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Dynamic compliance in a pandemic: A time-varying causality analysis of vaccination, mobility, and policy stringency during COVID-19

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Abstract

Most evaluations of the effectiveness of COVID-19 policies treat public compliance and policy stringency as static. Yet compliance is dynamic, shaped by evolving risk perception, trust in institutions, and changing pandemic conditions. This study investigates how the effectiveness of prevention campaigns and government-imposed stringency measures fluctuated over time, depending on actual mobility behavior across six countries. Using daily data from January 2021 to April 2022 across France, Germany, Italy, Japan, South Korea, and the United Kingdom, a time-varying Granger causality model was applied to capture the evolving relationships between vaccination rates, stringency measures, population mobility, COVID-19 case numbers, and mortality. Actual mobility data were integrated with the Oxford COVID-19 Government Response Stringency Index to account for *de jure* policy versus *de facto* behavior. Our analysis highlights that vaccination effectiveness in reducing cases and deaths was most pronounced when coupled with reduced mobility. Stringency measures alone provided temporary mitigation but were less effective than widespread vaccination. Notably, Japan exhibited high compliance and strong vaccination outcomes despite relatively lenient formal restrictions, suggesting that social norms and civic adherence may have contributed to these outcomes. Time-varying causality revealed that the impact of both policy and vaccination was not uniform over time but shifted with waves and public sentiment. Our findings underscore the critical role of dynamic public compliance in shaping pandemic outcomes. Beyond policy severity, trust, behavioral norms, and vaccine coverage may jointly influence health outcomes. Real-time causal modeling can help policymakers detect when enforcement or communication strategies need adjustment during health crises.

Keywords: COVID-19; Stringency measures; Vaccination; Civic norms; Voluntary compliance

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1. Introduction

During a public health crisis, people do not merely follow rules; they interpret, contest, adapt, or voluntarily exceed them. As governments around the world implemented strict lockdowns, mask mandates, and social distancing measures to contain the spread of COVID-19, compliance varied significantly across societies (Islam *et al.*, 2020). While policy measures were often treated in research and media as uniform and binary (strict vs. lenient), real-world adherence to those measures was shaped by a range of social, cultural, and behavioral factors, such as institutional trust, civic responsibility, fear of infection, and collective norms.

This study addresses a crucial but underexplored question: how does public compliance with pandemic control measures evolve over time, and how does it interact with policy stringency and vaccination campaigns to influence epidemiological outcomes? We argue that static analyses of policy effectiveness obscure the dynamic nature of compliance and its real-world impacts.

Using a time-varying Granger causality (TVGC) approach, we examine the shifting relationships between vaccination uptake, mobility behavior, stringency measures, and pandemic outcomes across six high-income countries: France, Germany, Italy, Japan, South Korea, and the United Kingdom (UK). By integrating actual mobility data with official stringency indices, our approach captures both what was mandated and how populations responded, revealing the effectiveness of policies as mediated by public behavior.

2. Literature review

The COVID-19 pandemic has sparked extensive research across disciplines, particularly on the efficacy of public health interventions. Early studies predominantly assessed the impact of non-pharmaceutical interventions (NPIs) such as lockdowns, social distancing, and travel restrictions using cross-sectional or panel regression models (Allen, 2022; Ambikapathy *et al.*, 2020; Booth *et al.*, 2021; Ferguson *et al.*, 2020). For example, Ambikapathy *et al.* (2020) found that movement restrictions of 2–3 weeks can reduce viral spread, but emphasized that a minimum of 42 days is needed for substantial containment effects (Ma *et al.*, 2021). Lavezzo *et al.* (2021), studying a localized lockdown in northern Italy, demonstrated the benefits of targeted social tracing for reducing morbidity and mortality.

These initial contributions treated policies as fixed inputs and assumed homogeneous population responses. Over time, however, the availability of large-scale data facilitated more complex analyses. Scholars increasingly employed the Oxford COVID-19 Government Response Stringency Index (Hale, Angrist, Goldszmidt, *et al.*, 2021; Hale, Angrist, Hale, *et al.*, 2021) to measure policy severity across countries. Studies like those by Violato *et al.* (2021) and Necesito *et al.* (2022) used this index to show that stricter measures were generally associated with lower case and death counts. However, such models often lacked nuance, assuming consistent compliance and treating stringency as equivalent across diverse contexts.

Recent work has begun to challenge these assumptions by incorporating actual mobility data as a proxy for behavioral compliance (Wang *et al.*, 2024; Washington *et al.*, 2020). Sun *et al.* (2021), Okamoto (2022), Rowe *et al.* (2023), and Chan *et al.* (2023) compared official restrictions to real-world behavioral patterns, revealing significant gaps between policy and compliance. Notably, Okamoto (2022) found that mobility in Japan declined substantially despite only modest increases in legal restrictions, reflecting a collectivist culture and high voluntary compliance. This finding underscores that *de jure* policy does not always match *de facto* behavior.

The cultural and institutional context further complicates these relationships. Japan's experience, for example, reveals how social cohesion and civic norms can substitute for legal enforcement. A strong reduction in mobility was achieved with relatively lenient rules, highlighting the power of non-coercive behavioral alignment, a pattern consistent with broader literature on collectivism in Asian societies and voluntary rule-following (Yamamura *et al.*, 2021). Conversely, Herby *et al.* (2023) argued that individuals' autonomous behavioral change often has a greater effect than coercive lockdowns. This is a crucial characteristic that differs among countries. Japan already had well-developed social norms and etiquette around infection prevention that were less established in some of the countries, with people commonly wearing masks or avoiding social interactions when sick even before the pandemic. As noted by Yamamura *et al.* (2021), the collectivist orientation and informal social accountability structures in Japan may reduce the need for formal enforcement, while social sanctions can function alongside legal enforcement to support adherence to social norms.

Scholars such as Öcal Özkaya and Sak (2022) even questioned the direction of causality, suggesting that factors such as gross domestic product per capita, age structure, and daily death rates may shape the degree of policy stringency itself. This raised concerns about endogeneity in conventional models, especially those assuming one-way policy-outcome relationships.

Two core challenges emerge in this literature. First,

the introduction of vaccines following their global rollout beginning in late 2020 introduced new dynamics in how NPIs interact with public health outcomes (Chung *et al.*, 2024; Haider *et al.*, 2023). Second, and more fundamentally, many comparative studies failed to account for the changing nature of compliance over time. Pandemic fatigue, shifting trust in institutions, and evolving risk perception mean that the same policy may have different effects at different moments.

Our contribution addresses these gaps directly. By applying a TVGC model, we uncover how the effects of vaccination, mobility, and policy stringency on pandemic outcomes change over time and across countries. We move beyond snapshot analyses to offer a behaviorally grounded, temporally sensitive understanding of when and why policies may succeed or fail depending on real-world public response.

The novelty of our approach lies not just in the methodology, but in its focus on compliance as a dynamic phenomenon. Much of the existing literature has not fully captured the possibility that *de facto* behavior may diverge sharply from *de jure* policy in either direction, instead relying on static analyses. Our approach therefore treats compliance as a dynamic phenomenon rather than assuming it to be constant over time. This is particularly important given the prolonged and multi-phased nature of the COVID-19 pandemic. We demonstrate that the effectiveness of public health interventions depended not only on their legal severity but also on how populations perceived, internalized, and adhered to them over time. Japan, for instance, presents a striking case where voluntary compliance, rooted in social norms, may have partially substituted for legal enforcement.

3. Data and methods

3.1. Data and preliminary analysis

This study utilized a high-frequency panel dataset covering the period from January 2021 to April 2022, enabling a detailed investigation into the dynamic effects of vaccination, public policy, and behavioral responses on COVID-19 outcomes. The analysis focused on six high-income countries, including France, Germany, Italy, Japan, South Korea, and the UK, representing a diverse range of pandemic responses, institutional capacities, and societal compliance norms. Although the six countries were characterized by different trajectories during earlier phases of the pandemic, the selected timeframe (January 2021 to April 2022) captures a broadly comparable period characterized by vaccine rollout and subsequent epidemic waves. This common window allows for cross-country comparability while focusing on the dynamic interaction between vaccination, policy measures, and behavioral responses during a similar phase of pandemic management.

The primary outcomes of interest are the daily number of newly confirmed COVID-19 cases and the daily number of deaths attributed to the virus. These data were obtained from the Johns Hopkins University Coronavirus Resource Center, a globally recognized source offering standardized, cross-nationally comparable figures throughout the pandemic (Dong *et al.*, 2022). The use of daily-level data allows for nuanced analysis of temporal variation and the evolving nature of policy effectiveness and public response.

Three key explanatory variables were employed in this study. The first is the full vaccination rate, defined as the proportion of the population that has received two doses of an approved vaccine. These data were obtained from the Our World in Data platform, which compiles vaccination statistics from national health agencies. The second is the Oxford COVID-19 Government Response Stringency Index, which ranges from 0 (no restrictions) to 100 (maximum stringency). This index aggregates information on NPIs such as school closures, curfews, and travel bans, and serves as a *de jure* indicator of state-imposed public health measures. The third variable, population mobility, was obtained from Google COVID-19 Community Mobility Reports. These reports provide anonymized, aggregated data on changes in movement trends across categories such as workplaces, retail, and transit stations, offering a behavioral proxy that captures behavioral responses to restrictions (Barber *et al.*, 2022; González-Leonardo *et al.*, 2022; Nouvellet *et al.*, 2021; Yabe *et al.*, 2022).

To harmonize the datasets, all variables were aligned on a daily basis by country and date. In cases of missing values, forward-filling imputation was employed, consistent with practices adopted in recent empirical studies using high-frequency pandemic data. This approach ensures continuity in time-series analysis while preserving the integrity of the subsequent causality testing.

The selection of countries is theoretically grounded in the contrasting approaches to public health governance. While the European cases, such as France, Germany, Italy, and the UK, adopted relatively strict, top-down containment measures, Japan and South Korea relied more heavily on voluntary compliance, civic norms, and soft guidance. This heterogeneity in institutional approaches and public behavior provides an informative backdrop against which the effectiveness of vaccination and policy measures can be analyzed, particularly through the lens of dynamic public compliance.

All data used in this study are publicly available,

anonymized, and ethically sourced. The Google mobility data follow strict privacy protocols and do not permit the identification of individuals. Similarly, the stringency and vaccination indices are maintained by academic institutions committed to research transparency and open access.

Finally, the datasets used in this study were derived from widely recognized and publicly available sources; however, while these datasets are extensively used in the literature, some degree of measurement error and cross-country variation in reporting practices may persist. In addition, differences in national reporting standards for COVID-19 mortality may affect cross-country comparability. Some countries may adopt broader or narrower definitions of COVID-19-related deaths, which could introduce measurement inconsistencies in the outcome variable.

The timeframe of our study covered the same 485-day period for each of the six countries in the study sample. The variables and their corresponding formats are listed in Table 1.

As shown in Figure 1, there is a strong association between the evolution of vaccination coverage for the first and second doses in each of the countries in the study sample. The convergence of the doses becomes particularly evident as vaccination coverage increases over time. All countries except the UK reached or exceeded 80% population coverage with the second dose during our period of analysis.

Figure 2 presents the evolution of the disease in each of the countries in the study sample. As shown in Figure 2, Japan and South Korea had lower initial case counts, showing that the disease was less prevalent in these countries than in their European counterparts in the sample at that point. France, Italy, and the UK reported a larger number of cases by the beginning of 2021, with the UK showing a relatively higher case-fatality ratio than the other countries in the study sample. A sharp increase in the number of cases was observed in all countries by the end of 2021, which coincided with the emergence and spread of the Delta variant during late 2021 and early 2022. The effect of the Delta variant on the number of deaths is evident for France, Germany, Italy, Japan, and South Korea; however, the UK shows a more gradual upward trend.

Our dataset allowed us to compare the performance of different country-level strategies during periods of particularly severe pandemic activity within the timeframe considered. To improve cross-country comparability and reduce potential bias arising from differences in population size, we employed population-standardized measures. As shown in Figure 3, the pandemic became less fatal over time in France and Italy, where mortality was initially higher. The death rate from the pandemic was more volatile over the course of the period in question in Japan and South Korea when the new variants appeared. Seasonal patterns, particularly during winter, are also apparent in the East Asian countries.

Figure 4 provides further descriptive analysis, with an inverse relationship between mobility and stringency measures frequently observed in all countries in the study sample. A negative correlation was observed in diagrams depicting the fatality rate (number of deaths relative to the number of cases). Italy deviates from this trend, with a stable fatality rate throughout 2021 that declines dramatically from early 2022. All country graphs show a marked decrease in fatalities from the beginning of 2022, which may be associated with increasing vaccination coverage and changes in the epidemiological characteristics and severity of circulating variants compared with the initial

Table 1. Details of the variables

Variable name	Dependent/independent	Frequency	Format
Number of deaths	Dependent	Daily	Logarithmically transformed
Number of cases	Dependent and independent	Daily	Logarithmically transformed
People vaccinated	Independent	Daily	Percentage of the total population
People fully vaccinated	Independent	Daily	Percentage of the total population
Stringency measures	Independent	Daily	Percentage (100 = strictest measures)
Mobility	Independent	Daily	Percentage change

Notes: The number of confirmed COVID-19 cases and deaths was logarithmically transformed. The people vaccinated (vaccination rate) variable refers to individuals who had received at least one dose of a COVID-19 vaccine, whereas the people fully vaccinated (full vaccination rate) variable refers to individuals who had completed the primary vaccination series during the study period. Both vaccination variables are expressed as percentages of the population. The stringency measure is expressed as an index ranging from 0 to 100, with higher values indicating greater policy stringency. The mobility variable represents the percentage change in mobility relative to the pre-pandemic baseline. These measurement formats facilitate comparability across countries; however, logarithmic transformation does not itself standardize for differences in population size.

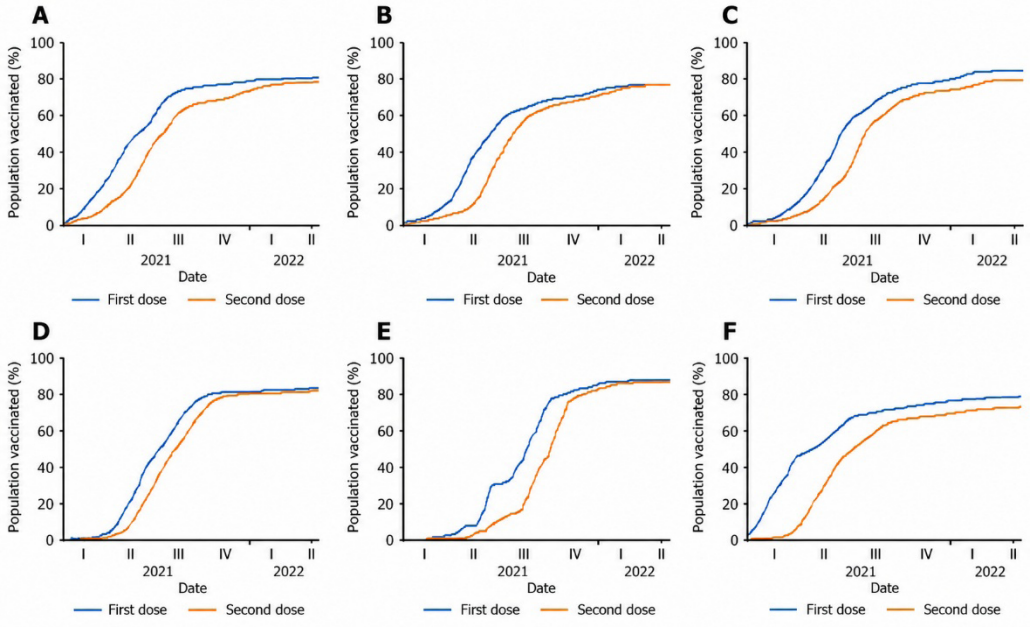


Figure 1. Percentage of the population vaccinated from January 2021 to April 2022 across six countries, using data from the Johns Hopkins University COVID-19 Data Repository: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom

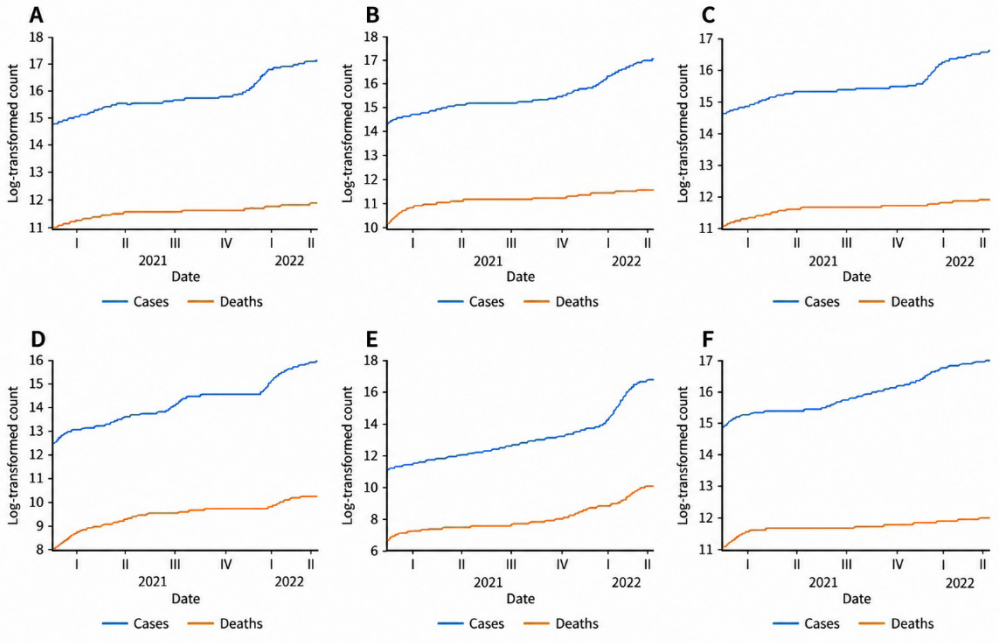


Figure 2. Overview of cases and deaths from January 2021 to April 2022 (log-transformed values) across six countries, using data from the Johns Hopkins University COVID-19 Data Repository: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom

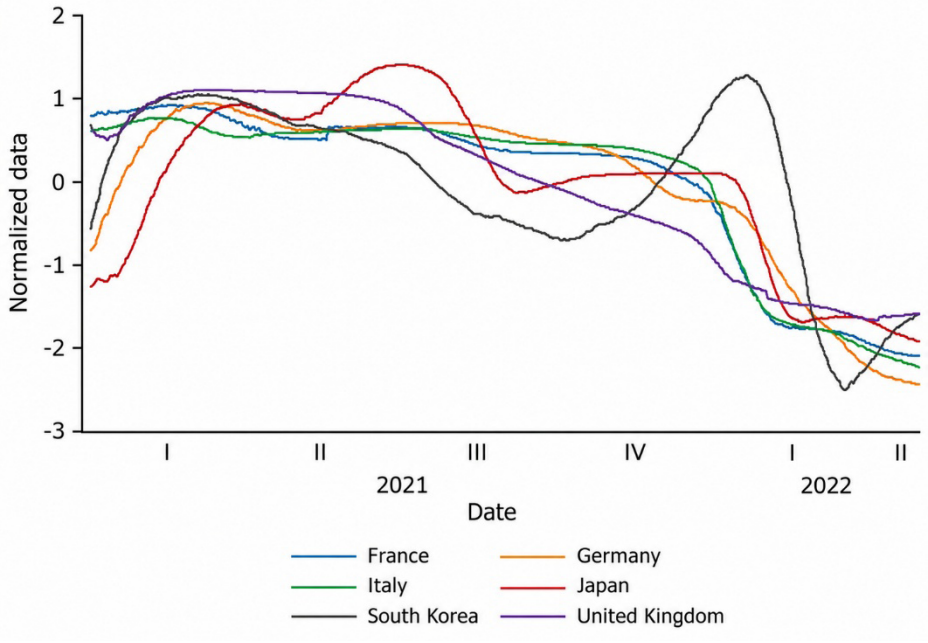


Figure 3. Deadliest episodes of the COVID-19 pandemic from January 2021 to April 2022, using data from the Johns Hopkins University COVID-19 Data Repository

strains.

Table 2 presents descriptive statistics on the stringency index and the percentage change in human mobility during the pandemic relative to the pre-pandemic period. Notably, mobility increased relative to the pre-pandemic period in all countries except Japan and the UK. The UK consistently implemented some of the strictest stringency measures, particularly during periods with increased death rates, suggesting an association between higher policy stringency and periods of elevated mortality; despite experiencing both the strictest and the most lenient stringency levels, mobility was consistently lower than during the pre-pandemic period. Conversely, Japan, while not enforcing measures as strict as those of the UK, maintained mobility levels below those observed during the pre-pandemic period. This pattern suggests that Japan maintained relatively lower mobility without relying on stringency measures as high as those implemented in the UK. Examining the data, Italy emerges as the country with the highest average stringency level, coupled with a significant decline in human mobility during the pandemic, with the reduction being second only to that observed in the UK.

Collectively, this tentative descriptive analysis offers preliminary evidence that countries may differ in their behavioral responses to the rules implemented to contain the spread of the virus. The countries in the study sample suggest that Japan was able to maintain lower human mobility without implementing rules as stringent as those observed in the UK. The UK implemented relatively strict measures, which coincided with comparatively large reductions in mobility. Italy and Germany implemented some of the strictest stringency measures, yet the average reduction in human mobility in these two countries was less pronounced than that in Japan or the UK.

3.2. Methodological rationale for the time-varying Granger causality approach

In this study, a TVGC method was employed to explore how vaccination coverage, government-imposed stringency measures, and actual human mobility were temporally associated with the progression of COVID-19 in six countries. The rationale for this choice is both methodological and empirical.

Granger causality determines whether one time series provides statistically significant predictive information about another by identifying statistically significant predictive relationships. Unlike standard regression models that estimate associations between variables, Granger causality tests the temporal predictive power of one variable for another. The use of TVGC allows us to explore how these predictive relationships evolve during different pandemic phases—a key advantage when dealing with a long-term, dynamic public health crisis (Rosoł *et*

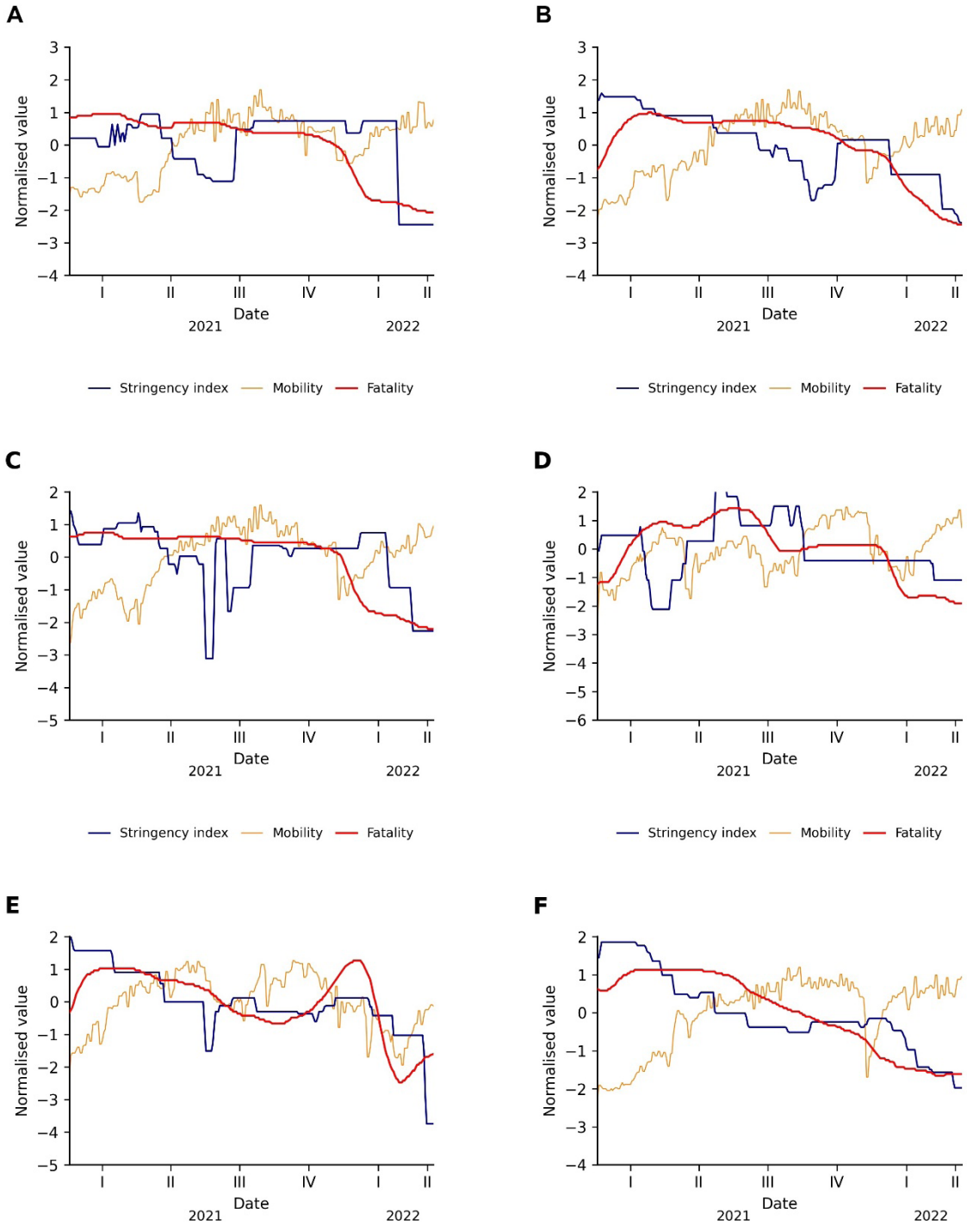


Figure 4. Fluctuations in the stringency index, mobility, and fatality from January 2021 to April 2022 (normalized values) across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. Data sources: COVID-19 Government Response Tracker (Oxford University); COVID-19 Community Mobility Reports (Google); and COVID-19 Data Repository (Johns Hopkins University).

Table 2. Stringency index and human mobility from January 2021 to April 2022

Statistic	France		Germany		Italy		Japan		South Korea		United Kingdom	
	Stringency Index	Mobility (%Δ)	Stringency Index	Mobility (%Δ)	Stringency Index	Mobility (%Δ)	Stringency Index	Mobility (%Δ)	Stringency Index	Mobility (%Δ)	Stringency Index	Mobility (%Δ)
Mean	61.4	−12.8	62.1	−22.7	71.2	−23.0	48.3	−24.6	50.0	−7.2	51.7	−37.0
Median	68.1	−9.0	63.9	−20.0	73.2	−20.0	47.2	−24.0	50.0	−6.0	46.8	−33.0
Maximum	75.0	24.0	85.2	13.0	83.3	11.0	55.1	−7.0	67.6	15.0	88.0	−12.0
Minimum	23.2	−69.0	26.9	−75.0	47.2	−83.0	42.6	−66.0	16.7	−46.0	13.0	−82.0

Data sources: COVID-19 Government Response Tracker (Oxford University) and COVID-19 Community Mobility Reports (Google).

al., 2022).

The limitations of static models are especially apparent when studying the pandemic. As noted by Violato *et al.* (2021), conventional regression approaches often assume a fixed direction of association, for instance, that rising cases lead to more deaths, or that stringency affects mobility unidirectionally. Yet in reality, feedback loops exist: increased deaths may prompt voluntary compliance, while overwhelmed health systems may exacerbate both case severity and mortality. If these endogenous relationships are not accounted for, parameter estimates risk being biased and misleading.

Time-varying Granger causality accommodates these complexities by estimating evolving predictive relationships within a vector autoregressive (VAR) framework. This approach allows all variables, including cases, deaths, vaccination rates, stringency measures, and mobility, to be treated as endogenous, capturing the bidirectional and time-sensitive dynamics between them.

Moreover, the TVGC model avoids rigid assumptions about disease progression and behavioral response. While the incubation period of COVID-19 is generally understood to range from 5 to 14 days (Bikbov & Bikbov, 2021; McAloon *et al.*, 2020; Salian *et al.*, 2021; Y. Zhou *et al.*, 2021), and the time from infection to death can vary by context (García-García *et al.*, 2021; F. Zhou *et al.*, 2020), these delays are difficult to model uniformly across countries and waves. The recursive 30-day window used in our TVGC estimation, as noted by Violato *et al.* (2021), provides a practical approximation of the disease cycle and behavioral adjustment timeline. This window is necessary to ensure statistical stability in the bootstrapped Wald test while remaining short enough to detect phase-specific shifts in predictive relationships. This interval also approximates a monthly epidemiological reporting cycle and accommodates the relatively frequent policy adjustments implemented by governments during the COVID-19 crisis.

Additionally, TVGC addresses data volatility. With high-frequency daily data from January 2021 to April 2022, we must account for short-term spikes in cases, mobility, or policy response. Static Granger or regression models may smooth over or fail to capture such changes, potentially obscuring critical policy effects during key inflection points. TVGC, by contrast, allows us to observe when significant predictive relationships emerge or change and whether these relationships vary during specific pandemic waves (e.g., Delta or Omicron variant surges).

In summary, our methodological choice reflects both the nature of the data and the research question.

To understand not just "if" but also "when" stringency measures and vaccination efforts were associated with changes in pandemic outcomes—especially in light of shifting public compliance—we require a model that captures temporally fluid and behaviorally contingent predictive relationships. The TVGC framework offers this capability.

3.3. Model specification and estimation strategy

Our model was based on a VAR framework, where each variable is explained by its own lagged values and the lagged values of the other variables in the system. This endogenous specification is essential in the context of COVID-19, where epidemiological outcomes, policy interventions, and behavioral responses may continuously influence one another.

In this study, we tested six Granger-causality scenarios:

(i) Case 1a: Causality from vaccination (first and second doses) to the number of new cases.
(ii) Case 1b: Same as Case 1a, with the inclusion of stringency measures.
(iii) Case 1c: Same as Case 1a, with the inclusion of actual mobility data.
(iv) Case 2a: Causality from vaccination to the number of deaths.
(v) Case 2b: Same as Case 2a, with the inclusion of stringency measures.
(vi) Case 2c: Same as Case 2a, with the inclusion of actual mobility data.

All models used daily data for each of the six countries, with a 28-day lag structure intended to capture the approximate temporal dynamics of disease progression and behavioral adjustment. This 28-day lag was selected to account for the overlapping temporal dynamics associated with COVID-19 transmission, disease progression, and behavioral responses, as described in the existing literature. Bikbov and Bikbov (2021) reported that the incubation period ranges from 5 to 14 days, while F. Zhou *et al.* (2020) and García-García *et al.* (2021) reported that the time from symptom onset to death can extend to 2–3 weeks in severe cases. The 28-day lag therefore provides a practical temporal window for capturing these sequential and potentially overlapping processes within the model.

The estimations were performed using the "tvgc" command in STATA v.15 (Computing Resource Center, USA).

A TVGC framework was adopted to evaluate how the Granger-causal relationships between explanatory variables, including vaccination rates, policy stringency, and population mobility, and pandemic outcomes evolved over time. Granger causality, in its classical form, assesses whether the past values of a variable X_t improve the prediction of another variable Y_t conditional on the past of Y_t itself. Formally, for two stationary time series, $\{X_t\}$ and $\{Y_t\}$, X_t Granger-causes Y_t if:

$$\mathbb{E}\left[Y_t \middle| \mathcal{F}_{t-1} \right] \neq \mathbb{E}\left[Y_t \middle| \mathcal{F}_{t-1}^{(-X)} \right] \tag{1}$$

where $\mathcal{F}_{t-1}$ is the information set including past values of both X and Y, and $\mathcal{F}_{t-1}^{(-X)}$ excludes X.

To allow the Granger-causal relationship to evolve over time, we implement a rolling-window VAR approach. For each country, we estimate a bivariate VAR of the form specified in **Equation 2**, with a fixed lag length p, using a window of T_w observations that rolls forward one day at a time:

$$\begin{aligned} Y_t &= \alpha_0 + \sum_{k=1}^{p} \alpha_k Y_{t-k} + \sum_{k=1}^{p} \beta_k X_{t-k} + \varepsilon_t \\ X_t &= \gamma_0 + \sum_{k=1}^{p} \gamma_k X_{t-k} + \sum_{k=1}^{p} \delta_k Y_{t-k} + \nu_t \end{aligned} \tag{2}$$

The null hypothesis $H_0 : \beta_k = 0 | \forall k$ is tested at each window using bootstrapped Wald statistics to generate empirical p-values.

This rolling procedure yields a time series of p-values indicating the statistical significance of Granger causality between the explanatory variable X_t (e.g., vaccination rate) and the outcome variable Y_t (e.g., new cases or deaths). We interpret statistically significant periods ($p < 0.05$) as intervals during which the explanatory variable provides statistically significant predictive information about the pandemic outcome.

Our implementation follows the approach outlined by Shi *et al.* (2018), which has been applied in macroeconomic and epidemiological time series contexts. The use of bootstrapping helps address potential small-sample distortions and heteroskedasticity, which are prevalent in rolling estimations with high-frequency data.

We estimated the aforementioned six models for each country: three for new cases and three for deaths. In each group, we tested the Granger-causal predictive relationship associated with: (i) vaccination alone, (ii) vaccination with stringency, and (iii) vaccination with mobility. This design allows us to distinguish the predictive contribution of vaccination from those of policy and behavioral variables.

4. Results

4.1. Causality between number of cases and full

vaccination

This section presents the TVGC results examining the relationship between the number of cases and full vaccination (i.e., vaccination with two doses). First, we refer to the baseline model, which does not include stringency measures or changes in mobility. Then, these two variables are added to the models to examine whether the predictive relationship between vaccination and new cases changes.

4.1.1. Case 1a: Granger causality from full vaccination to the number of cases

The first case omits the effects of the stringency measures and focuses on the vaccination campaign. As shown in Figure 5, the Granger-causal relationship between full vaccination and new cases was strongest in South Korea, followed by Japan, as indicated by the highest Wald test statistics among the countries in the study sample. These countries are followed by France and then Italy. Germany also shows a statistically significant Granger-causal relationship from full vaccination to new cases, yet its significance is not as strong as that observed in the other countries in the study sample. The results suggest that the inclusion of vaccination alongside tighter stringency measures may contribute to reducing the transmission of the disease. In general, our findings for South Korea and Japan are consistent with the earlier discussion of their relatively less restrictive approaches to social mobility. The results suggest that both Japan and South Korea relied substantially on vaccination as part of their strategies for responding to COVID-19.

4.1.2. Case 1b: Granger causality from full vaccination to the number of cases when stringency measures are considered

The immediate effect of introducing stringency measures on the Granger-causal relationship between vaccination and new cases is that the periods of statistically significant Granger causality become shorter, except for Japan. This contraction in the duration of statistically significant periods is greatest in Italy, followed by Germany, the UK,

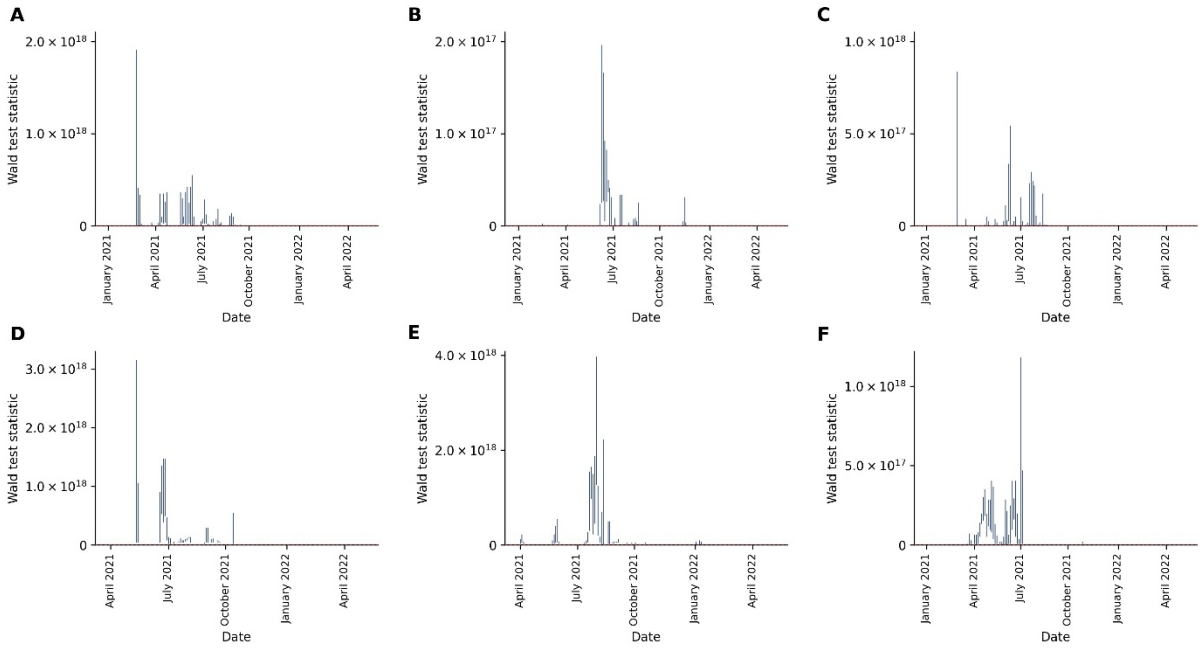


Figure 5. Time-varying Granger causality from full vaccination to new COVID-19 cases across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

France, and South Korea. This finding suggests that when both vaccination and stringency measures are included in the model, the incremental predictive contribution of vaccination to new cases becomes less pronounced, as some of the predictive information may be shared with the stringency measures. This finding can help to explain the case of Japan: there is no remarkable change in the span of statistically significant causality between full vaccination and new cases over the period of analysis, possibly reflecting the country's comparatively less stringent policy measures than those of other countries in the study sample. Figure 6 provides evidence that stringency measures were associated with additional predictive information regarding new cases.

4.1.3. Case 1c: Granger causality from full vaccination to the number of cases when actual mobility figures are considered

Actual mobility figures have differed substantially from theoretical expectations based on restrictions on human mobility imposed through rules and laws. Figure 7 shows that statistically significant causality between full vaccination and new cases persisted for a longer period than that shown in Figure 6. This may indicate that when actual human mobility is taken into account, the predictive relationship between vaccination and new cases becomes more persistent. In this respect, we can say that although the stringency index provides information about legally imposed restrictions, using actual mobility figures provides additional information about behavioral responses and suggests that the predictive contribution of stringency measures varied over time, particularly during the first quarter of 2022. Hence, under more relaxed stringency measures, vaccination may become a more prominent predictor of changes in new cases. This finding does not, however, establish that stricter restrictions would necessarily have been required in the absence of vaccination, but it highlights the potential importance of behavioral and policy responses when vaccination coverage is limited.

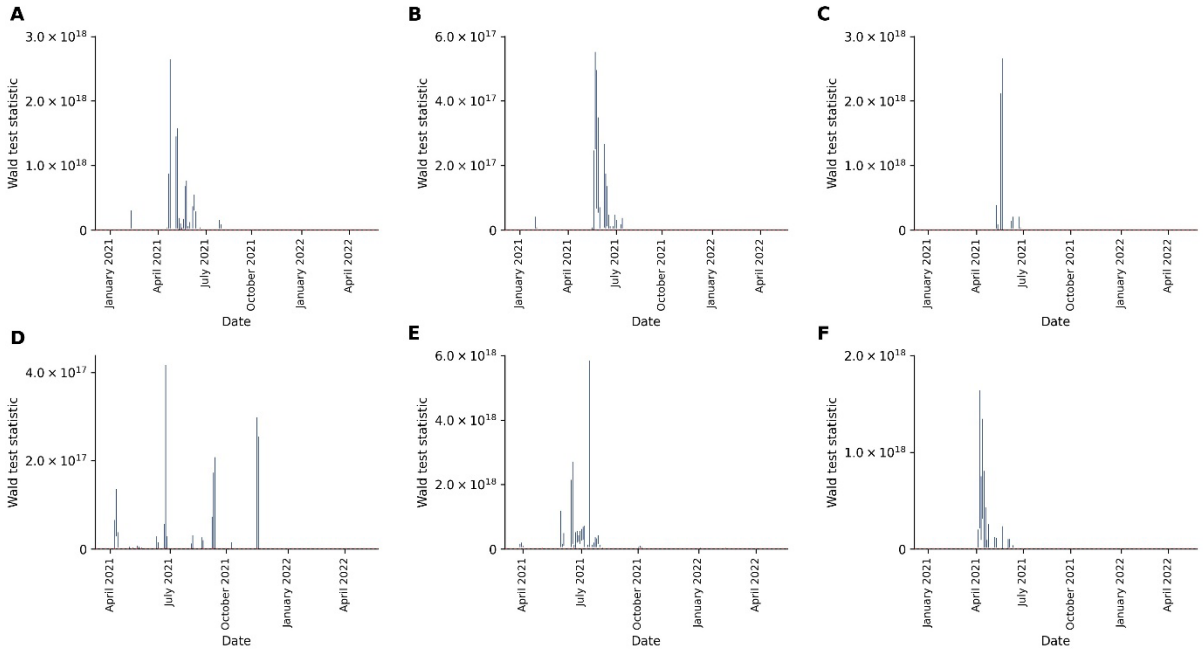


Figure 6. Time-varying Granger causality from full vaccination to new COVID-19 cases with stringency measures included across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

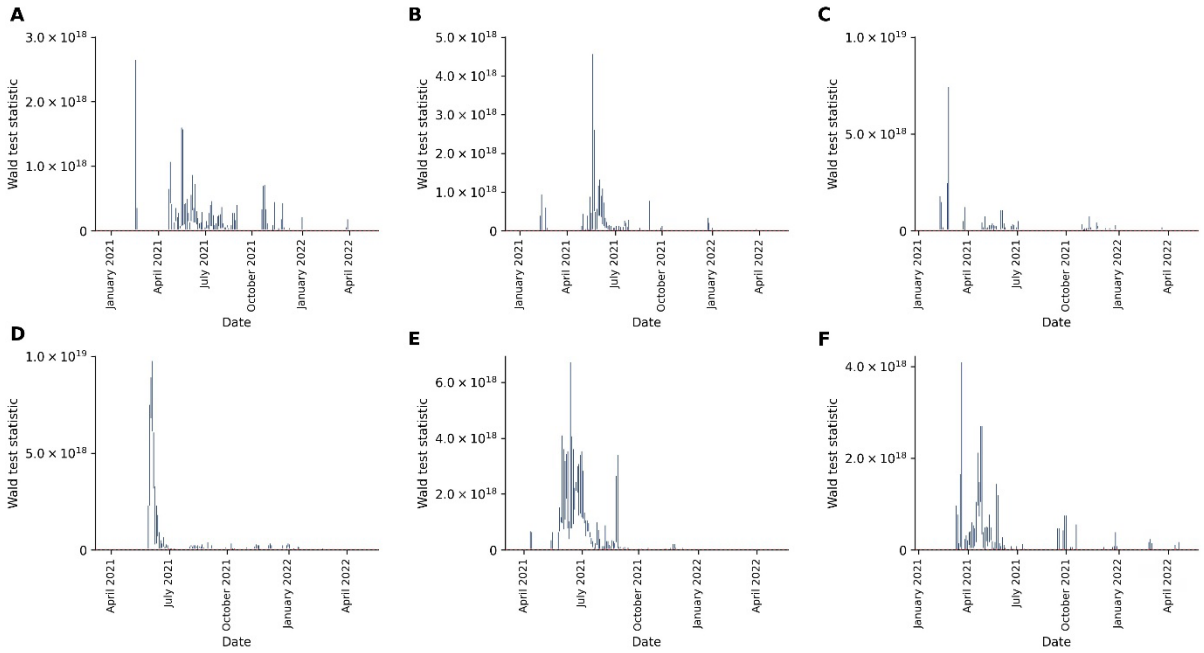


Figure 7. Time-varying Granger causality from full vaccination to new COVID-19 cases with actual mobility included across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

4.2. Causality between full vaccination and the number of deaths

4.2.1. Case 2a: Granger causality from full vaccination to the number of deaths

Figure 8 presents the baseline Granger-causality results for the relationship between full vaccination and the number of deaths, considering vaccination alone and excluding restrictions on human mobility. As shown in Figure 8, France, Germany, Italy, and Japan show statistically significant Granger causality from full vaccination to the number of deaths during the first quarter of 2021. In the UK and South Korea, statistically significant Granger causality was observed primarily during the second quarter of 2021. Nevertheless, it is important to emphasize that the analysis did not distinguish between the effects associated with the first and second vaccine doses, as the administration of the first and second doses (or additional doses, when applicable) overlapped during the study period. Consequently, the model does not allow the predictive contributions of individual doses to be separated.

As shown in Figure 1, the vaccination trajectories across the countries in the study sample reveal two distinct clusters:

(i) Cluster 1: France, Germany, Italy, and Japan.
(ii) Cluster 2: South Korea and the United Kingdom.

The first cluster administered both the first and second doses relatively rapidly, whereas the second cluster administered the first dose more rapidly but showed a slower progression in second-dose coverage.

Figure 8 clearly indicates a potential protective effect of vaccination against COVID-19 mortality when different vaccination strategies are taken into account: the first cluster of countries shows a stronger Granger-causal relationship between vaccination and the number of deaths.

4.2.2. Case 2b: Granger causality from full vaccination to the number of deaths when stringency measures are imposed

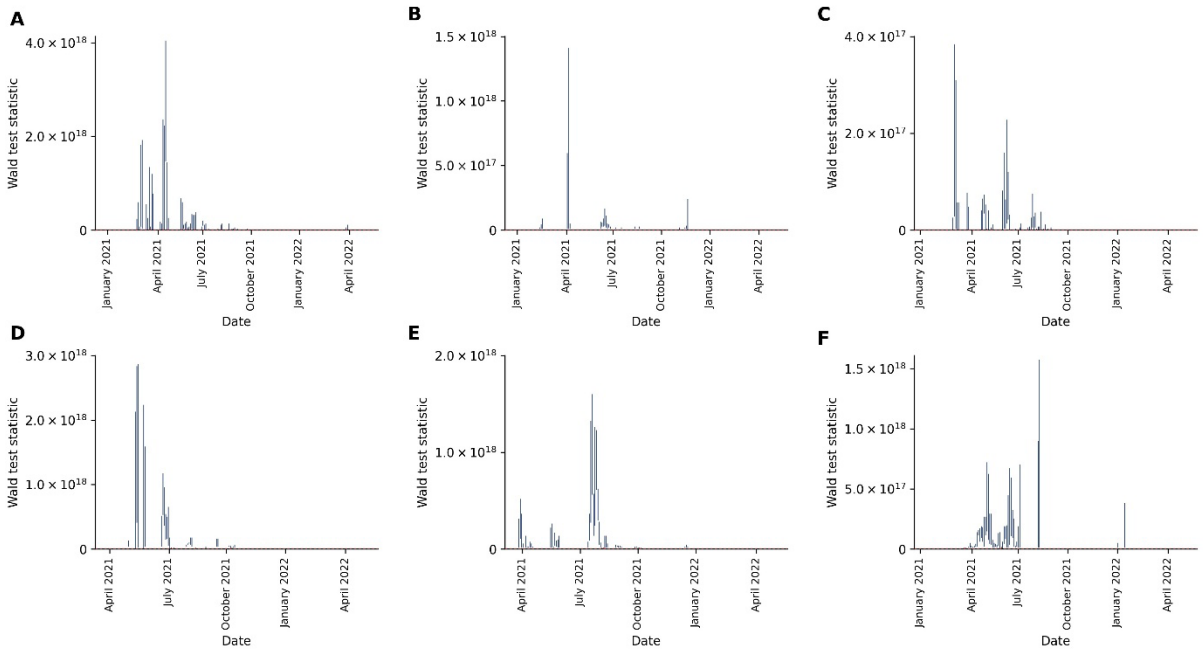


Figure 8. Time-varying Granger causality from full vaccination to COVID-19 deaths across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

Figure 9 shows a clear change in the Granger-causal relationship between full vaccination and the number of deaths. The two clusters disappear when stringency measures are considered. With the introduction of restrictions on human mobility, the Granger-causal relationship between vaccination and the number of deaths becomes statistically significant during the second quarter of 2021 at the earliest in all countries in the study sample. This can be interpreted as follows: when human mobility is taken into account, the predictive relationship vaccination and the number of deaths appears to be delayed by approximately one quarter, while when solely the impact of vaccination is investigated and the effects of human mobility are isolated, a significant Granger-causal relationship between vaccination and the new number of deaths emerges earlier. This point needs to be addressed further by considering actual mobility figures, as discussed in **Section 4.2.3**.

4.2.3. Case 2c: Granger causality from full vaccination to the number of deaths when actual mobility figures are considered

The last case investigates the Granger-causal relationship between full vaccination to the number of new deaths when actual mobility figures are considered. Figure 10 supports the anticipated outcome: the predictive relationship between vaccination and mortality becomes more evident when actual human mobility figures are taken into consideration. As shown in Figure 10, the Granger-causal relationship between vaccination and the number of deaths extends over a longer period, including when stringency measures are relaxed compared with those implemented during the initial phases of the pandemic. Nonetheless, this relationship appears to become more pronounced when stricter mobility restrictions are imposed. In this respect, the results suggest that the combination of vaccination and adequate stringency measures is associated with a more pronounced predictive relationship with mortality. As in the previous case, it is possible to identify some similarities

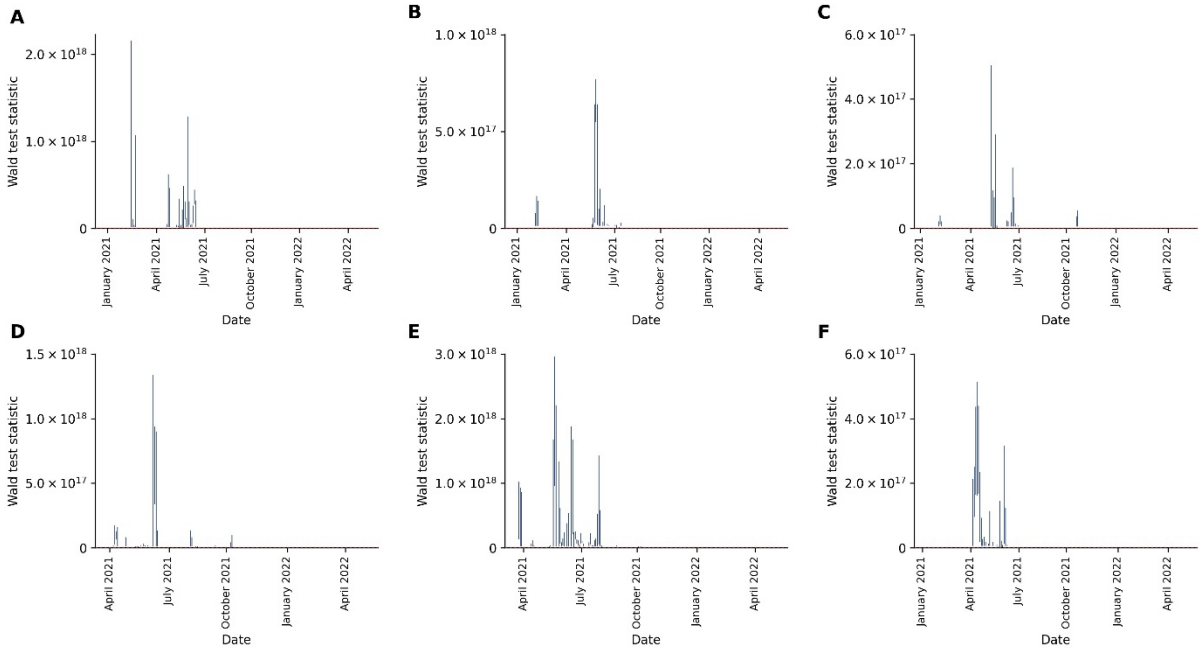


Figure 9. Time-varying Granger causality from full vaccination to COVID-19 deaths with stringency measures included across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

in the current scenario. Specifically, both South Korea and the UK exhibit multiple peaks, indicating more pronounced Granger-causal relationships between vaccination and the number of deaths. This observation may be linked to the similarities in the vaccination strategies if these these two countries. Notably, despite comparable average stringency measures, there are remarkable differences in actual mobility, as detailed in Table 2.

5. Discussion

This study is a pioneering example of investigating effective strategies for controlling the spread of COVID-19 and preventing COVID-19–related deaths using vaccination and restrictions on human mobility. Unlike other studies, this study adopted a dynamic time-series approach that can better capture the temporal behavior of daily data. In addition, rather than focusing solely on each country's official stringency index, we also used actual mobility data.

The adoption of TVGC allows the estimation of time-varying predictive relationships from one variable to another in the presence of overlapping periods, as observed during the pandemic. Specifically, recursive estimation allows these relationships to be examined as different waves of the disease unfold over time.

The findings demonstrate that when the impacts of the stringency measures are isolated, either in terms of the restrictions imposed or actual human mobility, vaccination shows a significant Granger-causal relationship with controlling the spread of the virus and reducing mortality associated with the pandemic. In addition, when the actual mobility figures are considered, the Granger-causal relationship between vaccination and COVID-19 cases and mortality becomes more pronounced. We note that vaccination strategies have been crucial, with countries showing patterns that clustered according to their vaccination policies rather than the stringency measures they imposed. This is a remarkable finding, given that although the stringency measures were impactful in controlling the spread and mortality of COVID-19, the results suggest that vaccination, particularly when rapidly

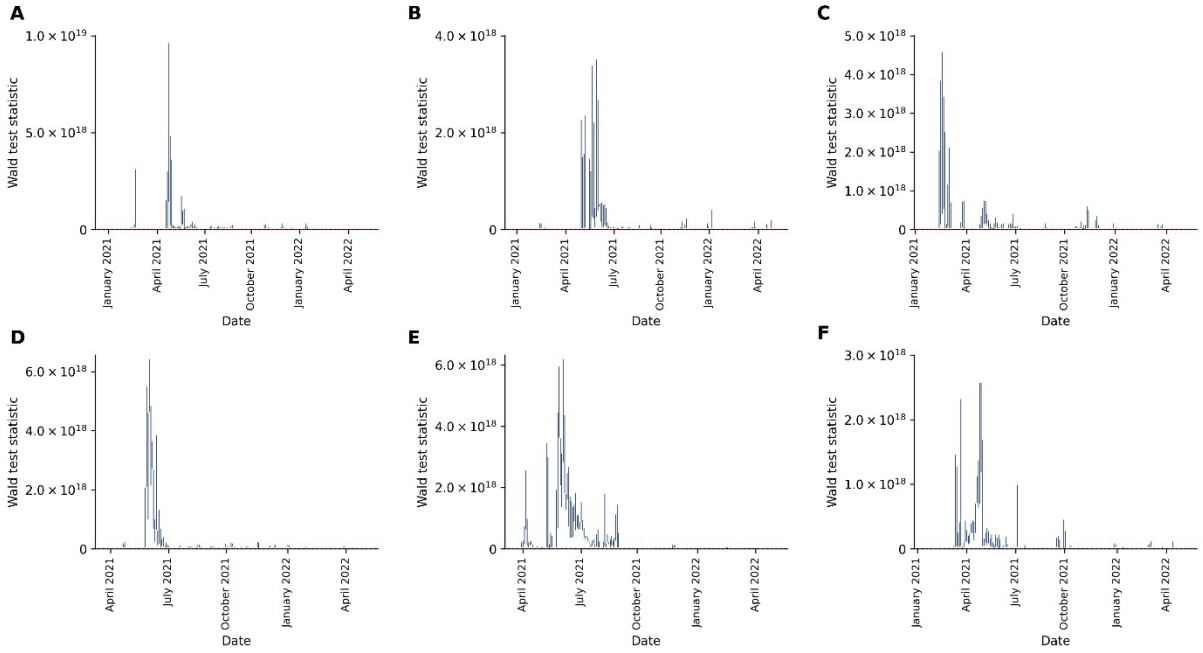


Figure 10. Time-varying Granger causality from full vaccination to COVID-19 deaths with actual mobility included across six countries: (A) France, (B) Germany, (C) Italy, (D) Japan, (E) South Korea, and (F) the United Kingdom. The red dotted line at zero represents the critical threshold for the Wald test statistic. The y-axis shows the Wald test statistic obtained from the vector autoregression specification with a 28-day lag. Higher values indicate stronger statistical evidence of a Granger-causal relationship from full vaccination to the emergence of new cases, rather than a greater magnitude of causality. The Wald test assesses whether past vaccination coverage provides statistically significant predictive information about subsequent new cases. When the Wald statistic exceeds the critical threshold, the null hypothesis of no Granger causality is rejected, indicating statistically significant predictive information from vaccination coverage over the preceding 28 days. When the Wald statistic falls below the threshold, the null hypothesis cannot be rejected, indicating insufficient evidence of a Granger-causal relationship between vaccination and subsequent new cases.

administered, was associated with more pronounced predictive relationships with pandemic outcomes.

Overall, Japan stands out as an example of the combination of a relatively less restrictive approach to mobility with an ambitious vaccination strategy. Comparable Granger-causal relationships between vaccination and the occurrence of new cases and COVID-19 mortality are also observed in other countries in the sample, especially those with higher levels of voluntary compliance with public health measures.

Beyond the methodological innovations proposed in this study, the findings support the broader principle articulated by Eco (2016), who argues that civil coexistence can impose limitations on individual freedom that may be difficult to accept or understand, even when such limitations are introduced in the interests of society as a whole. In fact, stringency measures were associated with reductions in pandemic outcomes, highlighting the importance of public compliance with public health measures.

6. Conclusion

Studies evaluating the effectiveness of COVID-19 policies usually treat public compliance and policy stringency as static factors. Yet compliance is dynamic, shaped by evolving risk perception, trust in institutions, and changing pandemic conditions. Therefore, to account for the dynamic nature of these relationships, a time-varying Granger causality model was applied to capture the evolving relationships between vaccination rates, stringency measures, population mobility, COVID-19 case numbers, and mortality in our sample of countries.

Our analysis indicates that the relationship between vaccination and reductions in cases and deaths was most pronounced when vaccination was accompanied by reduced mobility. Stringency measures alone were associated with temporary reductions in adverse pandemic outcomes but were less effective than widespread vaccination. Time-varying causality revealed that the relationships involving policy stringency and vaccination were not uniform over

time but varied across different phases of the pandemic. Our findings underscore the important role of changes in public compliance in shaping pandemic outcomes. Beyond policy stringency, trust, behavioral norms, and vaccine coverage may jointly influence health outcomes.

The dynamic nature of these relationships suggests that time-varying causal modeling can help policymakers identify when enforcement or communication strategies may require adjustment during health crises.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Alessandro De Matteis, Fethiye B. Turkmen Ceylan
Formal analysis: All authors
Investigation: All authors
Methodology: Fethiye B. Turkmen Ceylan
Writing–original draft: All authors
Writing–review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data used in this work were derived from the following databases: Google COVID-19 Community Mobility Reports, Johns Hopkins University COVID-19 Data Repository, and the Oxford COVID-19 Government Response Tracker. All of them are publicly available.

Further disclosure

A preliminary version of this paper was presented at the CALASS conference, organized by ALASS (Latin Association for the Analysis of Health Systems *[Asociación Latina para el Análisis de Sistemas de Salud]*), in Barcelona from September 1–3, 2022. All aspects of the work, including the study design, analysis, interpretation of results, and preparation of the manuscript, were carried out by the authors. Artificial intelligence (AI) tools were used solely to improve the readability, clarity, grammar, and language of the manuscript. AI tools were not used to generate scientific content, conduct analyses, interpret results, or draw scientific conclusions. The authors reviewed and verified all AI-assisted edits and take full responsibility for the accuracy, originality, and integrity of the final manuscript.

References

Allen, D. W. (2022). Covid-19 lockdown cost/benefits: A critical assessment of the literature. *International Journal of the Economics of Business*, *29*(1), 1–32.

https://doi.org/10.1080/13571516.2021.1976051

Ambikapathy, B., & Krishnamurthy, K. (2020). Mathematical modelling to assess the impact of lockdown on COVID-19 transmission in India: Model development and validation. *JMIR Public Health and Surveillance*, *6*(2), e19368.

https://doi.org/10.2196/19368

Barber, R. M., Sorensen, R. J. D., Pigott, D. M., Bisignano, C., Carter, A., Amlag, J. O., Collins, J. K., Abbafati, C., Adolph, C., Allorant, A., Aravkin, A. Y., Bang-Jensen, B. L., Castro, E., Chakrabarti, S., Cogen, R. M., Combs, E., Comfort, H., Cooperrider, K., Dai, X., *et al.* (2022). Estimating global, regional, and national daily and cumulative infections with SARS-CoV-2 through Nov 14, 2021: a statistical analysis. *The Lancet*, *399*(10344), 2351–2380.

https://doi.org/10.1016/s0140-6736(22)00484-6

Baum, C. F., Hurn, S., & Otero, J. (2022). Testing for time-varying Granger causality. *The Stata Journal: Promoting Communications on Statistics and Stata*, *22*(2), 355–378.

https://doi.org/10.1177/1536867x221106403

Bikbov, B., & Bikbov, A. (2021). Maximum incubation period for COVID-19 infection: do we need to rethink the 14-day quarantine policy? *Travel Medicine and Infectious Disease*, *40*, 101976.

https://doi.org/10.1016/j.tmaid.2021.101976

Booth, A., Reed, A. B., Ponzo, S., Yassaee, A., Aral, M., Plans, D., Labrique, A., & Mohan, D. (2021). Population risk factors for severe disease and mortality in COVID-19: A global systematic review and meta-analysis. *PLOS ONE*, *16*(3), e0247461.

https://doi.org/10.1371/journal.pone.0247461

Cekic, S., Grandjean, D., & Renaud, O. (2018). Time, frequency, and time-varying Granger-causality measures in neuroscience. *Statistics in Medicine*, *37*(11), 1910–1931.

https://doi.org/10.1002/sim.7621

Chan, H. Y., Cheung, K. K. C., & Erduran, S. (2023). Science communication in the media and human mobility during the COVID-19 pandemic: a time series and content analysis. *Public Health*, *218*, 106–113.

https://doi.org/10.1016/j.puhe.2023.03.001

Chung, Y. S., Lam, C. Y., Tan, P. H., Tsang, H. F., & Wong, S. C. C. (2024). Comprehensive review of COVID-19: epidemiology, pathogenesis, advancement in diagnostic and detection techniques, and post-pandemic treatment strategies. *International Journal of Molecular Sciences*, *25*(15), 8155.

https://doi.org/10.3390/ijms25158155

Dong, E., Ratcliff, J., Goyea, T. D., Katz, A., Lau, R., Ng, T. K., Garcia, B., Bolt, E., Prata, S., Zhang, D., Murray, R. C., Blake, M. R., Du, H., Ganjkhanloo, F., Ahmadi, F., Williams, J., Choudhury, S., & Gardner, L. M. (2022). The Johns Hopkins University Center for Systems Science and Engineering COVID-19 Dashboard: data collection process, challenges faced, and lessons learned. *The Lancet Infectious Diseases*, *22*(12), e370–e376.

https://doi.org/10.1016/s1473-3099(22)00434-0

Eco, U. (2016). *At Shrimp's Step: Hot Wars and Media Populism [A Passo Di Gambero. Guerre Calde E Populismo Mediatico]*. La nave di Teseo. [In Italian]. https://www.hoepli.it/libro/a-passo-di-gambero/9788893440189.html

Ferguson, N. M., Laydon, D., Nedjati-Gilani, G., Imai, N., Ainslie, A., Baguelin, M., Bhatia, S., Boonyasiri, A., Cucunubá, Z., Cuomo-Dannenburg, G., Dighe, A., Dorigatti, I., Fu, H., Gaythorpe, K., Green, W., Hamlet, A., Hinsley, W., Okell, L. C., van Elsland, S., *et al.* (2020). *Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID19 mortality and healthcare demand*. Imperial College London. doi:10.25561/77482

García-García, D., Vigo, M. I., Fonfría, E. S., Herrador, Z., Navarro, M., & Bordehore, C. (2021). Retrospective methodology to estimate daily infections from deaths (REMEDID) in COVID-19: The Spain case study. *Scientific Reports*, *11*(1).

https://doi.org/10.1038/s41598-021-90051-7

González-Leonardo, M., Rowe, F., & Fresolone-Caparrós, A. (2022). Rural revival? The rise in internal migration to rural areas during the COVID-19 pandemic. Who moved and Where?. *Journal of Rural Studies*, *96*, 332–342.

https://doi.org/10.1016/j.jrurstud.2022.11.006

Google. (2022). *COVID-19 Community Mobility Reports*. https://www.google.com/covid19/mobility/

Haider, N., Hasan, M. N., Guitian, J., Khan, R. A., McCoy, D., Ntoumi, F., Dar, O., Ansumana, R., Uddin, Md. J., Zumla, A., & Kock, R. A. (2023). The disproportionate case–fatality ratio of COVID-19 between countries with the highest vaccination rates and the rest of the world. *IJID Regions*, *6*, 159–166.

https://doi.org/10.1016/j.ijregi.2023.01.011

Hale, T., Angrist, N., Goldszmidt, R., Kira, B., Petherick, A., Phillips, T., Webster, S., Cameron-Blake, E., Hallas, L., Majumdar, S., & Tatlow, H. (2021). A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker). *Nature Human Behaviour*, *5*(4), 529–538.

https://doi.org/10.1038/s41562-021-01079-8

Hale, T., Angrist, N., Hale, A. J., Kira, B., Majumdar, S., Petherick, A., Phillips, T., Sridhar, D., Thompson, R. N., Webster, S., & Zhang, Y. (2021). Government responses and COVID-19 deaths: Global evidence across multiple pandemic waves. *PloS One*, *16*(7), e0253116.

https://doi.org/10.1371/journal.pone.0253116

Herby, J., Jonung, L., & Hanke, S. H. (2023). *A Systematic Literature Review and Meta-Analysis of the Effects of Lockdowns on COVID-19 Mortality II*. openRxiv.

https://doi.org/10.1101/2023.08.30.23294845

Hsiang, S., Allen, D., Annan-Phan, S., Bell, K., Bolliger, I., Chong, T., Druckenmiller, H., Huang, L. Y., Hultgren, A., Krasovich, E., Lau, P., Lee, J., Rolf, E., Tseng, J., & Wu, T. (2020). Publisher Correction: The effect of large-scale anti-contagion policies on the COVID-19 pandemic. *Nature*, *585*(7824), E7–E7.

https://doi.org/10.1038/s41586-020-2691-0

Islam, N., Sharp, S. J., Chowell, G., Shabnam, S., Kawachi, I., Lacey, B., Massaro, J. M., D'Agostino, R. B., Sr, & White, M. (2020). Physical distancing interventions and incidence of coronavirus disease 2019: natural experiment in 149 countries. *BMJ*, m2743.

https://doi.org/10.1136/bmj.m2743

Johns Hopkins University, *COVID-19 Data Repository*. Available at: https://github.com/sfu-db/covid19-datasets/blob/master/datasets-details/john_hopkins.md (15 June 2022, date last accessed)

Lavezzo, E., Franchin, E., Ciavarella, C., Cuomo-Dannenburg, G., Barzon, L., Del Vecchio, C., Rossi, L., Manganelli, R., Loregian, A., Navarin, N., Abate, D., Sciro, M., Merigliano, S., De Canale, E., Vanuzzo, M. C., Besutti, V., Saluzzo, F., Onelia, F., Pacenti, M., *et al.* (2021). Author Correction: Suppression of a SARS-CoV-2 outbreak in the Italian municipality of Vo'. *Nature*, *590*(7844), E11–E11.

https://doi.org/10.1038/s41586-020-2956-7

Ma, Q., Liu, J., Liu, Q., Kang, L., Liu, R., Jing, W., Wu, Y., & Liu, M. (2021). Global Percentage of Asymptomatic SARS-CoV-2 Infections Among the Tested Population and Individuals With Confirmed COVID-19 Diagnosis. *JAMA Network Open*, *4*(12), e2137257.

https://doi.org/10.1001/jamanetworkopen.2021.37257

McAloon, C., Collins, Á., Hunt, K., Barber, A., Byrne, A. W., Butler, F., Casey, M., Griffin, J., Lane, E., McEvoy, D., Wall, P., Green, M., O'Grady, L., & More, S. J. (2020). Incubation period of COVID-19: A rapid systematic review and meta-analysis of observational research. *BMJ Open*, *10*(8), e039652.

https://doi.org/10.1136/bmjopen-2020-039652

Murray, M. P. (1994). A Drunk and Her Dog: An Illustration of Cointegration and Error Correction. *The American Statistician*, *48*(1), 37–39.

https://doi.org/10.1080/00031305.1994.10476017

Necesito, I. V., Velasco, J. M. S., Jung, J., Bae, Y. H., Lee, J. H., Kim, S. J., & Kim, H. S. (2022). Understanding chaos in COVID-19 and its relationship to stringency index: Applications to large-scale and granular level prediction models. *PloS ONE*, *17*(6), e0268023.

https://doi.org/10.1371/journal.pone.0268023

Nouvellet, P., Bhatia, S., Cori, A., Ainslie, K. E. C., Baguelin, M., Bhatt, S., Boonyasiri, A., Brazeau, N. F., Cattarino, L., Cooper, L. V., Coupland, H., Cucunuba, Z. M., Cuomo-Dannenburg, G., Dighe, A., Djaafara, B. A., Dorigatti, I., Eales, O. D., van Elsland, S. L., Nascimento, F. F., *et al.* (2021). Reduction in mobility and COVID-19 transmission. *Nature Communications*, *12*(1).

https://doi.org/10.1038/s41467-021-21358-2

Okamoto, S. (2022). State of emergency and human mobility during the COVID-19 pandemic in Japan. *Journal of Transport & Health*, *26*, 101405.

https://doi.org/10.1016/j.jth.2022.101405

Oxford University, *COVID-19 Government Response Tracker*. Available at: https://github.com/OxCGRT/covid-policy-tracker (15 June 2022, date last accessed)

Öcal Özkaya, H. G., & Şak, N. (2022). The analysis of the factors affecting the stringency index during COVID-19 pandemic. *Journal of Applied Microeconometrics*, *2*(2), 67–79.

https://doi.org/10.53753/jame.2.2.03

Rosoł, M., Młyńczak, M., & Cybulski, G. (2022). Granger causality test with nonlinear neural-network-based methods: Python package and simulation study. *Computer Methods and Programs in Biomedicine*, *216*, 106669.

https://doi.org/10.1016/j.cmpb.2022.106669

Rowe, F., Calafiore, A., Arribas-Bel, D., Samardzhiev, K., & Fleischmann, M. (2023). Urban exodus? Understanding human mobility in Britain during the COVID-19 pandemic using Meta-Facebook data. *Population, Space and Place*, *29*(1).

https://doi.org/10.1002/psp.2637

Salian, V. S., Wright, J. A., Vedell, P. T., Nair, S., Li, C., Kandimalla, M., Tang, X., Carmona Porquera, E. M., Kalari, K. R., & Kandimalla, K. K. (2021). COVID-19 transmission, current treatment, and future therapeutic strategies. *Molecular Pharmaceutics*, *18*(3), 754–771.

https://doi.org/10.1021/acs.molpharmaceut.0c00608

Shi, S., Phillips, P. C., & Hurn, S. (2018). Change detection and the causal impact of the yield curve. *Journal of Time Series Analysis*, *39*(6), 966–987.

https://doi.org/10.1111/jtsa.12427

Sun, J., Kwek, K., Li, M., & Shen, H. (2021). Effects of social mobility and stringency measures on the COVID-19 outcomes: Evidence from the United States. *Frontiers in Public Health*, *9*.

https://doi.org/10.3389/fpubh.2021.779501

Tobías, A. (2020). Evaluation of the lockdowns for the SARS-CoV-2 epidemic in Italy and Spain after one month follow up. *Science of the Total Environment*, *725*, 138539.

https://doi.org/10.1016/j.scitotenv.2020.138539

Toda, H. Y., & Yamamoto, T. (1995). Statistical inference in vector autoregressions with possibly integrated processes. *Journal of Econometrics*, *66*(1–2), 225–250.

https://doi.org/10.1016/0304-4076(94)01616-8

Violato, C., Violato, E. M., & Violato, E. M. (2021). Impact of the stringency of lockdown measures on covid-19: A theoretical model of a pandemic. *PloS ONE*, *16*(10), e0258205.

https://doi.org/10.1371/journal.pone.0258205

Wang, W., Nie, Y., Li, W., Lin, T., Shang, M. S., Su, S., Tang, Y., Zhang, Y. C., & Sun, G. Q. (2024). Epidemic spreading on higher-order networks. *Physics Reports*, *1056*, 1–70.

https://doi.org/10.1016/j.physrep.2024.01.003

Washington, S., Karlaftis, M., Mannering, F., & Anastasopoulos, P. (2020). Bayesian Statistical Methods. In *Statistical and Econometric Methods for Transportation Data Analysis* (pp. 391–403). Chapman and Hall/CRC.

https://doi.org/10.1201/9780429244018-23

Yabe, T., Jones, N. K., Rao, P. S. C., Gonzalez, M. C., & Ukkusuri, S. V. (2022). Mobile phone location data for disasters: A review from natural hazards and epidemics. *Computers, Environment and Urban Systems*, *94,* 101777.

https://doi.org/10.1016/j.compenvurbsys.2022.101777

Zhou, F., Yu, T., Du, R., Fan, G., Liu, Y., Liu, Z., Xiang, J., Wang, Y., Song, B., Gu, X., Guan, L., Wei, Y., Li, H., Wu, X., Xu, J., Tu, S., Zhang, Y., Chen, H., & Cao, B. (2020). Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: A retrospective cohort study. *The Lancet*, *395*(10229), 1054–1062.

https://doi.org/10.1016/s0140-6736(20)30566-3

Zhou, Y. W., Xie, Y., Tang, L. S., Pu, D., Zhu, Y. J., Liu, J. Y., & Ma, X. L. (2021). Therapeutic targets and interventional strategies in COVID-19: mechanisms and clinical studies. *Signal Transduction and Targeted Therapy*, *6*(1).

https://doi.org/10.1038/s41392-021-00733-x