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The Impact of National Income and Vaccine Hesitancy on Country-Level COVID-19 Vaccine Uptake

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Abstract

Background: The rapid development and rollout of COVID-19 vaccines helped reduce the pandemic's mortality burden. The vaccine rollout, however, has been uneven; it is well known that vaccination rates tend to be lower in lower income countries. Vaccine uptake, however, ultimately depends on the willingness of individuals to get vaccinated. We investigated the impact on country-level COVID-19 vaccination rates of both national income and vaccine hesitancy. **Methods:** We estimated linear regression models of COVID-19 vaccine uptake across 147 countries. Vaccine uptake reflects the percentage of the population that had completed their primary vaccination series. Covariates include per capita GDP, and an estimate of the percentage of country residents who strongly disagreed that vaccines are safe. We estimated this model at each of four time points: 6, 12, 18, and 24 months after the onset of global vaccine distribution. Next, we estimated these models by time point and by country income quintile (bottom 40% and top 40%) to examine whether the impact of vaccine hesitancy varies by country income. **Results:** We find that GDP per capita has a pronounced impact on vaccine uptake starting at 6 months after global rollout. After controlling for hesitancy and other factors, there was a 23% difference in vaccination rates between the top 20% and the bottom 20% of countries ranked by per capita GDP; this difference grew to 39% by 12 months. The deleterious impact of vaccine hesitancy on vaccine uptake became apparent by 12 months and then increased over time. At 24 months, there was a 20% difference in vaccination rates between the top 20% and the bottom 20% of countries ranked by hesitancy. The income stratified models reveal that the deleterious impact of vaccine hesitancy on vaccine uptake is limited to lower income countries; hesitancy had only small effects on vaccination rates in higher income countries. **Conclusions:** Our study highlights the crucial role of both national income and vaccine hesitancy in determining COVID-19 vaccine uptake globally. There is a need to increase the supply and distribution of pandemic vaccines to low-income countries, and to take measures to improve vaccine confidence in these countries.

Keywords: COVID-19; vaccination; global rollout; vaccine hesitancy; equity

1. Introduction

Coronavirus disease-2019 (COVID-19) was declared a pandemic by the World Health Organization (WHO) in March 2020 [1]. Remarkably, the first COVID-19 vaccines were launched only nine months later, in December 2020 [2,3]. By July 2022, 12 billion COVID-19 vaccine doses had been administered globally and two thirds of the global population had received at least one dose [4]. Most vaccines have been found to reduce infection and mortality rates [3,5,6]. The rapid roll-out of vaccines has thus markedly reduced the mortality and morbidity burden of the COVID-19 pandemic [7].

Vaccine uptake, however, has varied across countries. Auld and Toxvaerd [8] report that COVID-19 vaccine uptake in March 2021 was much higher in higher-income countries than in low income countries. Basak and colleagues report the same findings for vaccine uptake at December 2021 [9].

Understanding the uptake of pandemic vaccines across countries has implications for global vaccine policy. One reason is equity – ideally, those who bear the highest mortality or morbidity risk should be afforded the opportunity to get vaccinated regardless of their country of residence [10,11]. Another reason is efficiency -- the duration and intensity of the global pandemic depends on the distribution of the vaccine across countries. One would want to vaccinate those who would otherwise pose the greatest risk of transmitting the virus, or its variants, regardless of where they reside. Global COVID-19 mortality, estimated at 6.8 million deaths as of February 2023, [4] could have been reduced had distribution been more efficient [12–15].

In this paper, we extend the extant literature in several ways to gather additional insights into the global roll-out of the pandemic vaccines. We do so by estimating linear regression models of country-level COVID-19 vaccine uptake, focusing on the role of two factors: country income and vaccine hesitancy. Income is captured by per capita gross domestic product (GDP) and country population. GDP per capita is a good measure of a country's ability to pay and acquire priority access to vaccines, as is clear from the empirical evidence presented by Auld and Toxvaerd, and Basak and colleagues [8,9]. It is also likely correlated with a country's ability to distribute vaccines to its residents. The total size of the market, measured using the country population, may also matter. It seems plausible that vaccine manufacturers may prioritize allocations to countries that offer larger total sales. But country income alone does not explain vaccine uptake. If there is widespread mistrust of vaccine safety and efficacy, then vaccine uptake will be low, regardless of the ability of a country to procure and distribute vaccine doses. Thus, we also include in our vaccine uptake model covariates that reflect vaccine hesitancy.

The roles of market size and vaccine hesitancy likely vary over time. Six months after vaccines first became available, many countries, both low [16] and high income [17,18], struggled to procure enough vaccine for residents who were willing to get immunized. Thus, vaccine hesitancy likely played little, if any, role in determining COVID-19 vaccine uptake. Later, in high income countries at least, there were enough vaccines for everyone to get vaccinated. Vaccine hesitancy likely became the limiting factor.

We explored the relative impacts of market size and vaccine hesitancy by estimating four models of country level vaccine uptake, at 6, 12, 18 and 24 months after the start of the global roll-out of COVID-19 vaccines. We also estimate variants of these models in which the impact of vaccine hesitancy on vaccine uptake is permitted to vary by country income. This allows us to determine if hesitancy played a larger role in vaccine uptake in high income countries 24 months post global roll-out than in low-income countries.

2. Methods

Our outcome variable, y_{it}, is the percentage of residents of country i who completed the initial vaccination protocol (2 doses for most vaccines, 1 or 3 for a few manufacturers) at the end of month t (t = June 2021, December 2021, June 2022, December 2022). Most of the vaccines given Emergency Use Listing status by the WHO at January 2022 require two doses. These include Pfizer/BioNTech (BNT162b2) [19], Oxford/AstraZeneca (ChAdOx1-S) [20], Moderna (mRNA-1273) [21], Sinopharm [22], Sinovac-CoronaVac [23], Bharat Biotech BBV152 COVAXIN [24], and Novavax [25]. The Janssen Ad26.COV2.S is the sole single-shot vaccine [26].

We used vaccine uptake and population data assembled by Our World in Data (OWD) to estimate y_{it} [4]. OWD analysts use the official numbers periodically reported by governments and health ministries for 226 jurisdictions to generate daily cumulative estimates of y_i [3]. The types of COVID-19 vaccines approved in each jurisdiction differ. Some countries rely on vaccines that have been given Emergency Use Listing status by the WHO; others do not.

We assumed that no vaccinations were provided in country i prior to the date that y_i was first reported by OWD. If data on y_i was unavailable at the end of month t, but data were available for an earlier and a later date, we used an interpolated value. If there were no data reported after the end of month t, we used the most recent available estimate. In most cases, the estimate we relied on was reported earlier in the same month, typically within a week of the target date. One country in our analysis sample, the United Arab Emirates, had an apparent data error: the percentage of people who completed the initial vaccination protocol exceed 100% for the final two values of t. We replaced these values with 100%.

Country level covariates reflect year 2020 values, except as otherwise noted. Country level data on GDP per capita were obtained from the International Monetary Fund (IMF) [27]. GDP was converted into U.S. dollar equivalents using average annual market exchange rates. There were no 2020 GDP data for one country in our analysis sample, Syria, and the most recent IMF estimate, for 2010, was too out-of-date. We therefore used the World Bank estimate for 2020 [28]. Data on country population, both totals and by age group, were obtained from the United Nations 2022 Revision of its World Population Prospects report [29].

Country level vaccine hesitancy was measured using several covariates. The primary covariate is the estimated percentage of residents who, as of December 2019, strongly disagreed with the statement that vaccines are safe. Data come from de Figueiredo and colleagues [30], who summarized various aspects of country-wide vaccine confidence using data from 290 surveys administered in 149 countries between September 2015 and December 2019. We focused on beliefs about vaccine safety. Although people's opinion about importance or effectiveness of vaccines may have played a role in the uptake of other vaccines, concern about side effects of COVID-19 vaccines was the most common reason for hesitancy [30,31].

We measured vaccine hesitancy using several additional covariates. These include the percentage of the population over 25 years who have post-secondary education and the elderly (age $\geq$ 65) share of the population. We hypothesized that individuals with more years of education and older adults are more accepting of vaccines. Those who are highly educated may be less influenced by misinformation campaigns and the elderly may be less concerned about any adverse effects of the COVID-19 vaccine than COVID-19 disease itself. Educational attainment data were obtained from projections for 2020 made by the Wittgenstein Centre for Demography and Global Human Capital [32]. The elderly share of the population was estimated using the United Nations population data.

In addition to these market size and vaccine hesitancy covariates, we controlled for population density, a variable that has been shown to be an important predictor of the uptake of vaccines [33,34]. This makes intuitive sense: residents of population dense countries will tend to be closer to a given number of vaccination centers than residents of countries in which populations are geographically dispersed. We used population weighted density estimated by the University of Southampton [35]. The standard density measure, people per square kilometer of land area, does not reflect the fact that in large countries like Australia, Canada and Russia, most of the population is concentrated in urban centres and vast swathes of land are uninhabited. The population weighted density we use divides the country into regions of size 100 squared metres and computes the geometric weighted average of the people per region where the weights are the fraction of the country population who live in the region. Uninhabited regions thus receive zero weight in this population density measure.

We also controlled for the geographic region in which the country is located: Western Europe, Eastern Europe and Central Asia, South Asia, East Asia and the Pacific, Middle East and North Africa, Sub-Saharan Africa, North America, and Latin America and the Caribbean. Western Europe formed the reference category. These locational indicators are intended to capture additional factors that affect market size, the capacity of the country to procure and distribute vaccines, or vaccine hesitancy. Ethics approval was not needed given that this study relies on aggregated, national-level data.

Our analysis sample consisted of 147 countries; this consisted of all but two of the jurisdictions for which vaccine hesitancy data were available. (The two jurisdictions with hesitancy data but no data on vaccine uptake were North Cyprus and Kosovo.) The population of the countries in the analysis sample constitute over 97% of the world population in 2020.

When positing the structure of a linear regression model of a fractional outcome, such as the vaccinated share of the population, some analysts log-transform continuous covariates [33]. We used a different functional form. For each continuous covariate, we grouped countries in the analysis sample into 5 quintiles and represented group membership with 4 indicator variables. The bottom 20% of countries for each covariate formed the reference group in each case. For instance, the indicator for the top income quintile equals one for the 20% of countries with the highest per capita GDP. The use of quintile indicators allows for a more flexible relationship between the covariate and vaccine uptake than does the log transform. Moreover, the use of quintile indicators minimizes the impact of mismeasurement in the covariate when the mismeasured and actual covariate values are in the same quintile.

We estimated the parameters of the regression models using ordinary least squares (OLS). Because the error term variance may vary across observations (i.e., the errors might be heteroskedastic), we estimated the OLS standard errors using the heteroskedasticity-robust covariance matrix estimator. We also estimated the standard errors of the income-stratified models using wild bootstrap estimator [36] as this estimator has been shown to be more reliable in smaller samples.

3. Results

Table 1 presents summary statistics for the outcome and explanatory variables across the 147 countries in the analysis sample. The mean percentage of the country population fully vaccinated against COVID-19 increased from 14% as of June 2021, to 43% in December 2021, and to 54% in December 2022. The estimated standard deviation for the four vaccine uptake variables was highest for the December 2021 measure. At this time, vaccine uptake varied from 0% in Ethiopia to 96% in the United Arab Emirates.

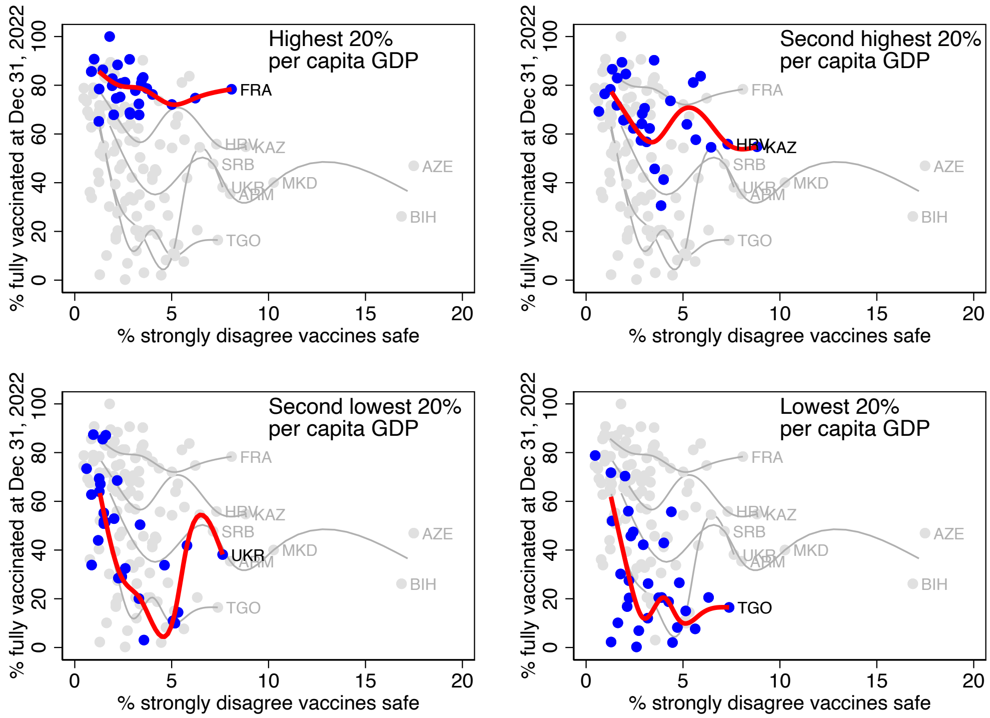
Per capita GDP varies markedly across countries, from the equivalent of $260 USD in Burundi to $117,064 USD in Luxembourg. Population size also varies widely, from 366,669 (Iceland) to 1.4 billion (China). The percentage of the population that strongly disagrees that vaccines are safe varies from 0.46% in Thailand to 17.49% in Azerbaijan; the mean is 3.3%. The percentage of the population 25+ with post-secondary education varies from 0.6% in Yemen to 64% in Canada. The elderly share of the population varies from 1.7% in the United Arab Emirates to 29.6% in Japan. Population weighted density varies from 46.9 in Botswana to 46,721 in Hong Kong.

Table 1 Summary statistics for outcome and explanatory variables.

VARIABLES	Count	Mean	SD	Min	Max
% Fully vaccinated (Jun 30, 2021)	147	13.87	16.46	0	65.31
% Fully vaccinated (Dec 31, 2021)	147	42.88	27.04	0	96.40
% Fully vaccinated (Jun 30, 2022)	147	50.74	26.65	0.116	100
% Fully vaccinated (Dec 31, 2022)	147	53.82	25.36	0.230	100
GDP per capita (constant 2015 US$)	147	14,618	20,471	259.9	117,064
Population (Million)	146	52.12	168.2	0.37	1411
% Strongly disagree that vaccine is safe	147	3.250	2.488	0.460	17.49
% Of 25+ with post-secondary education	147	20.06	13.27	0.600	63.80
% Age 65 or older	147	9.868	6.927	1.654	29.58
Population Weighted Density	147	1,567	4,305	46.90	46,721

Figure 1 displays vaccination rates at December 31, 2022, by the percentage of the population that strongly disagrees that vaccines are safe. Each panel highlights in blue observations on countries in a different income quintile and fits a spline curve to these observations. The data indicate that vaccination rates tend to be lower, the lower is per capita GDP. Also, within an income quintile, vaccination rates tend to be lower in countries with a greater degree of vaccine hesitancy.

Fig 1. Vaccination rates at December 31, 2022, by % of population that strongly disagrees that vaccines are safe.



Note: each panel highlights observations on countries in a different income quintile and fits a spline curve to these observations. Countries in which more than 7% of the population strongly disagrees that vaccines are safe are labelled. FRA = France, HRV = Croatia, SRB = Serbia, UKR = Ukraine, ARM = Armenia, AZE = Azerbaijan, BIH = Bosnia and Herzegovina, KAZ = Kazakhstan, MKD = North Macedonia, TGO = Togo.

Table 2 presents the vaccine uptake regression parameter estimates. Recall that we estimated the models of the share of the population that was fully vaccinated at four different dates: June 30, 2021, Dec. 31, 2021, June 30, 2022, and Dec. 31, 2022. The table reports, for each model, the estimated parameter, the standard error (in parentheses), and stars indicating the size of the p-value for a t-test that the parameter is equal to zero. The table also reports the number of observations and the unadjusted R square for each model.

Table 2 Estimated regression models for percentage of population fully vaccinated at 6, 12, 18 and 24 months post global roll-out.

Covariates	Vaccine uptake at: 2021-06-30	Vaccine uptake at: 2021-12-31	Vaccine uptake at: 2022-06-30	Vaccine uptake at: 2021-12-31
GDP per capita:				
Second quantile	4.346	7.764*	7.684	5.662
	(2.759)	(4.562)	(4.887)	(5.792)
Third quantile	4.798	10.28*	7.570	4.921
	(3.950)	(5.787)	(6.342)	(7.008)
Fourth quantile	14.09***	30.44***	26.97***	25.47***
	(4.774)	(6.708)	(7.142)	(7.750)
Fifth quantile	23.06**	39.09***	38.39***	36.90***
	(9.792)	(12.37)	(12.69)	(12.93)
Population:				
Second quantile	-5.547	-7.131*	-3.771	-2.930
	(3.875)	(4.026)	(4.567)	(4.928)
Third quantile	-3.680	-4.130	-4.418	-4.244
	(3.705)	(3.757)	(3.969)	(4.177)
Fourth quantile	-11.41***	-9.236**	-8.783**	-7.416*
	(3.535)	(3.952)	(4.079)	(4.321)
Fifth quantile	-9.670***	-8.495**	-3.689	-1.943
	(3.565)	(4.177)	(4.170)	(4.355)
% Strongly disagree that vaccine is safe:				
Second quantile	2.111	-3.967	-6.293	-6.029
	(3.735)	(4.458)	(5.163)	(5.478)
Third quantile	2.746	-11.59***	-16.71***	-16.58***
	(3.067)	(4.299)	(5.234)	(5.626)
Fourth quantile	1.896	-14.21***	-20.93***	-21.69***
	(2.678)	(4.087)	(5.200)	(5.446)
Fifth quantile	-0.399	-12.05***	-18.04***	-19.91***
	(2.999)	(4.379)	(5.673)	(6.055)
% Of 25+ with post-secondary education:				
Second quantile	-1.303	0.0856	-2.005	-2.474
	(2.869)	(4.877)	(5.079)	(6.020)
Third quantile	-1.160	7.361	5.345	4.055
	(3.523)	(5.761)	(6.341)	(7.017)
Fourth quantile	2.125	3.917	2.745	2.346
	(4.946)	(6.065)	(6.603)	(7.363)
Fifth quantile	-6.165	1.232	-2.633	-3.531
	(5.858)	(7.645)	(8.319)	(8.866)
% Age 65 or older:				
Second quantile	-6.407*	0.0156	4.880	5.220
	(3.595)	(5.822)	(6.451)	(7.189)

Covariates	Vaccine uptake at: 2021-06-30	Vaccine uptake at: 2021-12-31	Vaccine uptake at: 2022-06-30	Vaccine uptake at: 2021-12-31
Third quantile	-4.146	13.01	15.64*	15.79*
	(5.557)	(7.880)	(8.004)	(8.395)
Fourth quantile	-0.173	7.974	10.74	11.65
	(7.404)	(9.576)	(10.01)	(10.42)
Fifth quantile	6.307	13.41	15.80	14.74
	(7.742)	(10.70)	(10.62)	(10.67)
Population Weighted Density:				
Second quantile	-0.509	-1.361	-2.270	-0.776
	(2.891)	(2.896)	(3.372)	(4.029)
Third quantile	-0.867	0.719	0.413	0.0985
	(2.915)	(3.651)	(4.182)	(4.512)
Fourth quantile	2.921	4.773	4.722	4.097
	(3.557)	(3.741)	(4.146)	(4.537)
Fifth quantile	3.303	2.203	0.0881	-0.547
	(3.645)	(3.952)	(4.798)	(5.347)
Continents:				
East Asia and the Pacific	-7.987	8.710	10.15*	8.807*
	(5.561)	(6.277)	(5.180)	(4.529)
Eastern Europe and Central Asia	-4.529	-7.184	-4.869	-5.451
	(7.096)	(6.735)	(6.560)	(6.292)
Latin America and the Caribbean	-0.978	4.151	7.042	6.462
	(6.419)	(7.346)	(7.164)	(6.836)
Middle East and North Africa	1.466	-6.981	-10.38	-12.11*
	(7.309)	(7.569)	(7.097)	(6.454)
North America	10.58	6.579	8.686	8.051
	(9.722)	(6.600)	(9.225)	(9.591)
South Asia	-2.962	0.107	9.855	11.65
	(6.435)	(9.000)	(8.537)	(8.475)
Sub-Saharan Africa	-8.042	-7.797	-3.858	0.691
	(7.219)	(7.948)	(8.021)	(7.948)
Constant	14.52	31.34***	40.96***	45.15***
	(9.524)	(10.06)	(10.65)	(10.79)
Observations	147	147	147	147
R-squared	0.680	0.833	0.799	0.737
Robust standard errors in parentheses	*** p<0.01, ** p<0.05, * p<0.1			

We first examine the role of GDP per capita in explaining vaccine uptake at successive dates after the initial global vaccine roll-out. At 6 months post roll-out (June 30, 2021), we find a gradient in vaccination rates by GDP quintile. Countries in the top 20% of the distribution of per capita GDP have vaccinated an additional 23% of their residents compared to countries in the bottom quintile. The vaccination rate difference for the countries in the second highest quintile and those at the bottom are 14%. Countries in the second and third quintile have only slightly higher (4 to 5%) vaccine uptake than those in the lowest quintile group; these differences are not statistically significant at conventional levels.

The high-income advantage increases in the 12-month model (Dec. 31, 2021). Now the countries in the top 20% of the distribution of per capita GDP have vaccinated an additional 39% of their residents compared to countries in the bottom quintile. Countries in the second quintile have vaccinated an additional 30% of their residents compared to countries in the bottom quintile.

The difference in vaccine uptake between the countries in the top two income quintiles and those in the bottom quintile decrease slightly during 2022. This may reflect growth in the vaccine uptake of the bottom quintile; as evidence, the estimated constant increases from 15% at 6 months post roll-out to 45% at 24 months post roll-out.

The impact of population size on vaccine uptake also varies over time. At 6 months post roll-out, the largest countries – those in the fifth population size quintile – have vaccination rates that are about 10% lower than those in the smallest countries. The population-size-related differences in vaccine uptake, however, largely disappear over time. The magnitude of the estimated differences between population quintiles are much smaller and not significant at conventional levels in the 18- and 24-month models. The 6-month results may thus simply reflect the fact that it takes longer to vaccinate a large country than a smaller country.

We turn next to the impact on vaccine uptake of vaccine hesitancy, as measured by the percentage of the population that, just prior to the COVID-19 pandemic, strongly disagreed with the statement that vaccines are safe. Recall the covariate is measured using indicators of its 5 quintiles, with the indicator of the fifth quintile capturing the 20% of countries with the highest share of the population who feel that vaccines are unsafe. The inter-quintile differences get larger in the model of vaccine uptake 18 months post roll-out, suggesting that the role of vaccine hesitancy becomes more pronounced as a greater share of the population becomes vaccinated. These differences do not change appreciably between the 18-month and 24-month models.

Two groups of covariates had negligible estimated impacts on vaccine uptake at each of the four timepoints. These were the share of the population 25+ with post-secondary education, and population weighted density. There is some tentative evidence that countries with the largest elderly share of the population vaccinated a larger share of the population compared to those with the smallest elderly share. These estimates, however, have large estimated standard errors.

After controlling for GDP, vaccine hesitancy and other covariates, the geographic region in which a country is located has no consistent impact on vaccine uptake. The two possible exceptions are the countries located in the East Asia and the Pacific, and those in the Middle East and North Africa. At 24 months post global roll-out, the former countries have about an 9% higher vaccination rate, while the latter countries have a 12% lower vaccination rate compared to countries in the reference group (Western Europe).

The model fit, measured by the adjusted R squared, increases from 60% in the 6-month model, to 79% in the 12 month model and to 74% in the 18 month model; the R squared declines to 67% in the 24 month model. This indicates that the national income, vaccine hesitancy, and the remaining covariates explain most of the international variation in vaccine uptake in the period 12-18 months after first global vaccine roll-out.

Subgroup analyses

We re-estimated the regression model for vaccine uptake at 12 and at 24 months post global roll-out, allowing the model parameters to vary by GDP per capita. To do so, we estimate the models separately for the countries in the bottom 40% of countries by GDP per capita and in the top 40% of countries. We included indicators of the quintiles of the percentage who feel vaccines are unsafe, and geographic region. We used the natural logarithm of GDP per capita, instead of the quintile indicators given the smaller sample sizes. We excluded the remaining covariates given that these were largely insignificant in the 12-, 18- and 24-month models.

Estimates for vaccine uptake at 12 months post global roll-out appear in Table 3. We find that the estimated impact of vaccine hesitancy varies markedly between subgroups. In the high-income subgroup, vaccine hesitancy explains little of the country difference in vaccine uptake. In the low-income subgroup, however, vaccine uptake is 20% lower (in absolute terms) among countries in the highest quintile of vaccine hesitancy, compared to countries with the smallest quintile. The vaccine uptake difference is even more pronounced, at 22%, between the second highest and lowest quintile of vaccine hesitancy.

Among the lower income countries, there are large income related differences in vaccine uptake; there are no material income related differences in vaccine uptake among the higher income countries.

The geographic region indicators in the low-income subgroup reflect region level differences relative to the Sub-Saharan Africa low-income countries. (There are no Western European or North American countries in the low-income subgroup.) All regional groups, except for the Middle East and North African countries, have higher vaccination rates than in the Sub-Saharan Africa low-income countries. However only the Europe and Central Asia group of countries have vaccination rates that are significantly higher at conventional levels.

The geographic region indicators in the high-income subgroup reflect region level differences relative to the Western European countries. These indicators are largely insignificant, except for the Eastern Europe and Central Asia region countries, in which vaccination rates are 18% lower.

Table 3 Estimated regression models of percentage of population fully vaccinated at 12 months post global roll-out. Models stratified by income: countries in bottom two quintiles of per capita GDP and countries in top two quintiles of per capita GDP.

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2021	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2021
GDP per capita:		
Second quantile	11.63***	
	(3.901)	
Fifth quantile		0.627
		(4.593)
% Strongly disagree that vaccine is safe:		
Second quantile	-5.097	-1.142
	(7.607)	(5.879)
Third quantile	-17.12**	-0.969
	(7.732)	(4.884)
Fourth quantile	-20.80***	-2.387
	(7.032)	(4.868)
Fifth quantile	-18.95***	-2.091
	(6.763)	(3.943)
Continents:		
East Asia and the Pacific	17.75	4.831
	(11.83)	(5.303)
Eastern Europe and Central Asia	12.32***	-18.30***
	(4.432)	(5.673)
Latin America and the Caribbean	16.95**	-0.836
	(7.084)	(7.609)
Middle East and North Africa	1.567	0.997
	(7.912)	(7.546)
South Asia	11.46	
	(7.289)	
North America		-0.722
		(6.693)

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2021	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2021
Sub-Saharan Africa	*reference group*	0.330
		(5.136)
Constant	21.31***	71.83***
	(7.001)	(6.072)
Observations	59	58
R-squared	0.638	0.446
Robust standard errors in parentheses	*** p<0.01, ** p<0.05, * p<0.1	

Estimates for the models of vaccine uptake at 24 months post global roll-out, by income subgroup, appear in Table 4. We find even larger estimated impacts of vaccine hesitancy on vaccine uptake in the low-income countries compared to the estimates from the 12 month post global roll-out models. Among the countries in the bottom two quintiles of per capita GDP, the estimated difference in uptake between the top and bottom quintiles of vaccine hesitancy is now about 41%. By contrast, there are on material vaccine hesitancy related differences in vaccine uptake among high income countries. There is a marked impact of per capita GDP on vaccine uptake among the low-income countries but not among the high-income countries. Finally, there are large regional differences in vaccine uptake among low-income countries. Low-income countries in the Middle East and North Africa have vaccination rates that are about 27% lower than those in low-income Sub-Saharan countries. There are also some marked regional differences in vaccination rates among high-income countries. Countries in Eastern Europe and Central Asia have vaccination rates that are 18% lower than those in Western Europe (the reference region). High-income countries in the East Asia and the Pacific region, and the Sub-Saharan Africa region, meanwhile, have vaccination rates that are 8-10% higher than those in Western Europe.

Table 4 Estimated regression models for percentage of population fully vaccinated at 24 months post global roll-out. Models stratified by income: countries in bottom two quintiles of per capita GDP and countries in top two quintiles of per capita GDP.

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2022	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2022
GDP per capita:		
Second quantile	11.20**	
	(4.833)	
Fifth quantile		2.018
		(3.727)
% Strongly disagree that vaccine is safe:		
Second quantile	-11.38	0.940
	(7.483)	(3.877)
Third quantile	-31.33***	-0.841
	(9.395)	(3.674)
Fourth quantile	-37.40***	-5.298
	(7.953)	(4.195)
Fifth quantile	-39.12***	-2.404
	(7.527)	(3.099)
Continents:		
East Asia and the Pacific	4.100	7.819***
	(11.32)	(2.643)
Eastern Europe and Central Asia	1.889	-17.84***
	(5.323)	(4.762)
Latin America and the Caribbean	6.254	2.155
	(8.863)	(6.357)
Middle East and North Africa	-22.86**	-0.944
	(9.229)	(5.762)
South Asia	15.73*	
	(8.873)	
North America		1.678
		(6.567)
Sub-Saharan Africa	*reference group*	9.366**
		(4.247)
Constant	55.02***	76.78***
	(7.755)	(4.826)
Observations	59	58
R-squared	0.631	0.645

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2022	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2022
Robust standard errors in parentheses	*** p<0.01, ** p<0.05, * p<0.1	

We re-estimated the p-values for these income-specific regression models using the wild bootstrap estimator as implemented for Stata by Roodman and colleagues [36]. (This procedure generates the bootstrapped distribution of robust t-test statistics using 999 replications, with Rademacher weights and with the restriction that the parameter is equal to zero imposed.) The results of this procedure, which appear in Appendix 1, are consistent with our earlier findings.

4. Discussion

This paper explores how national income and vaccine hesitancy affected COVID-19 vaccine uptake at various time points after vaccines became available globally. At 6 months post roll-out (June 30, 2021), we find a 23% difference in vaccination rates across quintiles of per capita GDP; vaccine hesitancy had no material effects. Factors outside the model played an important role in determining vaccine uptake in the short term. Rosen, Waitzberg and Israeli [37] examine some of these factors in the context of Israel's vaccine uptake. They attribute Israel's rapid vaccine uptake to, *inter alia*, "well-developed infrastructure for implementing prompt responses to large-scale national emergencies", and the "organizational, IT and logistical capacities of Israel's community-based health care providers." There are undoubtedly other factors that explain the short run vaccine uptake in other countries.

At 12 months post rollout, the income-related differences in country vaccine uptake increase to 39%, declining only slightly thereafter. Moreover, vaccine hesitancy related differences in vaccine uptake become apparent and these grow larger over time. At 24 months, there was a 20% difference in vaccination rates between the top 20% and the bottom 20% of countries ranked by hesitancy.

We also estimated the regression models separately by country income levels – the bottom and the top 40% of countries ranked by per capita GDP – to determine if there were income-related differences in the impact of vaccine hesitancy on the percentage of the population fully vaccinated. We hypothesized that hesitancy would play a larger role in high income countries given that at, say 24 months post global roll-out, all residents of high-income countries who wanted to be fully vaccinated would have done so, leaving just the vaccine hesitant unvaccinated. Conversely, in low-income countries, even at 24 months not all individuals who were willing to get vaccinated would be, so that vaccine procurement and distribution capacity, not hesitancy, would be the constraining factor.

We found that the opposite was true. Hesitancy played a much larger role in determining vaccine uptake in low-income countries than in high-income countries. The income-stratified models reveal that the deleterious impact of vaccine hesitancy on vaccine uptake is limited to the 40% of countries with the lowest per capita GDP; hesitancy had no material effects on vaccination rates in higher income countries. Among the lower income countries, there was 20% difference in vaccine uptake between the countries with the lowest and highest rates of vaccine hesitancy at 12 months post rollout. By 24 months, this difference grew to 41%.

These results are tempered by a limitation common to regression models estimated with observational data, namely, the possibility that the mean of the error term distribution varies with covariate values. This can occur in several ways. First, it is possible that there are omitted covariates, captured in the error term, that are correlated with included covariates. We are unaware of factors correlated with GDP and vaccine hesitancy that remain in the error term after conditioning on geographic region and population density. But of course such factors could exist.

Second, there may be measurement error in key covariates. This is a possibility given that the vaccine hesitancy measure was estimated from survey data. If this measurement error is "classical", i.e., additive, and uncorrelated with the true vaccine hesitancy, then regression estimates are attenuated. Finally, there could be simultaneity bias: the covariate values are influenced by the outcome variable values. This does not seem to be a problem since all covariates in our models were measured in 2020 or earlier, before the outcome (vaccine uptake) was determined.

This paper builds on the work by Auld and Toxvaerd [8] who explored, among other things, how both GDP and perceptions of COVID-19 infection risk affected country-level vaccine uptake at March 2021, three months after global vaccine roll-out. Infection risk perception was proxied by the country COVID-19 death toll up to the time of the initial vaccine roll-out in December 2020 and the increase in COVID-19 cases in November 2020. These measures of COVID-19 infection risk, however, had little predictive ability after controlling for GDP. We find that both per capita GDP and mistrust of vaccine safety to have important effects on COVID-19 vaccine uptake. The deleterious impact of vaccine mistrust on vaccine uptake, however, appears to be limited to low-income countries. Further research into vaccine confidence in lower income countries is thus required to improve vaccine coverage in these countries. Doing so will pay dividends in improving the effectiveness of available vaccines in ameliorating future pandemics.

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Appendix 1

Table A1 Estimated regression models of percentage of population fully vaccinated at 12 months post global roll-out. Models stratified by income: countries in bottom two quintiles of per capita GDP and countries in top two quintiles of per capita GDP. Bootstrapped p-values used.

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2021	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2021
Log GDP per capita	11.68***	0.552
	(0.002)	(0.911)
% Strongly disagree that vaccine is safe:		
Second quantile	-2.468	-1.204
	(0.748)	(0.824)
Third quantile	-14.76*	-0.901
	(0.070)	(0.861)
Fourth quantile	-21.53***	-2.359
	(0.007)	(0.660)
Fifth quantile	-20.29**	-2.002
	(0.020)	(0.609)
Continents:		
East Asia and the Pacific	15.72	5.037
	(0.298)	(0.325)
Eastern Europe and Central Asia	9.844*	-18.23***
	(0.063)	(0.003)
Latin America and the Caribbean	13.87**	-0.555
	(0.035)	(0.953)
Middle East and North Africa	-1.526	1.192
	(0.842)	(0.875)
South Asia	10.47	
	(0.176)	
North America		-0.697
		(0.910)
Sub-Saharan Africa	*reference group*	0.661
		(0.892)
Observations	59	58
R-squared	0.681	0.446
Wild bootstrap p-values (999 replications) in parentheses	*** p<0.01, ** p<0.05, * p<0.1	

Table A2 Estimated regression models of percentage of population fully vaccinated at 24 months post global roll-out. Models stratified by income: countries in bottom two quintiles of per capita GDP and countries in top two quintiles of per capita GDP. Bootstrapped p-values used.

Covariates	Vaccine uptake for lowest 40% per capita GDP @ Dec 31 2022	Vaccine uptake for highest 40% per capita GDP @ Dec 31 2022
Log GDP per capita	12.48**	1.432
	(0.010)	(0.583)
% Strongly disagree that vaccine is safe:		
Second quantile	-8.487	0.814
	(0.314)	(0.862)
Third quantile	-29.02***	-0.600
	(0.007)	(0.879)
Fourth quantile	-38.02***	-5.197
	(0.000)	(0.222)
Fifth quantile	-40.74***	-2.142
	(0.000)	(0.456)
Continents:		
East Asia and the Pacific	0.935	8.323**
	(0.929)	(0.013)
Eastern Europe and Central Asia	-1.107	-18.00***
	(0.809)	(0.000)
Latin America and the Caribbean	2.125	2.539
	(0.817)	(0.736)
Middle East and North Africa	-26.76**	-0.545
	(0.011)	(0.919)
South Asia	14.40	
	(0.115)	
North America		1.792
		(0.791)
Sub-Saharan Africa	*reference group*	9.882
		(0.292)
Observations	59	58
R-squared	0.673	0.645
Wild bootstrap p-values (999 replications) in parentheses	*** p<0.01, ** p<0.05, * p<0.1	