Research Article

Insights into Controlling the Spread of COVID-19: A Study Inspired by Seven of the Earliest Vaccinated Countries

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Background. The aim of the study is to derive deeper insights into the control of the spread of COVID-19 during the second half of 2021, from seven countries that are among the earliest to have accelerated the deployment of COVID-19 vaccines. Methodology. This study used data from the Global COVID-19 Index and Google COVID-19 Community Mobility Reports. Data was extracted on the 5th of each month from July to December 2021. Seven countries were selected—United Kingdom, United States of America, Israel, Canada, France, Italy, and Austria. The sample comprised number of new cases, hospitalisations, ICU admissions and deaths due to COVID-19, government stringency measures, partial and full vaccination coverage, and changes in human mobility. Principal component analysis was conducted, and the results were interpreted and visualized through 2-dimensional and 3-dimensional plots to reveal the systematic patterns of the data. Results. The first three principal components captured around 77.3% of variance in the data. The first component was driven by the spread of COVID-19 (31.6%), the second by mobility activities (transit, retail, and recreational) (24.3%), whereas the third by vaccination coverage, workplace-related mobility, and government stringency measures (21.4%). Visualizations showed lower or moderate levels of severity in COVID-19 during this period for most countries. By contrast, the surge in the USA was more severe especially in September 2021. Human mobility activities peaked in September for most countries and then receded in the following months as more stringent government measures were imposed, and countries began to grapple with a surge in COVID-19 cases. Conclusion. This study delineated the spread of COVID-19, human mobility patterns, widespread vaccination coverage, and government stringency measures on the overall control of COVID-19. While at least moderate levels of stringency measures are needed, high vaccine coverage is particularly important in curbing the spread of this disease.

1. Introduction

It is evident that the COVID-19 pandemic has brought about a global health crisis with massive premature loss of life [1, 2]. The pandemic has also resulted in severe economic consequences all over the world and has led to disruptions in business and other industries [3–5]. In reactive responses, countries are applying various policy measures, seeking to contain the COVID-19 pandemic, and making a move towards reopening economies. Among the major policy interventions adopted by many developed countries around the world, accelerating vaccination coverage in their respective countries has been a focus [6, 7].

Notable in the rapid conduct of mass vaccination, not to the exclusion of a number of other example nations, have been the United Kingdom, several other countries from the European continent, North America, and also Israel [6, 8, 9]. Within these examples, there have been those nations that experienced some of the earliest surges in the COVID-19 pandemic, rapidly followed by associated devastating
Concomitantly during the second half of 2021, the COVID-19 Delta variant of concern, which was first identified in India in December 2020, has emerged as the dominant strain across much of the European region and caused concerns over Europe’s economic rebound [24–26]. The Delta variant has been found to be 40–60% more transmissible than the Alpha variant and leads to an increased risk in hospitalizations, ICU admissions, and deaths [27, 28]. Despite this, the pandemic has been perceived to be largely controlled, alongside widespread vaccine coverage in the UK, Israel, and parts of Europe [6, 7, 26]. Those who have been vaccinated were much less likely to end up in hospital and were protected from developing severe disease, hospitalization, and death due to the Delta variant [16, 29, 30]. However, inferential analysis studying the effects on vaccination on the Delta variant has implied that the effects of vaccination decrease over time [31, 32]. Moreover, the highly transmissible Delta variant has caused resurgence of infections, even in areas with high vaccination coverage. As booster vaccinations may help to control transmission, several countries such as Israel and the UK have started administering COVID-19 vaccine boosters, but to targeted population groups during the second half of 2021 [16, 30, 33].

Many events have unfolded during the second half of 2021 in many of these developed countries—widespread mass COVID-19 vaccination; the easing of government restrictions which led to reopening of economies and increase in human mobility; and a surge in COVID-19 cases as the deadly and highly transmissible Delta variant became the dominant strain. Therefore, deeper insights are needed on the overall state of the COVID-19 pandemic, when all of these confounding factors are taken into consideration. Moreover, there is scarcity in research of a similar pandemic period, where all of these factors are examined simultaneously. Hence, we attempt to examine, through an unsupervised machine learning approach of the following dimensions during the second half of 2021, the spread of COVID-19, mass vaccination rollout, stringent measures by governments, and human mobility patterns. During this period, Delta is the dominant strain, while Omicron is yet evident.

2. Methods

In this section, we describe the dataset of the study, the principal component analysis technique as a suitable tool to achieve the objectives of this study, and the analytical procedures.

2.1. Dataset

2.1.1. Global COVID-19 Index. We have acquired access to data from the Global COVID-19 Index (GCI) provided by PEMANDU Associates [34]. The GCI is an independent data engine covering 180 economies and consolidates to provide open data. This includes the daily number of COVID-19 cases, deaths, recoveries, hospitalizations, and vaccination from the COVID-19 Data Repositories by the World Health Organisation, Our World in Data, Johns Hopkins Center for Systems Science and Engineering (JHU CSSE) and Oxford University’s Blavatnik School of Government [8, 35]. For the purpose of this study, we have also cross-referenced country-specific sources such as the Ministry of Health of Israel.

2.1.2. Google COVID-19 Community Mobility Reports. We have also utilized the Google COVID-19 Community Mobility Reports (GCMR) which uses aggregated and anonymized data to chart changes in mobility with respect to different classes of places—retail and recreation, groceries and pharmacies, parks, transit, workplace, and residential (https://www.google.com/covid19/mobility/). Mobility indicators are calculated based on the frequency and length of visits to places.

The data used in this study were extracted from the Global COVID-19 Index and GCMR on the 5th of each month from July to December 2021. Countries selected for inclusion are among the earliest countries to have started vaccination of its population against COVID-19, i.e., the United Kingdom (GBR), United States of America (USA), Israel (ISR), Canada (CAN), France (FRA), Italy (ITA), and Austria (AUT). These countries also share similar characteristics in terms of income level and age structures. Additional was the criterion that complete data is needed to be available for new case numbers, deaths, hospitalisations, ICU admissions, and vaccinations (full and partial) due to COVID-19. Hence, the dataset consists of new cases, hospitalisations, ICU admissions and deaths due to the virus, stringency of government responses to the pandemic, partial (single dose) and full (double doses) vaccinations, and changes in human mobility across the six different classes of places.

New cases, number of hospitalisations, number of ICU admissions, and number of deaths due to COVID-19 collectively indicate the spread of the virus and the severity in the country. Partial and full vaccinations indicate the proportion of each country’s population having received single or double doses of COVID-19 vaccines, respectively. The stringency
measure is an indicator which reflects the stringency of government responses to the COVID-19 pandemic, with lower values also implying the easing of restrictions within the country. The six different mobility indicators from GCMR reflect the changes in mobility in each class of places—retail and recreation, groceries and pharmacies, parks, transit, workplace, and residential.

2.2. Data Analysis. Principal component analysis (PCA) was employed in this study. PCA is a robust multivariate technique for dimensionality reduction and data visualization [36, 37]. Supposing that there are \( n \) observations with measurements on a set of \( p \) variables, this technique uses dependencies between variables \( (X_1, X_2, \ldots, X_p) \) to produce a low-dimensional representation of a dataset, while preserving as much information as possible. The PCA technique derives the principal components by finding a sequence of linear combinations of the variables that have maximal variance and are mutually uncorrelated [36]. The first principal component, \( Z_1 \), accounts for the maximal amount of the total variance of the observed variables. The second component, \( Z_2 \), is orthogonal to the first component and will account for the maximal amount of variance in the dataset that was not accounted for by the first component. Likewise, the third principal component, \( Z_3 \), is the direction which maximizes variance among all directions, not accounted for by the first and second components.

The first three principal components are given by the following formulæ:

\[
Z_1 = \phi_{11}X_1 + \phi_{21}X_2 + \cdots + \phi_{p1}X_p, \\
Z_2 = \phi_{12}X_1 + \phi_{22}X_2 + \cdots + \phi_{p2}X_p, \\
Z_3 = \phi_{13}X_1 + \phi_{23}X_2 + \cdots + \phi_{p3}X_p.
\]

PCA is based on the decomposition of the original data matrix into the scores and loading matrices. The scores (e.g., for \( Z_1; z_{11}, \ldots, z_{n1} \)) classify the samples, whereas loadings (e.g., for \( \phi_1; \phi_{11}, \ldots, \phi_{p1} \)) classify the variables and are referred to as the weight for each variable [36]. More details about the PCA technique can be found elsewhere [36, 37].

The PCA technique is suitable for achieving the research objective of this study. This technique examines multiple variables in a multivariate context, reducing the dimensionality of the data and improving interpretability while preserving as much information as possible. Other researchers have also used this technique as a dimensionality reduction and feature extraction tool in various research areas [38–41].

We first presented the summary statistics on new cases, hospitalisations, ICU admissions, and deaths due to COVID-19, stringency of government responses to the pandemic, and partial and full vaccinations. We computed the correlation matrix on these variables and Google mobility indicators, then followed by principal component analyses. The PCA technique was performed using the “prcomp” command of the R statistical software, after standardizing each variable to have mean zero and standard deviation of one. Standardization involves rescaling the variables such that each will have the properties of a standard normal distribution with a mean of zero and a standard deviation of one. The principal component score vectors were extracted from the results and visualized through 2-dimensional and 3-dimensional plots using the “ggplot2” and “scatterplot3d” R packages [42, 43].

3. Results

Summary statistics from data extracted on the 5th of each month from July to December 2021, are presented in Table 1 grouped by the seven respective countries. During this period, the numbers of new cases, hospitalisations, ICU admissions, and deaths were on average higher in the USA compared to the other countries. By 5th December 2021, all seven countries have administered full COVID-19 vaccine to at least 60% of its population. The proportion for the USA is comparatively the lowest at 60%, whereas Canada achieved the highest at 76%.

The average stringency levels in Canada is also comparatively higher than those in the other six countries, as its stringency index hovers between 57 and 72 throughout this period. The UK government’s stringency measures have hovered around average levels (41–51). There is a similar pattern in the stringency levels for Austria, France, Italy, and Israel as its stringency values have increased gradually (not shown here) from 5th July to 5th December 2021. Oddly, the stringency in the USA has decreased from 62 on the 5th of July 2021, to the value of 48 on the 5th of December 2021 (not shown here).

The correlation matrix is presented in Table 2. New cases, hospitalizations, ICU admissions, and deaths due to COVID-19 are strongly positively correlated with each other (0.80–1.0). Full and partial vaccinations show strong (0.80–1.0) positive correlation with each other and moderate (0.40–0.59) positive association with stringency measures. Notably, full vaccination is moderately negatively correlated (0.40–0.59) with park mobility, but weaker (<0.4) with other variables such as new cases, hospitalisations, and retail and recreation mobility.

On the other hand, the strength and direction of correlation between mobility indicators vary. Residential mobility is negatively correlated with all other mobility indicators. In terms of strength, it has a strong association (>0.60) with transit and workplace-related mobility, but moderate association (0.40–0.59) with retail and recreation and grocery and pharmacy-related mobility. Correlations also show that transit and workplace mobility are strongly associated with each other, similarly to the association between retail and recreation and groceries and pharmacies. Park mobility has a moderate association (0.40–0.59) with both retail and recreation and grocery and pharmacy mobility.

Table 3 displays the proportion of variance explained by all of the principal components. As there are 13 variables in the analysis, 13 principal components (PC1, PC2, PC3, ..., PC13) are produced. The variance of the data contributed by the first (PC1), second (PC2), and third (PC3) principal components is around 31.6%, 24.3%, and 21.4%, respectively. Taken together, the first three components can
explain around 77.3% of the variance in the data. Of the remaining variance, the fourth component captures around 8.5%, whereas the rest captures less than 5% each.

The principal component loading vectors are presented in Table 4. The first loading vector places rather large, positive, and approximately equal weights on confirmed cases, hospital and ICU admissions, and deaths due to the virus. The weights for full and partial vaccinations, stringency, and mobility indicators are relatively smaller. Hence, this first component seems to clearly correspond towards an indication of the level of severity of the COVID-19 surge in the country. Countries with large positive scores on the first component would indicate high severity levels.

In the second loading vector, the weights of retail and recreation, grocery and pharmacy, transit, and residential mobility indicators are relatively large compared to the rest of the variables. These indicators have negative projections, except for residential mobility. Therefore, the second component appears to reflect more on human mobility patterns, where countries with large negative scores would indicate more of transit, retail, and recreational types of mobility.

The third loading vector places rather large, positive, and approximately equal weights on workplace mobility and full and partial vaccinations. Hence, countries with large positive scores on this component would indicate higher government stringency measures and less mobility trends for places of residences. The weights for workplace and residential mobility are rather intuitive, as there is a strong negative correlation between these indicators.

In the fourth loading vector, the weights of stringency measures and parks are negative and comparatively larger. Hence, countries with large negative scores would also indicate, albeit to a lesser degree, higher government stringency measures and less mobility trends for places of residences. The weights for workplace and residential mobility are rather intuitive, as there is a strong negative correlation between these indicators.

In the fourth loading vector, the weights of stringency measures and parks are negative and comparatively larger. Hence, countries with large negative scores imply more stringent measures imposed by its government, as well as higher park-related mobility. However, this principal component contributes only 8.5% of the variance in the data.
|                         | New cases | Hosp. | ICU  | Deaths | Full Vac. | Partial Vac. | Stringency | Retail & recreational | Grocery & pharmacies | Parks | Transit | Workplace | Residence |
|-------------------------|-----------|-------|------|--------|-----------|---------------|-------------|----------------------|----------------------|-------|---------|-----------|-----------|
| New cases               | 1         | 0.96  | 0.94 | 0.89   | -0.06     | -0.06         | -0.2        | -0.06                | -0.29                | -0.23 | -0.03   | 0.03      | 0         |
| Hosp.                   | 0.96      | 1     | 1    | 0.91   | -0.13     | -0.15         | -0.11       | -0.02                | -0.26                | -0.17 | 0.02    | 0         | -0.02     |
| ICU                     | 0.94      | 1     | 1    | 0.92   | -0.14     | -0.18         | -0.09       | -0.02                | -0.26                | -0.16 | 0       | -0.02     | -0.01     |
| Deaths                  | 0.89      | 0.91  | 0.92 | 1      | -0.08     | -0.09         | -0.11       | -0.06                | -0.3                 | -0.24 | -0.03   | 0.03      | -0.01     |
| Full Vac.               | -0.06     | -0.13 | -0.14| -0.08  | 1         | 0.85          | 0.44        | -0.24                | -0.18                | -0.52  | -0.07   | 0.39      | -0.04     |
| Partial Vac.            | -0.06     | -0.15 | -0.18| -0.09  | 0.85      | 1             | 0.58        | -0.2                 | -0.14                | -0.33  | -0.21   | 0.37      | 0         |
| Stringency             | -0.2      | -0.11 | -0.09| -0.11  | 0.44      | 0.58          | 1           | -0.09                | 0.08                 | -0.1   | -0.05   | 0.24      | -0.06     |
| Retail & recreational  | -0.06     | -0.02 | -0.02| -0.06  | -0.24     | -0.2          | -0.09       | 1                    | 0.72                 | 0.51   | 0.41    | 0.18      | -0.44     |
| Grocery & pharmacies    | -0.29     | -0.26 | -0.26| -0.3   | -0.18     | -0.14         | 0.08        | 0.72                 | 1                    | 0.4    | 0.56    | 0.22      | -0.42     |
| Parks                   | -0.23     | -0.17 | -0.16| -0.24  | -0.52     | -0.33         | -0.1        | 0.51                 | 0.4                  | 1      | 0.02    | -0.18     | -0.16     |
| Transit                 | -0.03     | 0.02  | 0    | -0.03  | -0.07     | -0.21         | -0.05       | 0.41                 | 0.56                 | 0.02   | 1       | 0.61      | -0.75     |
| Workplace               | 0.03      | 0     | -0.02| 0.03   | 0.39      | 0.37          | 0.24        | 0.18                 | 0.22                 | -0.18 | 0.61    | 1         | -0.86     |
| Residence              | 0         | -0.02 | -0.01| -0.04  | 0         | -0.06         | -0.44       | -0.42                | -0.16                | -0.75  | -0.86   | 1         | 0         |
The first component is driven by the spread of COVID-19, the second component by mobility activities (transit, retail, and recreational), whereas the third by COVID-19 vaccination coverage, workplace-related mobility, and government stringency measures. As these three principal components contribute to a substantial amount of variance in the data (77.3%), we have presented them in plots to further aid in interpretation. We can examine differences between the seven countries via two 2-dimensional plots of three principal component score vectors as shown in Figures 1 and 2. Each country is displayed as coloured text, labelled according to the country’s ISO code and month, and represents the scores of the principal components in the corresponding plots.

On the first principal component (PC1) (Figure 1), Austria, Canada, France, the UK, Israel, and Italy appear either near the origin (0, 0) or on the left of the PC1 axis, indicating moderate or lower severity in the COVID-19 pandemic between July and December 2021. Though Austria appears to be facing a higher surge in December. By contrast, the USA has large positive scores on the first component, indicating especially a severe surge in the month of September.

On the second principal component (PC2) (Figure 1), Austria, Canada, France, Italy, and Israel as captured in September have larger negative scores on PC2, reflecting higher transit, retail, and recreational-related mobility during that month. Coincidentally, the USA appears on the bottom right quadrant in the plot indicating very high mobility behaviour and a severe COVID-19 surge concurrently in September. Interestingly, mobility patterns in Austria as seen in September are starkly different from those in December.

The third principal component (PC3) (Figure 2) indicates clearly the rollout in full and partial vaccinations, as well as workplace mobility. It is clearly seen that from July to December 2021, all seven countries have increased vaccination coverage of its population and workplace-related mobility has also increased. PC3 also somewhat indicates more stringent measures imposed by governments. In December 2021, France, Italy, and Canada appear at the top of PC3, indicating high vaccination coverage of its population, as well as stricter government response to the pandemic. As these countries appear to the left of the PC1 axis, it appears that the COVID-19 situation in these countries is under good control. It is also notable that high vaccination coverage together with moderate levels of government stringency appears adequate in controlling the spread of COVID-19, as seen in Israel and the UK. The spread of COVID-19 is more severe in the USA, although the country’s stringency is at a moderate level. The country’s stringency level is rather similar to the UK in December, but its full vaccination coverage of its population is the lowest compared to the other six countries in the study.

The 3-dimensional plots (Figures 3(a)–3(f)) of the seven countries reveal the patterns in the data captured through the three principal components, according to months. Throughout the 6 months, it can be seen that Austria, Canada, France, Italy, and the UK are somewhat clustered together and have rather similar patterns in terms of human mobility behaviour, vaccination coverage, government stringency measures, and overall control of the pandemic. On the other hand, the USA appears to have had a somewhat similar experience in July 2021. However, as the country continued to ease restrictions since July, its initial control of the pandemic has diverged beginning August 2021, although vaccine coverage increased.
4. Discussion

The order of principal components reflects the amount of variance captured from the data. Hence, it is evident that this data of seven countries, captured between 5th July and 5th December 2021, primarily explains the severity of the COVID-19 pandemic, followed by transit, retail, and recreational-related mobility patterns, then followed by the vaccination coverage, workplace-related mobility, and government stringency measures. During this period, the Delta variant has spread widely in these countries and has more than doubled the risk of hospital admissions and death compared to the Alpha variant [24, 27]. However, with widespread vaccine coverage and at least moderate levels of government stringency measures, our findings indicate that the COVID-19 pandemic has largely
Figure 3: Continued.
Figure 3: Continued.
been contained in Austria, France, Italy, Israel, Canada, and the UK.

It is also apparent that the pandemic and accompanying government regulations and restrictions have influenced human mobility behaviour [23]. Our findings reveal changes in human mobility patterns in these seven countries during the second half of 2021, considering the widespread vaccination rollout and rather moderate levels of government stringency measures and the spread of COVID-19 simultaneously. Human mobility activities peaked in September for most countries, particularly with regard to transit, retail, recreation, groceries, and pharmacy types of mobility. These activities then receded in the following months as countries began to grapple with a surge in COVID-19 cases and severity, and governments such as France and Italy have imposed more stringent measures. The striking change in human mobility patterns in Austria in December of 2021 coincides with the
COVID-19 vaccine protection through widespread vaccination rollout is essential to ensure that hospitals are not overwhelmed with severe cases, to revive economic activities and labour markets, and to allow the return to some semblance of normalcy. However, the public’s perception, belief, and attitudes towards the COVID-19 vaccine have undue influence on the rate of vaccine uptake [49]. Culture and other macroenvironmental factors can also influence a nation’s vulnerability and effectiveness in handling the pandemic [50]. Moreover, paranoia and widespread misinformation will continue to impede the attainment of herd immunity and recovery from the COVID-19 pandemic [51, 52]. Hence, governments need to proactively engage with the public on the importance and safety of vaccination, and for some nations, the communication needs to be culturally sensitive and inclusive to all religious societies [50, 53]. Effective communication through media and news agencies is imperative to dispel fears, mental anxieties, and battle of COVID-19 infodemics [51].

It is also necessary to continuously assess risks and adjust countermeasures. We believe that these findings reveal the importance of governments establishing strong data collection mechanisms that can track and categorise severity of symptoms, hospitalisations, and ICU admissions. These will enable mathematical models to be applied to provide real-time advisory to policy-makers on appropriate responses and time frames, of which measures can either be loosened or even tightened in light of what the models are able to forecast.

5. Conclusions

This study utilises PCA, a multivariate unsupervised learning technique, to derive deeper insights into the control of the spread of COVID-19, during the period of 5th July to 5th December 2021, from seven of the earliest vaccinated countries. We have delineated these dimensions, the spread of COVID-19, human mobility patterns, widespread vaccination rollout, and government stringency measures, on the overall control of the COVID-19 pandemic. Another novelty from this study is the utilisation of this multivariate technique as a visualization tool to reveal hidden patterns in the data during this period when the highly transmissible COVID-19 Delta strain was dominant.

The key findings from this study are summarized as below:

(i) The variance in the data related to these seven countries during this period reveals that the spread of COVID-19 was most dominant. Slightly less dominant were the human mobility patterns, the widespread vaccination rollout, and government stringency measures, respectively.

(ii) PCA visualizations indicate comparatively lower or moderate levels of severity in the COVID-19 pandemic between July and December 2021, in Austria, Italy, France, Israel, Canada, and the UK. By contrast,
the USA faced more severe COVID-19 outbreaks especially in September of 2021

(iii) Human mobility activities peaked in September for most countries and then receded in the following months as more stringent government measures were imposed, and countries began to grapple with a surge in COVID-19 cases

(iv) All seven countries have increased vaccination coverage of their population, and workplace-related mobility has also increased during this period

(v) Widespread vaccination rollout is particularly important. High vaccination coverage, together with at least moderate levels of government stringency measures, is able to control the spread of COVID-19, as seen in Austria, Italy, France, Israel, Canada, and the UK

There are limitations in the study. Here, the PCA technique is applied solely for exploratory data analysis. As PCA is often viewed as a dimensionality reduction technique, the model complexity is determined in terms of the number of principal components that explain most of the systematic variation in the data [36, 37, 54]. The first three principal components were extracted, visualized, and interpreted through loading vectors and visualizations. These three main components account for around three-fourths of the variance in the data. The remaining components, each, captured less than 10% of the variance. Hence, they were not visualized and discussed in our study. However, we argue that the first three components are highly representative of the variance in the data and can clearly delineate the different dimensions which are most dominant.

Moreover, due to lack of COVID-19 vaccination coverage and incomplete and insufficient data on ICU and hospital admissions in other countries, only seven countries were included in the multivariate analysis. Data from more countries, captured on shorter time intervals, may provide for a deeper analysis. For future research, the waning effects of vaccination and other confounding factors at play during the Omicron wave may deserve apt attention, when more data becomes available. Our findings provide suggestions for governments globally to consider and serve as a reference when the next pandemic of highly infectious disease comes along.

**Data Availability**

We have acquired access to data from the Global COVID-19 Index (GCI) provided by PEMANDU Associates. The GCI is an independent data engine covering 180 economies and consolidates to provide open data (https://covid19.pemandu.org/). We also utilized the Google COVID-19 Community Mobility Reports (GCMR) which uses aggregated and anonymized data to chart changes in mobility with respect to different classes of places—retail and recreation, groceries and pharmacies, parks, transit, workplace, and residential (https://www.google.com/covid19/mobility/).

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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**References**

[1] United Nations, “Everyone included: social impact of COVID-19,” 2020 https://www.un.org/development/desa/dspd/everyone-included-covid-19.html.

[2] H. K. Koh, A. C. Geller, and T. J. VanderWeele, “Deaths from COVID-19,” JAMA, vol. 325, no. 2, pp. 133-134, 2021.

[3] N. Donthu and A. Gustafsson, “Effects of COVID-19 on business and research,” Journal of Business Research, vol. 117, pp. 284–289, 2020.

[4] B. Dyatkin and Y. S. Meng, “COVID-19 disrupts battery materials and manufacture supply chains, but outlook remains strong,” MRS Bulletin, vol. 45, no. 9, pp. 700–702, 2020.

[5] T. Haryanto, “Editorial: COVID-19 pandemic and international tourism demand,” Journal of Developing Economies, vol. 5, no. 1, pp. 1–4, 2020.

[6] G. W. Warren and R. Lofstedt, “COVID-19 vaccine rollout management and communication in Europe: one year on,” Journal of Risk Research, pp. 1–20, 2021.

[7] C. Baraniuk, “Covid-19: how the UK vaccine rollout delivered success, so far,” BMJ, vol. 372, p. n421, 2021.

[8] Our World in Data, “Coronavirus (COVID-19) vaccinations,” 2022 https://ourworldindata.org/covid-vaccinations.

[9] PEMANDU Associates, “COVID-19 vaccinations table / vaccine administered,” 2022 https://covid19.pemandu.org/vaccinations/.

[10] Z. Ceylan, “Estimation of COVID-19 prevalence in Italy, Spain, and France,” Science of the Total Environment, vol. 729, p. 138817, 2020.

[11] J. K. L. Teh, D. A. Bradley, J. B. Chook et al., “Multivariate visualization of the global COVID-19 pandemic: a comparison of 161 countries,” PLoS One, vol. 16, no. 5, article e0252273, 2021.

[12] T. N. Vilches, S. M. Moghadas, P. Sah et al., “Estimating COVID-19 infections, hospitalizations, and deaths following the US vaccination campaigns during the pandemic,” JAMA Network Open, vol. 5, no. 1, pp. e2142725–e2142725, 2022.

[13] S. M. Moghadas, T. N. Vilches, K. Zhang et al., “The impact of vaccination on coronavirus disease 2019 (COVID-19) outbreaks in the United States,” Clinical Infectious Diseases, vol. 73, no. 12, pp. 2257–2264, 2021.

[14] D. Y. Lin, Y. Gu, B. Wheeler et al., “Effectiveness of Covid-19 vaccines over a 9-month period in North Carolina,” The New England Journal of Medicine, vol. 386, no. 10, pp. 933–941, 2022.

[15] V. J. Hall, S. Foulkes, A. Saei et al., “COVID-19 vaccine coverage in health-care workers in England and effectiveness of BNT162b2 mRNA vaccine against infection (SIREN): a prospective, multicentre, cohort study,” The Lancet, vol. 397, no. 10, pp. 1725–1735, 2021.

[16] N. Andrews, E. Tessier, J. Stowe et al., Vaccine effectiveness and duration of protection of Comirnaty, Vaxzevria and Spikevax
against mild and severe COVID-19 in the UK, medRxiv, 2021, 2021.09.15.21263583.

[17] Organisation for Economic Co-operation and Development, “Designing active labour market policies for the recovery. OECD Policy Responses to Coronavirus (COVID-19),” 2021, https://www.oecd.org/coronavirus/policy-responses/designing-active-labour-market-policies-for-the-recovery-79c833cf/.

[18] T. K. Burki, “Lifting of COVID-19 restrictions in the UK and the Delta variant,” The Lancet Respiratory Medicine, vol. 9, no. 8, p. e85, 2021.

[19] S. Bauer, S. Contreras, J. Dehning et al., “Cross-country cluster analysis, Does the COVID-19 pandemic change human mobility equally worldwide? Cross-country cluster analysis,” Cross-Country Cluster Analysis. Economies, vol. 9, no. 4, p. 182, 2021.

[20] D. K. Miles, A. H. Heald, and M. Stedman, “How fast should social restrictions be eased in England as COVID-19 vaccinations are rolled out?,” International Journal of Clinical Practice, vol. 75, no. 7, article e14191, 2021.

[21] S. M. Grundel, S. Heyder, T. Hotz, T. K. S. Ritschel, P. Sauerweit, and K. Worthmann, “How to coordinate vaccination and social distancing to mitigate SARS-CoV-2 outbreaks,” SIAM Journal on Applied Dynamical Systems, vol. 20, no. 2, pp. 1135–1157, 2021.

[22] R. Li, O. N. Bjørnstad, and N. C. Stenseth, “Switching vaccination among target groups to achieve improved long-lasting benefits,” Royal Society Open Science, vol. 8, no. 6, p. 210292, 2021.

[23] K. Czech, A. Davy, and M. Wielechowski, “Does the COVID-19 pandemic change human mobility equally worldwide? Cross-country cluster analysis,” Cross-Country Cluster Analysis. Economies, vol. 9, no. 4, p. 182, 2021.

[24] WHO European Region, “SARS-CoV-2 Delta variant now dominant in much of European region; efforts must be reinforced to prevent transmission, warns WHO Regional Office for Europe and ECDC,” https://www.euro.who.int/en/media-centre/sections/press-releases/2021/sars-cov-2-delta-variant-now-dominant-in-much-of-european-region-efforts-must-be-reinforced-to-prevent-transmission,-warns-who-regional-office-for-europe-and-ecdc#:--text=Surveillance%20data%20reported%20to%20the%20WHO%20completes%20genetic%20sequencing.

[25] M. Arnold, Spread of Delta variant casts shadow over Europe’s economic rebound, in Financial Times, The Financial Times Ltd., 2021.

[26] D. Sikora and P. Rzymski, “COVID-19 vaccination and rates of infections, hospitalizations, ICU admissions, and deaths in the European economic area during autumn 2021 wave of SARS-CoV-2,” Vaccine, vol. 10, no. 3, p. 437, 2022.

[27] S. Shiehzadegan, N. Alaghemand, M. Fox, and V. Venketaraman, “Analysis of the Delta Variant B.1.617.2 COVID-19,” Clinics and Practice, vol. 11, no. 4, pp. 778–784, 2021.

[28] C. Trobajo-Sanmartin, I. Martinez-Baz, A. Miqueliz et al., “Differences in transmission between SARS-CoV-2 Alpha (B.1.1.7) and Delta (B.1.617.2) variants,” Microbiology Spectrum, vol. 10, no. 2, article e000082, 2022.

[29] World Health Organization, “Coronavirus disease (COVID-19) 19 science conversation: Episode #44 - Delta variant and vaccines,” 2021 https://www.who.int/emergencies/diseases/novel-coronavirus-2019/media-resources/science-in-5/episode-44—delta-variant-and-vaccines.
[49] D. Seddig, D. Maskileyson, E. Davidov, I. Ajzen, and P. Schmidt, "Correlates of COVID-19 vaccination intentions: attitudes, institutional trust, fear, conspiracy beliefs, and vaccine skepticism," Social Science & Medicine, vol. 302, p. 114981, 2022.

[50] M. Aljukhadar, "National vulnerability to pandemics: the role of macroenvironmental factors in COVID-19 evolution," Journal of Environmental and Public Health, vol. 2022, Article ID 9524407, 10 pages, 2022.

[51] Z. Su, D. McDonnell, J. Wen et al., "Mental health consequences of COVID-19 media coverage: the need for effective crisis communication practices," Globalization and Health, vol. 17, no. 1, p. 4, 2021.

[52] S. R. Neely, C. Eldredge, R. Ersing, and C. Remington, "Vaccination hesitancy and exposure to misinformation: a survey analysis," Journal of General Internal Medicine, vol. 37, no. 1, pp. 179–187, 2022.

[53] S. M. Sherman, J. Sim, M. Cutts et al., "COVID-19 vaccination acceptability in the UK at the start of the vaccination programme: a nationally representative cross-sectional survey (CoVaccS – wave 2)," Public Health, vol. 202, pp. 1–9, 2022.

[54] S. Wold, K. Esbensen, and P. Geladi, "Principal component analysis," Chemometrics and Intelligent Laboratory Systems, vol. 2, no. 1-3, pp. 37–52, 1987.