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Influences of vaccination and public health strategies on COVID-19 dynamics in the United States: Evaluating policy impacts, behavioral responses, and variant proliferation

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Abstract

Background and Aim: The United States (US) government implemented interventions against COVID-19, but their effects on variant-related risks remain inconclusive. We aimed to assess the causal effects of vaccination rates, booster uptakes, face mask mandates, and public area mobility (societal behavioral factor) on early-stage COVID-19 case and death growth rates and identify the most effective public health response for controlling COVID-19 in the US.

Materials and Methods: We performed retrospective analyses using four standard correlated random effects models, analyzing a robust panel dataset that encompasses 16,700 records across all fifty US states. Models 1 and 3 analyzed COVID-19 case rates and death growth rates, respectively, from January 2021 to November 2021. In contrast, using the data from August 2021 to November 2021, Models 2 and 4 assessed the effect of Delta variants and booster shots on COVID-19 case and death growth rates, respectively.

Results: We found that face mask mandate ($p < 0.01$) and workplace mobility ($p < 0.05$) led to lower COVID-19 case growth rates. COVID-19 vaccination uptake rate reduced COVID-19 death growth rates ($p < 0.01$). Furthermore, contrary to Epsilon variant ($p < 0.01$), which contributed to reduced COVID-19 case growth rates, Delta variant led to significant increases in COVID-19 cases ($p < 0.001$).

Conclusion: This study suggests that immediate public health interventions, like mask mandates, are crucial for crisis mitigation, while long-term solutions like vaccination effectively address pandemics. The findings of this study not only sheds light on the recent pandemic but also equips policy-makers and health professionals with tools and knowledge to tackle future public health emergencies more effectively.

Keywords: COVID-19, face mask mandate, public mobility, vaccination, variants.

Introduction

The COVID-19 pandemic has undeniably affected almost every aspect of our society and is an unprecedented challenge to public health. Preliminary data suggest a declining trend in the COVID-19 pandemic, but recent data indicate an alarming resurgence in the form of a new wave [1]. This emphasizes the dynamic and unpredictable nature of viral outbreaks and the importance of continued vigilance in public health responses. Since the outbreak of the COVID-19 pandemic in March 2020, the federal, state, and local governments in the United States (US) have developed and implemented a series of policies and interventions to mitigate COVID-19 infection cases and death risks [2, 3]. The spectrum of policy interventions includes, but is not limited to, (a) COVID-19 vaccination administration [4–6], (b) social distancing policies such as mask mandate in public spaces [7, 8], and (c) public space mobility behavior guidance [9, 10].

Studies have highlighted the effectiveness of COVID-19 policies and interventions in mitigating the adverse effects of the pandemic. In particular, these measures have contributed to reducing the number of COVID-19-related cases and deaths. In the US, for example, social distancing orders have been associated with a 29% reduction in cases and a 35% decrease in deaths in the early stages of COVID-19. The face mask mandate decreased the weekly growth rates of COVID-19 cases and deaths by 10% each week from March 07, 2020 to June 03, 2020 [11]. In addition, due to the increasing use of vaccinations, there has been a notable decline in the profound burden imposed by COVID-19 [12]. However, only a few studies have explored potential causal relationships [11] that could provide policymakers with deeper insights into the effectiveness of pandemic-related policies and interventions.

Conversely, the global repercussions of "Long-COVID," encompassing both its direct health consequences and its indirect effects, remain palpable [13, 14]. For example, the COVID-19 lockdown policy during the early stages of COVID-19 resulted in a decrease in income and wealth for about half of all Americans [15]. In addition, in the absence of any offsetting measures, the economic contraction and job loss associated with lockdown measures in many countries led to an increase in poverty of almost 100 million people by 2020, resulting in 745 million people experiencing poverty [16]. In addition, COVID-19 lockdown policy remains unclear in terms of its costs and benefits [17], which affects trade-off strategies developed under pandemic conditions [18]. Therefore, despite the waning phase of the COVID-19 pandemic, further exploration of the factors that have effectively reduced cases and deaths is crucial, not only for its current relevance but also for its lasting impact beyond the pandemic's immediate context. The knowledge derived from such understanding is invaluable, enabling U.S. policymakers to prioritize and fine-tune their strategies for current and future public health pandemics [1], while also significantly enhancing the global scientific community's preparedness for impending health crises.

Based on the study by Chernozhukov *et al*. [11], which sought to understand and pinpoint effective mitigation factors for COVID-19, our study takes a step further. In addition to evaluating public health policies and interventions, we also analyzed the influence of vaccination and booster shots on COVID-19 case rates and fatalities due to the emergence of new variants. We performed retrospective analyses at the US state level from January 2021 to November 2021.

This study aimed to (1) assess the causal effects of vaccination rates, booster uptakes, face mask mandates, and public area mobility (societal behavioral factor) on early-stage COVID-19 case and death growth rates and (2) identify the most effective public health response for controlling COVID-19 in the US.

Materials and Methods

Ethical approval

Ethical approval was not required for this study as it exclusively utilized publicly available data.

Study period and location

The data were extracted from October 2021 to January 2022 at the University of Texas Health Science Center at Houston.

Data source

The data in this study were queried from multiple sources: Our World in Data, COVID-19 US State Policy (CUSP) database, Google's COVID-19 community mobility reports, CoVariants website, and the Center for Systems Science and Engineering at Johns Hopkins University. All the data are publicly available and have been cross-referenced using the federal information processing standards code and date.

Study sample

Our data sample comprised panel data obtained from January 2021 to November 2021 at the fifty US state level, including 16,700 case records. The availability of COVID-19 variant data restricted our analysis of COVID-19 from January 2021 to November 2021. In Google's COVID-19 community mobility reports from January 01, to January 06, 2021, there were 300 missing records of public area mobility. Fifty observations were missing from the variants because no observations were made on November 30, 2021. In addition, 922 vaccination observations for COVID-19 vaccination rate were missing. Furthermore, since the introduction of COVID-19 booster shots in August 2021, there have been 11,970 fewer cases compared with the initial COVID-19 vaccination.

Study variables

Dependent variables

The primary outcomes of interest in this study were COVID-19 case growth rates and deaths obtained from the Center for Systems Science and Engineering at Johns Hopkins University.

Independent variables

We aimed to study the effect of four primary exposure factors as follows:

1. Vaccination and booster uptake rates. Daily vaccination and total booster rates were derived from the COVID-19 dataset from our world in data. We calculated the daily vaccination rate using a 7-day rolling average. This approach is useful when dealing with counties where vaccination data are not reported daily. We assumed that vaccination rates remained steady in those days when there were gaps in the data. Daily vaccination rates per million people were calculated as a percentage of the state's total population per million people. The total booster vaccination rate was calculated per 100 people in a state's total population. We separately analyzed COVID-19 growth rates: First from January to November 2021 and then from August to November 2021. With the significant rise of Delta variant cases from August to December 2021, given the approval of the Pfizer-BioNTech booster dose (Pfizer Inc. developed this coronavirus vaccine in partnership with BioNTech SE) for select groups by the US FDA in August 2021, our analysis also encompassed booster uptake rates from August to November 2021.
2. Government social distancing policy: State-level data on face mask mandates were sourced from

the CUSP database, which detailed the start and end dates of public mask mandates for each state.
3. Public area mobility (societal behavioral factor): This behavioral metric is based on median values from (a) workplaces, (b) retail and recreational spots such as restaurants, shopping centers, and theaters, (c) grocery outlets and pharmacies, and (d) transit hubs such as subways and buses. These values reflect the frequency and duration of visits compared to a baseline set from January 03, to February 06, 2020. These data come from Google's COVID-19 community mobility reports, which monitor public movement trends across different venues.
4. COVID-19 variants: Delta, Alpha, and Epsilon variant data, indicating their proportion in state sequences over time.

Covariates

To adjust for other related factors and account for unobserved heterogeneity in the US, we incorporated two key covariates: (1) Retrospective COVID-19 data from January to November 2021: State and national growth rates of cases (with a 7-day lag) and deaths (with a 21-day lag). These data were chiefly utilized to study the impact of information dissemination and (2) state-level characteristics such as the number of COVID-19 tests, population density, land area, unemployment rate, poverty rate, percentage of illness-susceptible individuals, and state governor political affiliation. These data were obtained from the CUSP database.

Statistical analysis

We conducted a descriptive analysis on weekly metrics, including numbers of cases, deaths, laboratory tests, new vaccinated (daily new doses administered per million people at the state level), booster uptakes (total boosters per 100 residents at the state level), face mask mandates, public area mobility, COVID-19 variants, and state attributes. Weekly counts for cases, deaths, and tests were derived by summing daily data from Day t to Day t-6. As Chernozhukov *et al*. [11] pointed out, daily case and death data can vary according to reporting and testing schedules. To minimize these variations, we compiled data into weekly totals. This method provides a more accurate picture, taking into account the usual lag between cases and case confirmation.

We employed correlated random effects models to assess the impact of exposure variables on the growth rates of COVID-19 cases and deaths. Random effects, including state-level characteristics and time-random effects [11], were parameterized as functions of observable characteristics. These variables capture the heterogeneity across states and the temporal dynamics that could influence the outcomes. Stochastic shocks {εit}Tt=1 were assumed to be independent across states but time-dependent within a state [19]. Our analyses included the following four models:

Model 1: Estimated the effect of vaccination rates, mask mandate policy, public area mobility variables, and COVID-19 variants on COVID-19 case growth rates (as 7-day lag variables), using data from January 2021 to November 2021.

Model 2: Estimated the effect of vaccination rates, booster uptake rates, mask mandate policy, public area mobility variables, and COVID-19 Delta variants on COVID-19 case growth rates (as 7-day lag variables), using data from August 2021 to November 2021. Given the dominance of Delta variant during this period, we incorporated Delta variants and booster uptake rates. The data from August 2021 showed that Delta variant accounted for almost all COVID-19 variants. Alpha and Epsilon variants were, therefore, omitted from Model 2.

Model 3: Estimated the effect of vaccination rates, mask mandate policy, public area mobility variables, and COVID-19 variants on COVID-19 death growth rates (as 21-day lag variables), using data from January 2021 to November 2021.

Model 4: Estimated the effect of vaccination rates, booster uptake rates, mask mandate policy, public area mobility variables, and COVID-19 Delta variants on COVID-19 death growth rates (as 21-day lag variables), using data from August 2021 to November 2021. Similar to Model 2, Model 4 factored in Delta variants and booster uptake rates, excluding Alpha and Epsilon variants.

The random effect model is as follows:

$$Y_{i,t+l} = \sigma' VA_{it} + \pi' P_{it} + \alpha' B_{it} + \rho' V_{it} + \mu' I_{it} + \delta_Y' W_{it} + \varepsilon_{it}^{y}$$

Given, $\varepsilon_{it}^{y} \perp VA_{it}, P_{it}, B_{it}, V_{it}, I_{it}, W_{it}$

where, $Y_{i,t+l}$ indicates the growth rates of COVID-19 cases (Models 1–2) and deaths (Models 3–4); VA_{it} represents the COVID-19 vaccination rate; P_{it} represents the mandatory mask policy; B_{it} represents public area mobility (behavioral factors); V_{it} indicates the COVID-19 variant; I_{it} represents the information dissemination, including the lagged value of past cases, case growth rates, deaths, and death growth rates at the state and national levels; and W_{it} encompasses combined covariates, comprising state-level attributes and monthly indicators. Models 1 and 2 use Y_i, t+l to represent the growth rates of COVID-19 cases, where the time lag is set at 7 days. The lag reflects the delay between infection and case confirmation. Meanwhile, for Models 3 and 4, where Y_i, t+l denotes the growth rates of COVID-19 deaths, the time lag was set to 21 days to account for the time interval between infection and death.

For Models 1 and 2, we computed 7-day moving averages for vaccination, face mask mandates, public area mobility, variants, and all the covariates between days t-7 and t-14 for the COVID-19 case growth rate. For Models 3 and 4, their average spanned from days t-21 to t-28. This method mitigates short-term fluctuations and emphasizes long-term trends [11]. On the basis of Chernozhukov *et al*. [11], we also examined interactions between monthly variables and state characteristics to detect state- or period-specific effects.

All analyses were performed using R Programming software (version 4.2.1, R Foundation, Boston, MA, USA). All tests were two-tailed, and the significance level was set at $p \leq 0.05$.

Results

Descriptive statistics

Table-1 presents descriptive statistics based on daily data from all fifty US states between January 2021 and November 2021. Each entry denotes the data for a specific state for a given day. On average, 693,042 daily COVID-19 cases were reported in each state, with a notable standard deviation of 803,650, indicating significant state-to-state variability. The average daily death toll per state was 11,845.78, with a significant standard deviation of 14,048.61. The median state's daily vaccination rate was 3250 per million, based on a 7-day rolling average, with an interquartile range of 3,549.5. In addition, an average of 5.69 booster shots was administered per hundred individuals, with a variability of 4.31. However, 37.8% of booster data were unavailable, mainly because widespread booster shots vaccination started only after August 26, 2021. Our analysis started on August 01, 2021, aligning with the rise in prevalence of Delta variant. The data also showed the presence of a prominent mask mandate with an average of 0.38 days based on a 7-day moving average, with a deviation of 0.48.

Public mobility shows different trends across sectors. Relative to the baseline period (January 03–February 06, 2020), there were daily changes in visits and stay durations as follows: Workplaces (−0.23%, standard deviation [SD]: ±0.06), groceries and pharmacies (0.02%, SD: ±0.01), transit stations (−0.09%, SD: ±0.23), and retail and recreation outlets (−0.05%, SD: ±0.12). In terms of variant distribution, Delta variant dominated across states with a daily mean of 0.42% (SD: ±0.42). Alpha and Epsilon variants trailed with means of 0.20% (SD: ±0.27) and 0.04% (SD: ±0.08), respectively. Demographically, the states averaged a population of 6,529,299.58 and a land area of 75,933.52 sq. miles, with respective standard deviations of 7,298,056.75 and 96,352.10. The unemployment rate hovered around 4.69% (SD: ±0.99) and the poverty rate was 12.85% (SD: ±2.80). The average state had 38.27% of its population susceptible to illness (SD: ±3.58), indicating varying health and socioeconomic landscapes across states.

These descriptive statistics highlight significant differences in COVID-19 indicators, mobility, demographics, and socioeconomic indicators in the US. These state-level differences were pivotal in our subsequent analysis.

Random effects model statistics

Table-2 summarizes the results for Model 1 and Model 2. Implementing a face mask mandate resulted in a 7.2% decrease in the COVID-19 case growth rate ($p = 0.003$). On the other hand, Delta variant surged the growth rate by 48.9% ($p = 0.001$), suggesting its heightened transmissibility. Epsilon variant resulted in a 76.4% reduction in the case growth rate ($p = 0.001$).

Model 1 also estimated the effect of societal behavior on COVID-19 case growth rate. This model pinpointed a 41.4% decline ($p = 0.014$) in the case growth rate in areas where workplace precautions are practiced. However, in Model 1, vaccination rates did not significantly influence the case growth rate. Model

Table-1: Descriptive statistics of daily state averages.

Variables	Mean (daily)	Standard deviation (±)	n	Missing (%)
COVID-19 cases	693,041.92	803,649.57	16,700	0
COVID-19 deaths	11,845.78	14,048.61	16,700	0
COVID-19 tests	171,991.32	262,957.20	16,346	354 (2.1)
Vaccination rate	4,085.45	2,689.39	15,778	922 (5.5)
Booster rate	5.69	4.31	3,763	2,287 (37.8)
Workplace mobility	−0.23	0.06	16,400	300 (1.8)
Grocery and pharmacy mobility	0.02	0.10	16,400	300 (1.8)
Transit station mobility	−0.09	0.23	16,400	300 (1.8)
Retail and recreation mobility	−0.05	0.12	16,400	300 (1.8)
Mask mandates	0.38	0.48	16,400	300 (1.8)
V20I Alpha variant	0.20	0.27	16,650	50 (0.3)
V21C Epsilon variant	0.04	0.08	16,650	50 (0.3)
V21J Delta variant	0.42	0.42	16,650	50 (0.3)
V21A Delta variant	0.02	0.04	16,650	50 (0.3)
V21I Delta variant	0.04	0.05	16,650	50 (0.3)
COVID-19 cases	693,041.92	803,649.57	16,700	0
COVID-19 deaths	11,845.78	14,048.61	16,700	0
COVID-19 tests	171,991.32	262,957.20	16,346	354 (2.1)
Population	6,529,299.58	7,298,056.75	16,700	0
Total area (*mi*²)	75,933.52	96,352.10	16,700	0
Unemployment rate	4.69	0.99	16,700	0
Poverty rate	12.85	2.80	16,700	0
Percentage of people who are subject to illness	38.27	3.58	16,700	0
Population	6,529,299.58	7,298,056.75	167,00	0

Table-2: Direct effect of behavior and policies on case growth (PBI→Y).

Interventions	Items	Dependent variable	
		$\Delta \log \Delta C_{it}$	$\Delta \log \Delta C_{it}$
		Model 1	**Model 2**
Vaccination	Lag (Vaccination rate, 7)	−0.142	11.860
		(0.187)	(6.053)
	Lag (Booster rate, 7)	NA	18.480
		NA	(11.910)
Policy intervention	Lag (Face mask mandate, 7)	−0.072**	−0.041
		(0.025)	(0.031)
Public mobility (behavior)	Lag (Workplace mobility, 7)	−0.414*	−0.582**
		(0.165)	(0.217)
	Lag (Retail mobility, 7)	0.176	1.737***
		(0.290)	(0.265)
	Lag (Groceries and pharmacies mobility, 7)	−0.252	−0.932***
		(0.296)	(0.200)
	Lag (Transit stations mobility, 7)	0.064	−0.113
		(0.106)	(0.068)
COVID-19 Variants	Lag (Alpha variant, 7)	−0.200	NA
		(0.122)	NA
	Lag (Epsilon variant, 7)	−0.764**	NA
		(0.001)	NA
	Lag (Delta variant_ V21J, 7)	0.489***	11.310*
		(0.000)	(5.736)
	Lag (Delta variant_ V21A, 7)	NA	11.620*
		NA	(5.882)
	Lag (Delta variant_ V21I, 7)	NA	11.070*
		NA	(5.604)
Information dissemination	Lag (past cases, 7)	−0.303**	−0.050**
		(0.112)	(0.019)
	Lag (past cases growth rate, 7)	−0.279***	−0.210***
		(0.018)	(0.045)
	Lag (past cases of national, 7)	0.192*	−0.117*
		(0.082)	(0.057)
	Lag (past cases growth rate of national, 7)	0.033	0.035
		(0.0582)	(0.059)
	COVID-19 testing rate	0.460***	0.444***
		(0.054)	0.080
State variables		Yes	Yes
Month variables		Yes	Yes
Month * state variables		Yes	Yes
Observations		15,044	4,350
R^2		0.3699	0.331
Adjust R^2		0.3664	0.326

*p < 0.05; **p < 0.01; ***p < 0.001,
Values highlighted in bold signify statistical significance.

2 showed no statistically significant effect from face mask mandate, but Delta variants increased the case growth rate by 11%. Detailed outcomes are provided in supplementary data.

Table-3 summarizes Model 3's results and reveals that the vaccination rate led to a 55.2% decline in the COVID-19 death growth rate (p = 0.002). The impact of COVID-19 variants varied: Alpha variant resulted in a 29.4% decrease (p = 0.002), whereas Epsilon variant resulted in a more pronounced 46.4% decline (p = 0.002). Conversely, Model 4 identified no factors significantly influencing the death growth rate. The supplementary material provides a detailed breakdown in Table-S2 (supplementary data).

To assess the potential correlation between booster shots and Delta variants, we also performed a supplementary analysis (Model 5 for COVID-19 cases and Model 6 for deaths, as shown in Table-S3 (supplementary data), spanning from August 01, to November 30, 2021. Unlike Models 2 and 4, Models 5 and 6 excluded booster shots. In contrast to Model 2, Delta variants did not significantly influence the COVID-19 case growth rate. This suggests a strong relationship between booster shots and Delta variants. In addition, workplace measures led to a 58.1% decline in case growth rates (p = 0.007), whereas grocery and pharmacies measures resulted in a 91.6% reduction (p = 0.001). However, in Model 6, no significant relationships were found between COVID-19 death growth rate and the examined variables.

Discussion

Our study builds on earlier studies, probing the causal impacts of several factors, including vaccination

Table-3: Direct effect of behavior and policies on death growth (PBI→Y).

Interventions	Items	Dependent variable	
		$\Delta\log \Delta C_{it}$	$\Delta\log \Delta C_{it}$
		Model 3	**Model 4**
Vaccination	Lag (Vaccination rate, 21)	−0.552**	−32.425
		(0.179)	(31.349)
	Lag (Booster rate, 21)	NA	27.719
		NA	(31.476)
Policy intervention	Lag (Face mask mandate, 21)	−0.012	−0.105
		(0.021)	(0.070)
Public mobility (behavior)	Lag (Workplace mobility, 21)	−0.152	−0.045
		(0.295)	(0.460)
	Lag (Retail mobility, 21)	−0.183	−0.055
		(0.277)	(0.571)
	Lag (Groceries and pharmacies mobility, 21)	0.150	0.438
		(0.266)	(0.385)
	Lag (Transit stations mobility, 21)	0.080	−0.100
		(0.086)	(0.203)
COVID-19 Variants	Lag (Alpha variant, 21)	−0.294*	NA
		(0.122)	NA
	Lag (Epsilon variant, 21)	−0.464**	NA
		(0.153)	NA
	Lag (Delta variant_ V21J, 21)	0.196	−17.900
		(0.113)	(21.676)
	Lag (Delta variant_ V21A, 21)	NA	−16.798
		NA	(21.839)
	Lag (Delta variant_ V21I, 21)	NA	−16.038
		NA	(21.015)
Information dissemination	Lag (past cases, 21)	−0.015	−0.185
		(0.019)	(0.099)
	Lag (past cases growth rate, 21)	0.017	−0.020
		(0.019)	(0.116)
	Lag (past cases of national, 21)	0.038	0.731*
		(0.054)	(0.057)
	Lag (past cases growth rate of national, 21)	0.014	−0.868**
		(0.101)	(0.301)
	COVID-19 testing rate	0.262*	0.172
		(0.114)	0.203
State variables		Yes	Yes
Month variables		Yes	Yes
Month * state variables		Yes	Yes
Observations		13,644	2,950
R^2		0.0407	0.061
Adjust R^2		0.0353	0.0524

*p < 0.05; *p < 0.01; ***p < 0.001,
Values highlighted in bold signify statistical significance.

and booster uptake, mask mandates, public mobility, and the emergence of a new COVID-19 variant, on the growth rates of COVID-19 cases. The influence of covariates, such as COVID-19 information dissemination, state-specific attributes, and the interplay between monthly indicators and state characteristics, was also assessed. The main exceptions are mask mandates and reduced workplace mobility, which reduced the growth rate of cases, whereas increased vaccination and boosters significantly reduced the rate of death in the US.

Our findings indicated that face mask mandates effectively slowed the spread of COVID-19, consistent with the previous studies [20, 21]. Face mask mandates have been recognized as a temporary yet effective strategy to limit transmission risks at population level [22]. However, the efficacy of wearing masks may be influenced by the transmissibility of specific variants. This could elucidate why the face mask mandate did not exhibit significant effects during the period when Delta variant predominated in the US during our study.

In terms of public mobility, our results indicated that protective behaviors, particularly in workplaces, resulted in reduced COVID-19 case growth rates. During the period when Delta variant was prevalent, decreased mobility in both workplaces and grocery and pharmacy stores resulted in decreased case growth rates. Our results also echo findings from previous studies that suggest measures such as lockdowns or stay-at-home directives effectively curtail COVID-19's spread [23, 24]. These insights contribute to a valuable perspective at community level for strengthening preparedness in the event of potential public health crises.

Moreover, higher vaccination uptake curtails the growth rate of COVID-19 deaths, which is consistent with the previous research [10, 25, 26]. Some studies suggest that vaccines reduce the severity of COVID-19 symptoms, the persistence of long-lasting COVID-19 symptoms and hospitalization [27]. It supports our observation that the death growth rate is reduced. Contrarily, we did not observe a significant impact of vaccinations or boosters on COVID-19 case growth rates, contrary to the majority of earlier research [28]. However, vaccines may primarily attenuate symptoms rather than prevent infections [29]. If accurate, vaccination remains crucial for reducing COVID-19-related mortality. Governments and policymakers should therefore consistently prioritize and allocate resources to expand vaccination coverage and reduce COVID-19 deaths.

In addition, we observed that Epsilon variant reduced the growth rates of both COVID-19 cases and deaths; however, this finding is perplexing given prior research suggesting its high transmissibility [30, 31]. Consistent with an earlier study [32], Delta variant was associated with notably high COVID-19 cases. Contrary to the majority of studies [33, 34], our findings indicated that Delta variant did not significantly affect the COVID-19 death growth rate. This discrepancy may have stemmed from our study's limited observation span. Specifically, Model 4's brief duration, covering only August to November 2021, might not sufficiently represent the broader effects of elements such as vaccination rates, booster uptake, mask mandates, and Delta variant's impact on COVID-19 death rates. On the other hand, Model 4 did not highlight any significant predictors; therefore, it is still important to consider their potential relevance.

Furthermore, our results suggest that sharing historical case data and growth rates at the state level led to a reduction in the number of COVID-19 cases, consistent with the previous research [35]. Enhanced risk awareness, bolstered by effective information dissemination, has been linked to proactive COVID-19 prevention behaviors, such as reduced public mobility, thereby lowering the number of cases [11]. It stresses the importance of continuous refinement and use of information platforms to provide timely updates on COVID-19 promote public awareness and promote proactive responses.

A primary limitation of our study is its limited timeframe, spanning from January to November 2021. It captures only the early phase of the COVID-19 pandemic and omits subsequent variants such as Omicron. Face mask mandates had eased and vaccine discussions intensified by the time Omicron surfaced, introducing factors outside our study's scope. This shortcoming should be addressed in future research, in particular as the evolution of the pandemic dynamics and the expansion of data may alter the observed relationships. Another limitation is the population-level focus of our study, excluding individual-centric data. This may inadvertently ignore aspects such as cultural norms, access to personal health, and individual health status. In addition, our US-centric data may limit the broader applicability of our findings.

Conclusion

Building on the robust foundation of extensive US big data, our research stands out as one of the seminal analyses unraveling the intricate effects of diverse interventions and determinants on the pandemic's trajectory. Our findings, while based on the US context, reverberate with global significance as nations face looming threat of a new wave of COVID-19. These findings highlight the importance of developing proactive pandemic response strategies and highlight the importance of timely international policy interventions on an international scale. Immediate measures, such as a general ban on face masks and harmonized restrictions on public mobility, offer a swift solution to addressing acute health crises. At the same time, a persistent global focus on vaccination and international cooperation in the distribution of vaccines is becoming a cornerstone for long-term pandemic mitigation. In view of this pressing urgency and our accumulated knowledge, policymakers worldwide are strongly advised to adopt a dual-faceted strategy in the event of imminent health crises that may go beyond borders. By judiciously disseminating resources, strengthening international cooperation and prioritizing transparent health communication, nations can collectively create a strong and adaptable defense against serious health challenges that await them.

Data Availability

Supplementary data can be available from the corresponding author on a reasonable request.

Authors' Contributions

JMP, SMJ, XL, and VM: Conceptualized and designed the study. XL and JMP: Drafted the manuscript. JMP, SMJ, and XL: Data collection and statistical analysis. XL, JMP, VM, and GWW: Edited the manuscript. All authors contributed intellectually and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

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References

1. Del Rio, C. and Malani, P.N. (2023) COVID-19 in the fall of 2023-forgotten but not gone. *JAMA*, 330(16): 1517–1518.
2. Bruine de Bruin, W., Saw, H.W. and Goldman, D.P. (2020) Political polarization in US residents' COVID-19 risk perceptions, policy preferences, and protective behaviors. *J. Risk Uncertain*., 61(2): 177–194.
3. Sprengholz, P., Felgendreff, L., Böhm, R. and Betsch, C. (2022) Vaccination policy reactance: Predictors, consequences, and countermeasures. *J. Health Psychol*., 27(6): 1394–1407.
4. Forman, R., Shah, S., Jeurissen, P., Jit, M. and Mossialos, E. (2021) COVID-19 vaccine challenges: What have we learned so far and what remains to be done? *Health Policy*, 125(5): 553–567.
5. Mello, M.M., Opel, D.J., Benjamin, R.M., Callaghan, T., DiResta, R., Elharake, J.A., Flowers, L.C., Galvani, A.P., Salmon, D.A., Schwartz, J.L. and Brewer, N.T. (2016) Effectiveness of vaccination mandates in improving uptake of COVID-19 vaccines in the USA. *Lancet*, 400(10351): 535–538.
6. Jones, M., Khader, K. and Branch-Elliman, W. (2022) Estimated impact of the US COVID-19 vaccination campaign-getting to 94% of deaths prevented. *JAMA Netw. Open*, 5(7): e2220391.
7. Wellenius, G.A., Vispute, S., Espinosa, V., Fabrikant, A., Tsai, T.C., Hennessy, J., Dai, A., Williams, B., Gadepalli, K., Boulanger, A. and Pearce, A. (2021) Impacts of social distancing policies on mobility and COVID-19 case growth in the US. *Nat. Commun*., 12(1): 3118.
8. Yan, Y., Malik, A.A., Bayham, J., Fenichel, E.P., Couzens, C. and Omer, S.B. (2021) Measuring voluntary and policy-induced social distancing behavior during the COVID-19 pandemic. *Proc. Natl. Acad. Sci. U S A*, 118(16): e2008814118.
9. Badr, H.S., Du, H., Marshall, M., Dong, E., Squire, M.M. and Gardner, L.M. (2020) Association between mobility patterns and COVID-19 transmission in the USA: A mathematical modelling study. *Lancet Infect. Dis*., 20(11): 1247–1254.
10. Jacobsen, G.D. and Jacobsen, K.H. (2020) Statewide COVID Gardner, L.M. (2020) Association between mobility patterns and COVID-*World Med. Health Policy*, 12(4): 347–356.
11. Chernozhukov, V., Kasahara, H. and Schrimpf, P. (2021) Causal impact of masks, policies, behavior on early COVID-19 pandemic in the US. *J. Econom*., 220(1): 23–62.
12. McNamara, L.A., Wiegand, R.E., Burke, R.M., Sharma, A.J., Sheppard, M., Adjemian, J., Ahmad, F.B., Anderson, R.N., Barbour, K.E., Binder, A.M. and Dasgupta, S. (2022) Estimating the early impact of the US COVID-19 vaccination programme on COVID-19 cases, emergency department visits, hospital admissions, and deaths among adults aged 65 years and older: An ecological analysis of national surveillance data. *Lancet*, 399(10320): 152–160.
13. O'Mahoney, L.L., Routen, A., Gillies, C., Ekezie, W., Welford, A., Zhang, A., Karamchandani, U., Simms-Williams, N., Cassambai, S., Ardavani, A. and Wilkinson, T.J. (2022) The prevalence and long-term health effects of Long Covid among hospitalised and non-hospitalised populations: A systematic review and meta-analysis. *EClinicalMedicine*, 55: 101762.
14. Zeng, N., Zhao, Y.M., Yan, W., Li, C., Lu, Q.D., Liu, L., Ni, S.Y., Mei, H., Yuan, K., Shi, L. and Li, P. (2023) A systematic review and meta-analysis of long term physical and mental sequelae of COVID-19 pandemic: Call for research priority and action. *Mol. Psychiatry*, 28(1): 423–433.
15. Dreger, C. and Gros, D. (2021) Lockdowns and the US unemployment crisis. *Econ. Disaster Clim. Chang*., 5(3): 449–463.
16. Kharas, H. and Dooley, M. (2021) Extreme Poverty in the Time of COVID-19. Brookings Institution. Available from: https://africaportal.org/wp-content/uploads/2023/06/extreme-poverty-during-the-time-of-covid-19.pdf. Retrieved on 10-01-2023.
17. Allen, D.W. (2022) Covid-19 lockdown cost/benefits: A critical assessment of the literature. *Int. J. Econ. Bus*., 29(1): 1–32.
18. Eichenbaum, M.S., Rebelo, S. and Trabandt, M. (2021) The macroeconomics of epidemics. *Rev. Financ. Stud*., 34(11): 5149–5187.
19. Clark, T.S. and Linzer, D.A (2015) Should I use fixed or random effects? *Polit. Sci. Res. Methods*, 3(2): 399–408.
20. Karaivanov, A., Lu, S.E., Shigeoka, H., Chen, C. and Pamplona, S. (2021) Face masks, public policies and slowing the spread of COVID-19: Evidence from Canada. J. Health Econ., 78: 102475.
21. Misra, M., Joshi, H., Sarwal, R. and Rao, K.D. (2022) Exit strategies from lockdowns due to COVID-19: A scoping review. *BMC Public Health*, 22(1): 488.
22. Levine, Z. and Earn, D.J. (2022) Face masking and COVID-19: Potential effects of variolation on transmission dynamics. *J. R. Soc. Interface*, 19: 20210781.
23. Carella, G., Pérez Trufero, J., Álvarez, M. and Mateu, J. (2022) A Bayesian spatial analysis of the heterogeneity in human mobility changes during the first wave of the COVID-19 epidemic in the United States. *Am. Stat*., 76(1): 64–72.
24. Navazi, F., Yuan, Y. and Archer, N. (2022) The effect of the Ontario stay-at-home order on Covid-19 third wave infections including vaccination considerations: An interrupted time series analysis. *PLoS One*, 17(4): e0265549.
25. Marín-Hernández, D., Schwartz, R.E. and Nixon, D.F. (2021) Epidemiological evidence for association between higher influenza vaccine uptake in the elderly and lower COVID-19 deaths in Italy. *J. Med. Virol*., 93(1): 64–65.
26. Moghadas, S.M., Sah, P., Fitzpatrick, M.C., Shoukat, A., Pandey, A., Vilches, T.N., Singer, B.H., Schneider, E.C. and Galvani, A.P. (2021) COVID-19 deaths and hospitalizations averted by rapid vaccination rollout in the United States. *medRxiv*, 2021-07.
27. Rahmani, K., Shavaleh, R., Forouhi, M., Disfani, H.F., Kamandi, M., Oskooi, R.K., Foogerdi, M., Soltani, M., Rahchamani, M., Mohaddespour, M. and Dianatinasab, M. (2022) The effectiveness of COVID-19 vaccines in reducing the incidence, hospitalization, and mortality from COVID-19: A systematic review and meta-analysis. *Front. Public Health*, 10: 873596.
28. Mohammed, I., Nauman, A., Paul, P., Ganesan, S., Chen, K.H., Jalil, S.M.S., Jaouni, S.H., Kawas, H., Khan, W.A., Vattoth, A.L. and Al-Hashimi, Y.A. (2022). The efficacy and effectiveness of the COVID-19 vaccines in reducing infection, severity, hospitalization, and mortality: A systematic review. *Hum. Vaccin. Immunother*., 18(1): 2027160.
29. Swan, D.A., Bracis, C., Janes, H., Moore, M., Matrajt, L., Reeves, D.B., Burns, E., Donnell, D., Cohen, M.S., Schiffer, J.T. and Dimitrov, D. (2021) COVID-19 vaccines that reduce symptoms but do not block infection need higher coverage and faster rollout to achieve population impact. *Sci. Rep*., 11(1): 15531.
30. Deng, X., Garcia-Knight, M.A., Khalid, M.M., Servellita, V., Wang, C., Morris, M.K., Sotomayor-González, A., Glasner, D.R., Reyes, K.R., Gliwa, A.S., Reddy, N.P., San-Martin, C.S., Federman, S., Cheng, J., Balcerek, J., Taylor, J., Streithorst, J.A., Miller, S., Kumar., G.R., Sreekumar., Chen, P.Y., Schulze-Gahmen, U., Taha, T.Y., Hayashi, J., Simoneau, G.R., McMahon, S., Lidsky, P.V., Xiao, Y.H., Hemarajata, P., Green, N.M., Espinosa, A., Kath, C., Haw, M., Bell, J., Hacker, J,K., Hanson, C., Wadford, D.A., Anaya, C., Ferguson, D., Lareau, L.F., Frankino, P.A., Shivram, H., Wyman, S.K., Ott, M., Andino, R., and Chiu, C.Y. (2021) Transmission, infectivity, and antibody neutralization of an emerging SARS-CoV-2

variant in California carrying a L452R spike protein mutation. *medRxiv*, 2021-03-09.
31. Carroll, T., Fox, D., van Doremalen, N., Ball, E., Morris, M.K., Sotomayor-Gonzalez, A., Servellita, V., Rustagi, A., Yinda, C.K., Fritts, L. and Port, J.R. (2022) The B. 1.427/1.429 (epsilon) SARS-CoV-2 variants are more virulent than ancestral B. 1 (614G) in Syrian hamsters. *PLoS Pathog*., 18(2): e1009914.
32. Earnest, R., Uddin, R., Matluk, N., Renzette, N., Turbett, S.E., Siddle, K.J., Loreth, C., Adams, G., Tomkins-Tinch, C.H., Petrone, M.E. and Rothman, J.E. (2022) Comparative transmissibility of SARS-CoV-2 variants Delta and Alpha in New England, USA. *Cell Rep. Med*., 3(4): 100583.
33. Dyer, O. (2021) Covid-19: Unvaccinated face 11 times risk of death from delta variant, CDC data show. *BMJ*, 374: n2282.
34. Shiehzadegan, S., Alaghemand, N., Fox, M. and Venketaraman, V. (2021) Analysis of the delta variant B. 1.617. 2 COVID-19. *Clin. Pract*., 11(4): 778–784.
35. Ma, R., Deng, Z. and Wu, M. (2020) Effects of health information dissemination on user follows and likes during COVID-19 outbreak in China: Data and content analysis. *Int. J. Environ. Res. Public Health*, 17(14): 5081.

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