | $-0.03^{**}$ | (0.01) | 0.90 | $-0.01$ | (0.01) | 7983 |
| Third born | 0.70 | $-0.05^{**}$ | (0.02) | 0.85 | $-0.00$ | (0.01) | 3144 |
| Fourth born | 0.54 | $-0.01$ | (0.03) | 0.81 | $-0.01$ | (0.03) | 984 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 15 month immunisation event at age 16 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 24 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A7:** Child characteristics and vaccine uptake at the 5 month immunisation event

| | 6 months | | | 14 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Ethnicity* | | | | | | | |
| European | 0.88 | $-0.00$ | (0.01) | 0.94 | $-0.00$ | (0.00) | 11016 |
| Māori | 0.71 | $-0.05^{***}$ | (0.01) | 0.90 | $-0.05^{***}$ | (0.01) | 8025 |
| Pacific People | 0.82 | $-0.01$ | (0.02) | 0.95 | $-0.02^{*}$ | (0.01) | 2520 |
| Asian | 0.96 | $-0.01^{*}$ | (0.01) | 0.98 | 0.01 | (0.00) | 4956 |
| *Panel B: Sex* | | | | | | | |
| Male | 0.83 | $-0.01$ | (0.01) | 0.93 | $-0.01^{*}$ | (0.00) | 14124 |
| Female | 0.84 | $-0.02^{*}$ | (0.01) | 0.94 | $-0.02^{***}$ | (0.00) | 13440 |
| *Panel C: Birth order* | | | | | | | |
| First born | 0.86 | $-0.01$ | (0.01) | 0.95 | $-0.01^{*}$ | (0.00) | 14055 |
| Second born | 0.85 | $-0.01$ | (0.01) | 0.94 | $-0.01^{*}$ | (0.01) | 8532 |
| Third born | 0.80 | $-0.03^{*}$ | (0.01) | 0.93 | $-0.02^{*}$ | (0.01) | 3288 |
| Fourth born | 0.73 | $-0.07^{*}$ | (0.03) | 0.90 | $-0.06^{**}$ | (0.02) | 1047 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 5 month immunisation event at age 6 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 14 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A8:** Child characteristics and vaccine uptake at the 3 month immunisation event

| | 4 months | | | 12 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Ethnicity* | | | | | | | |
| European | 0.87 | 0.00 | (0.01) | 0.89 | 0.01 | (0.01) | 10557 |
| Māori | 0.75 | $-0.03^{**}$ | (0.01) | 0.83 | $-0.03^{***}$ | (0.01) | 7980 |
| Pacific People | 0.85 | −0.00 | (0.01) | 0.91 | −0.01 | (0.01) | 2649 |
| Asian | 0.97 | −0.01 | (0.01) | 0.98 | −0.00 | (0.00) | 4860 |
| *Panel B: Sex* | | | | | | | |
| Male | 0.85 | −0.01 | (0.01) | 0.89 | −0.01 | (0.01) | 13890 |
| Female | 0.85 | −0.00 | (0.01) | 0.89 | −0.00 | (0.01) | 13149 |
| *Panel C: Birth order* | | | | | | | |
| First born | 0.87 | −0.00 | (0.01) | 0.91 | −0.00 | (0.00) | 14142 |
| Second born | 0.86 | −0.01 | (0.01) | 0.90 | −0.01 | (0.01) | 8133 |
| Third born | 0.81 | −0.00 | (0.01) | 0.86 | −0.00 | (0.01) | 3087 |
| Fourth born | 0.72 | 0.02 | (0.03) | 0.81 | 0.00 | (0.02) | 1005 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 3 month immunisation event at age 4 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 12 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A9:** Child characteristics and vaccine uptake at the 6 week immunisation event

| | 2 months | | | 11 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Ethnicity* | | | | | | | |
| European | 0.92 | 0.01 | (0.01) | 0.92 | $0.01^{*}$ | (0.01) | 10836 |
| Māori | 0.87 | $-0.02^{**}$ | (0.01) | 0.89 | $-0.02^{**}$ | (0.01) | 8028 |
| Pacific People | 0.94 | −0.01 | (0.01) | 0.96 | $-0.02^{*}$ | (0.01) | 2796 |
| Asian | 0.98 | −0.00 | (0.00) | 0.98 | −0.00 | (0.00) | 4839 |
| *Panel B: Sex* | | | | | | | |
| Male | 0.92 | $-0.01^{*}$ | (0.00) | 0.93 | $-0.01^{*}$ | (0.00) | 14184 |
| Female | 0.92 | 0.00 | (0.00) | 0.92 | 0.00 | (0.00) | 13320 |
| *Panel C: Birth order* | | | | | | | |
| First born | 0.93 | −0.00 | (0.00) | 0.94 | −0.00 | (0.00) | 14337 |
| Second born | 0.92 | −0.01 | (0.01) | 0.93 | −0.00 | (0.01) | 8319 |
| Third born | 0.89 | −0.02 | (0.01) | 0.91 | −0.01 | (0.01) | 3174 |
| Fourth born | 0.83 | 0.02 | (0.02) | 0.86 | 0.02 | (0.02) | 1020 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 6 week immunisation event at age 2 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 11 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A10:** Parental characteristics, place of residence and the 15 month immunisation event

| | 16 months | | | 24 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean (1) | Estimate (2) | S.E. (3) | Mean (4) | Estimate (5) | S.E. (6) | (7) |
| *Panel A: Earnings* | | | | | | | |
| Low earnings | 0.64 | $-0.05^{***}$ | (0.01) | 0.85 | $-0.03^{***}$ | (0.01) | 8964 |
| Medium earnings | 0.77 | $-0.02^{*}$ | (0.01) | 0.90 | $-0.00$ | (0.01) | 8529 |
| High earnings | 0.85 | $-0.02^{**}$ | (0.01) | 0.92 | $0.01^{*}$ | (0.01) | 8982 |
| *Panel B: Benefit receipt* | | | | | | | |
| No benefit receipt | 0.81 | $-0.02^{***}$ | (0.01) | 0.91 | 0.01 | (0.00) | 20049 |
| Benefit receipt | 0.56 | $-0.05^{***}$ | (0.01) | 0.83 | $-0.05^{***}$ | (0.01) | 6426 |
| *Panel C: Education level* | | | | | | | |
| No degree | 0.69 | $-0.04^{***}$ | (0.01) | 0.87 | $-0.01^{*}$ | (0.01) | 14298 |
| Bachelor's degree or higher | 0.85 | $-0.01$ | (0.01) | 0.92 | 0.01 | (0.01) | 10401 |
| *Panel D: Marital status* | | | | | | | |
| Unmarried parents | 0.66 | $-0.04^{***}$ | (0.01) | 0.86 | $-0.02^{**}$ | (0.01) | 13212 |
| Married parents | 0.83 | $-0.02^{**}$ | (0.01) | 0.92 | 0.01 | (0.00) | 13266 |
| *Panel E: Birth place* | | | | | | | |
| Born in NZ | 0.70 | $-0.04^{***}$ | (0.01) | 0.86 | $-0.01^{*}$ | (0.01) | 16230 |
| Born overseas | 0.83 | $-0.02^{**}$ | (0.01) | 0.93 | 0.00 | (0.01) | 10248 |
| *Panel F: Region* | | | | | | | |
| Northland Region | 0.61 | $-0.07^{*}$ | (0.03) | 0.80 | $-0.04$ | (0.03) | 1029 |
| Canterbury Region | 0.81 | $-0.02$ | (0.01) | 0.92 | 0.01 | (0.01) | 3213 |
| Otago Region | 0.84 | 0.03 | (0.02) | 0.93 | 0.02 | (0.01) | 1002 |
| Southland Region | 0.80 | $-0.00$ | (0.04) | 0.90 | $-0.01$ | (0.03) | 531 |
| Auckland Region | 0.79 | $-0.04^{***}$ | (0.01) | 0.91 | $-0.02^{**}$ | (0.01) | 8952 |
| Gisborne/Hawke's Bay | 0.64 | 0.01 | (0.03) | 0.85 | $0.05^{**}$ | (0.02) | 1338 |
| Tasman/Nelson/Malborough/West | 0.76 | $-0.04$ | (0.03) | 0.85 | $-0.00$ | (0.02) | 858 |
| Waikato Region | 0.69 | $-0.07^{***}$ | (0.02) | 0.86 | $-0.04^{**}$ | (0.01) | 2898 |
| Bay of Plenty Region | 0.65 | $-0.03$ | (0.02) | 0.83 | $-0.00$ | (0.02) | 1788 |
| Taranaki Region | 0.67 | 0.01 | (0.03) | 0.82 | 0.04 | (0.03) | 732 |
| Manawatu-Wanganui Region | 0.67 | 0.00 | (0.02) | 0.88 | $-0.01$ | (0.02) | 1425 |
| Wellington Region | 0.80 | $-0.02$ | (0.02) | 0.91 | 0.01 | (0.01) | 2691 |
| *Panel G: Area deprivation level* | | | | | | | |
| Low deprivation | 0.84 | $-0.04^{***}$ | (0.01) | 0.91 | 0.01 | (0.01) | 5772 |
| Medium deprivation | 0.78 | $-0.03^{***}$ | (0.01) | 0.90 | $-0.01$ | (0.01) | 9705 |
| High deprivation | 0.67 | $-0.02^{*}$ | (0.01) | 0.87 | $-0.01$ | (0.01) | 11001 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 15 month immunisation event at age 16 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 24 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A11:** Parental characteristics, place of residence and the 5 month event

| | 6 months | | | 14 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean (1) | Estimate (2) | S.E. (3) | Mean (4) | Estimate (5) | S.E. (6) | (7) |
| *Panel A: Earnings* | | | | | | | |
| Low earnings | 0.74 | $-0.03^{**}$ | (0.01) | 0.90 | $-0.03^{***}$ | (0.01) | 9378 |
| Medium earnings | 0.86 | $-0.02^{*}$ | (0.01) | 0.95 | $-0.01^{**}$ | (0.00) | 9111 |
| High earnings | 0.92 | $-0.01^{*}$ | (0.01) | 0.96 | 0.00 | (0.00) | 9072 |
| *Panel B: Benefit receipt* | | | | | | | |
| No benefit receipt | 0.89 | −0.01 | (0.00) | 0.95 | −0.00 | (0.00) | 21621 |
| Benefit receipt | 0.68 | $-0.06^{***}$ | (0.01) | 0.89 | $-0.05^{***}$ | (0.01) | 5943 |
| *Panel C: Education level* | | | | | | | |
| No degree | 0.79 | $-0.02^{***}$ | (0.01) | 0.93 | $-0.03^{***}$ | (0.00) | 13992 |
| Bachelor's degree or higher | 0.91 | −0.01 | (0.01) | 0.96 | 0.00 | (0.00) | 10806 |
| *Panel D: Marital status* | | | | | | | |
| Unmarried parents | 0.77 | $-0.03^{***}$ | (0.01) | 0.92 | $-0.03^{***}$ | (0.01) | 13233 |
| Married parents | 0.90 | −0.01 | (0.01) | 0.96 | −0.00 | (0.00) | 14331 |
| *Panel E: Birth place* | | | | | | | |
| Born in NZ | 0.79 | $-0.02^{***}$ | (0.01) | 0.92 | $-0.02^{***}$ | (0.00) | 16356 |
| Born overseas | 0.91 | $-0.01^{*}$ | (0.01) | 0.96 | −0.00 | (0.00) | 11211 |
| *Panel F: Region* | | | | | | | |
| Northland Region | 0.71 | −0.02 | (0.03) | 0.89 | $-0.05^{*}$ | (0.02) | 1032 |
| Canterbury Region | 0.91 | −0.00 | (0.01) | 0.96 | −0.00 | (0.01) | 3264 |
| Otago Region | 0.91 | 0.00 | (0.02) | 0.96 | 0.01 | (0.01) | 1056 |
| Southland Region | 0.83 | 0.02 | (0.03) | 0.95 | 0.00 | (0.02) | 552 |
| Auckland Region | 0.87 | $-0.03^{***}$ | (0.01) | 0.95 | $-0.01^{**}$ | (0.00) | 9603 |
| Gisborne/Hawke's Bay | 0.75 | 0.01 | (0.02) | 0.92 | $-0.04^{*}$ | (0.02) | 1302 |
| Tasman/Nelson/Malborough/West | 0.80 | $0.06^{*}$ | (0.03) | 0.90 | 0.03 | (0.02) | 879 |
| Waikato Region | 0.78 | −0.03 | (0.02) | 0.92 | $-0.04^{***}$ | (0.01) | 2970 |
| Bay of Plenty Region | 0.76 | −0.03 | (0.02) | 0.89 | −0.01 | (0.01) | 1968 |
| Taranaki Region | 0.84 | $-0.08^{**}$ | (0.03) | 0.95 | $-0.07^{***}$ | (0.02) | 720 |
| Manawatu-Wanganui Region | 0.79 | 0.00 | (0.02) | 0.92 | 0.00 | (0.01) | 1434 |
| Wellington Region | 0.89 | −0.00 | (0.01) | 0.96 | −0.00 | (0.01) | 2760 |
| *Panel G: Area deprivation level* | | | | | | | |
| Low deprivation | 0.90 | −0.01 | (0.01) | 0.95 | 0.00 | (0.01) | 5814 |
| Medium deprivation | 0.86 | −0.01 | (0.01) | 0.94 | −0.01 | (0.00) | 10032 |
| High deprivation | 0.79 | $-0.02^{**}$ | (0.01) | 0.93 | $-0.03^{***}$ | (0.01) | 11715 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 5 month immunisation event at age 6 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 14 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A12:** Parental characteristics, place of residence and the 3 month immunisation event

| | 4 months | | | 12 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Earnings* | | | | | | | |
| Low earnings | 0.77 | $-0.02^{*}$ | (0.01) | 0.84 | $-0.02^{**}$ | (0.01) | 8784 |
| Medium earnings | 0.87 | 0.00 | (0.01) | 0.90 | 0.00 | (0.01) | 8865 |
| High earnings | 0.92 | $-0.00$ | (0.01) | 0.93 | 0.00 | (0.01) | 9387 |
| *Panel B: Benefit receipt* | | | | | | | |
| No benefit receipt | 0.89 | 0.00 | (0.00) | 0.92 | 0.00 | (0.00) | 20841 |
| Benefit receipt | 0.72 | $-0.05^{***}$ | (0.01) | 0.81 | $-0.05^{***}$ | (0.01) | 6198 |
| *Panel C: Education level* | | | | | | | |
| No degree | 0.81 | $-0.02^{*}$ | (0.01) | 0.87 | $-0.02^{**}$ | (0.01) | 13944 |
| Bachelor's degree or higher | 0.92 | $-0.00$ | (0.01) | 0.93 | 0.01 | (0.00) | 10314 |
| *Panel D: Marital status* | | | | | | | |
| Unmarried parents | 0.80 | $-0.02^{*}$ | (0.01) | 0.86 | $-0.02^{**}$ | (0.01) | 13260 |
| Married parents | 0.91 | $-0.00$ | (0.00) | 0.93 | 0.00 | (0.00) | 13776 |
| *Panel E: Birth place* | | | | | | | |
| Born in NZ | 0.81 | $-0.02^{*}$ | (0.01) | 0.86 | $-0.01^{**}$ | (0.01) | 16008 |
| Born overseas | 0.91 | 0.00 | (0.01) | 0.93 | 0.00 | (0.00) | 11031 |
| *Panel F: Region* | | | | | | | |
| Northland Region | 0.73 | $-0.01$ | (0.03) | 0.81 | $-0.02$ | (0.02) | 1050 |
| Canterbury Region | 0.90 | 0.00 | (0.01) | 0.92 | 0.00 | (0.01) | 3234 |
| Otago Region | 0.92 | $-0.00$ | (0.02) | 0.93 | 0.01 | (0.02) | 1014 |
| Southland Region | 0.86 | $-0.01$ | (0.03) | 0.91 | 0.01 | (0.03) | 516 |
| Auckland Region | 0.88 | $-0.01$ | (0.01) | 0.92 | $-0.01$ | (0.01) | 9447 |
| Gisborne/Hawke's Bay | 0.80 | $-0.02$ | (0.02) | 0.89 | $-0.03$ | (0.02) | 1302 |
| Tasman/Nelson/Malborough/West | 0.83 | 0.03 | (0.03) | 0.84 | 0.04 | (0.02) | 840 |
| Waikato Region | 0.80 | $-0.01$ | (0.01) | 0.85 | $-0.00$ | (0.01) | 2970 |
| Bay of Plenty Region | 0.77 | 0.01 | (0.02) | 0.82 | 0.01 | (0.02) | 1776 |
| Taranaki Region | 0.83 | $-0.05$ | (0.03) | 0.87 | $-0.04$ | (0.03) | 693 |
| Manawatu-Wanganui Region | 0.81 | $-0.01$ | (0.02) | 0.86 | $-0.01$ | (0.02) | 1413 |
| Wellington Region | 0.89 | 0.01 | (0.01) | 0.92 | 0.01 | (0.01) | 2742 |
| *Panel G: Area deprivation level* | | | | | | | |
| Low deprivation | 0.89 | 0.00 | (0.01) | 0.91 | $0.02^{*}$ | (0.01) | 5568 |
| Medium deprivation | 0.87 | $-0.01$ | (0.01) | 0.90 | $-0.00$ | (0.01) | 9873 |
| High deprivation | 0.81 | $-0.01$ | (0.01) | 0.87 | $-0.02^{*}$ | (0.01) | 11598 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 3 month immunisation event at age 4 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 12 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A13:** Parental characteristics, place of residence and the 6 week immunisation event

| | 2 months | | | 11 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean | Estimate | S.E. | Mean | Estimate | S.E. | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Earnings* | | | | | | | |
| Low earnings | 0.88 | $-0.02^{**}$ | (0.01) | 0.90 | $-0.02^{**}$ | (0.01) | 8580 |
| Medium earnings | 0.93 | 0.00 | (0.01) | 0.93 | 0.00 | (0.01) | 9012 |
| High earnings | 0.95 | 0.00 | (0.00) | 0.95 | 0.00 | (0.00) | 9912 |
| *Panel B: Benefit receipt* | | | | | | | |
| No benefit receipt | 0.93 | 0.00 | (0.00) | 0.94 | 0.00 | (0.00) | 21180 |
| Benefit receipt | 0.87 | $-0.03^{***}$ | (0.01) | 0.89 | $-0.03^{***}$ | (0.01) | 6324 |
| *Panel C: Education level* | | | | | | | |
| No degree | 0.90 | $-0.01^{*}$ | (0.01) | 0.91 | $-0.01^{*}$ | (0.00) | 14100 |
| Bachelor's degree or higher | 0.94 | 0.00 | (0.00) | 0.95 | 0.00 | (0.00) | 10512 |
| *Panel D: Marital status* | | | | | | | |
| Unmarried parents | 0.90 | $-0.02^{**}$ | (0.01) | 0.91 | $-0.01^{**}$ | (0.01) | 13437 |
| Married parents | 0.94 | 0.00 | (0.00) | 0.94 | 0.00 | (0.00) | 14064 |
| *Panel E: Birth place* | | | | | | | |
| Born in NZ | 0.90 | $-0.01^{*}$ | (0.00) | 0.91 | $-0.01^{*}$ | (0.00) | 16326 |
| Born overseas | 0.95 | 0.00 | (0.00) | 0.95 | 0.00 | (0.00) | 11172 |
| *Panel F: Region* | | | | | | | |
| Northland Region | 0.82 | 0.01 | (0.03) | 0.85 | 0.02 | (0.03) | 729 |
| Canterbury Region | 0.94 | $0.02^{*}$ | (0.01) | 0.94 | $0.02^{*}$ | (0.01) | 2196 |
| Otago Region | 0.94 | 0.00 | (0.02) | 0.94 | 0.01 | (0.02) | 666 |
| Southland Region | 0.93 | 0.03 | (0.03) | 0.93 | 0.03 | (0.03) | 348 |
| Auckland Region | 0.94 | $-0.01^{*}$ | (0.01) | 0.95 | $-0.01^{*}$ | (0.01) | 6327 |
| Gisborne/Hawke's Bay | 0.90 | −0.02 | (0.02) | 0.93 | −0.03 | (0.02) | 864 |
| Tasman/Nelson/Malborough/West | 0.88 | 0.02 | (0.03) | 0.90 | 0.01 | (0.02) | 537 |
| Waikato Region | 0.87 | −0.01 | (0.01) | 0.88 | −0.01 | (0.01) | 1959 |
| Bay of Plenty Region | 0.86 | 0.02 | (0.02) | 0.88 | 0.02 | (0.02) | 1182 |
| Taranaki Region | 0.89 | −0.01 | (0.03) | 0.91 | −0.01 | (0.03) | 447 |
| Manawatu-Wanganui Region | 0.92 | $-0.04^{*}$ | (0.02) | 0.94 | −0.03 | (0.02) | 936 |
| Wellington Region | 0.95 | −0.01 | (0.01) | 0.95 | −0.00 | (0.01) | 1851 |
| *Panel G: Area deprivation level* | | | | | | | |
| Low deprivation | 0.93 | 0.01 | (0.01) | 0.93 | 0.01 | (0.01) | 3750 |
| Medium deprivation | 0.92 | −0.00 | (0.01) | 0.93 | 0.00 | (0.01) | 6606 |
| High deprivation | 0.91 | $-0.01^{*}$ | (0.00) | 0.93 | $-0.01^{**}$ | (0.00) | 17145 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 6 week immunisation event at age 2 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 11 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

**Table A14:** Place of residence and the 4 year immunisation event

| | 49 months | | | 57 months | | | N |
|---|---|---|---|---|---|---|---|
| | Mean (1) | Estimate (2) | S.E. (3) | Mean (4) | Estimate (5) | S.E. (6) | (7) |
| *Panel A: Region* | | | | | | | |
| Northland Region | 0.46 | $-0.13^{***}$ | (0.03) | 0.78 | $-0.09^{**}$ | (0.03) | 1116 |
| Canterbury Region | 0.67 | $-0.16^{***}$ | (0.02) | 0.94 | $-0.02^{**}$ | (0.01) | 3105 |
| Otago Region | 0.72 | $-0.18^{***}$ | (0.03) | 0.94 | $-0.04^{**}$ | (0.02) | 1038 |
| Southland Region | 0.72 | $-0.19^{***}$ | (0.04) | 0.93 | $-0.04$ | (0.02) | 564 |
| Auckland Region | 0.65 | $-0.15^{***}$ | (0.01) | 0.92 | $-0.06^{***}$ | (0.01) | 8610 |
| Gisborne/Hawke's Bay | 0.45 | $-0.16^{***}$ | (0.03) | 0.88 | $-0.11^{***}$ | (0.02) | 1338 |
| Tasman/Nelson/Malborough/West | 0.65 | $-0.06$ | (0.03) | 0.89 | $-0.01$ | (0.02) | 870 |
| Waikato Region | 0.47 | $-0.19^{***}$ | (0.02) | 0.89 | $-0.13^{***}$ | (0.01) | 2928 |
| Bay of Plenty Region | 0.56 | $-0.12^{***}$ | (0.02) | 0.88 | $-0.07^{***}$ | (0.02) | 1830 |
| Taranaki Region | 0.57 | $-0.10^{**}$ | (0.04) | 0.90 | $-0.05$ | (0.02) | 753 |
| Manawatu-Wanganui Region | 0.57 | $-0.09^{***}$ | (0.03) | 0.89 | $-0.03$ | (0.02) | 1422 |
| Wellington Region | 0.66 | $-0.13^{***}$ | (0.02) | 0.93 | $-0.06^{***}$ | (0.01) | 2562 |
| *Panel B: Area deprivation level* | | | | | | | |
| Low deprivation | 0.69 | $-0.18^{***}$ | (0.01) | 0.95 | $-0.04^{***}$ | (0.01) | 6108 |
| Medium deprivation | 0.63 | $-0.14^{***}$ | (0.01) | 0.91 | $-0.04^{***}$ | (0.01) | 9396 |
| High deprivation | 0.54 | $-0.14^{***}$ | (0.01) | 0.88 | $-0.10^{***}$ | (0.01) | 10635 |

Notes: This table summarises the heterogeneous effects of the pandemic on the 4 year immunisation event at age 49 months (mean of the unaffected cohort in column 1, point estimate in column 2, robust standard error in column 3) and 57 months (columns 4 to 6). Each estimate represents the results from a separate regression for a subgroup of the sample indicated on the left. All regressions include controls for the child's calendar month of birth and sex. $^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$.

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