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What Impacts Do Human Mobility and Vaccination Have on Trends in COVID-19 Infections? Evidence from four developed countries[1]

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Abstract

This paper examines the dynamics of country-wide coronavirus disease 2019 (COVID-19) infections from an economic perspective using a relatively large and aggregated data set constructed based on publicly available data. Based on the “Residential” category of Google's COVID-19 Community Mobility Reports and the number of new positive polymerase chain reaction (PCR) tests per week per 100,000 population (logarithmic values) using state, provincial, or prefectural panel data from Canada, Germany, Italy, and Japan, we found that vaccinations strongly encouraged people to go outside in all countries except Japan, and that vaccinations reduced the number of new positive PCR tests in Japan and Italy. The results from Japan, where vaccination-induced outreach was relatively low, suggest that a 100% vaccine uptake rate would suppress the number of new positive PCR tests by 0.639-2.951%. We also analyzed the effects of vaccination on economic activities using mobility data as proxy variables. The results indicated that vaccination increases mobility, and that Canada, Germany, and Italy showed stronger effects on promoting outings than did Japan. These findings suggest that governments should continue to inform citizens that the effectiveness of vaccines are limited in terms of suppressing positive cases, implement appropriate risk controls and alerts to avoid forced lockdowns, and promote voluntary stay-at-home behavior to avoid an explosion of positive cases.

Keywords: COVID-19, Mobility, Vaccination, Economic activity
JEL classification: C23, I18, O47

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1. Introduction

The novel coronavirus disease 2019, COVID-19, was first detected in Wuhan, Hubei Province, China, in early 2020 and rapidly spread around the world, leading the World Health Organization to declare a global pandemic. In early 2022, a new mutation from South Africa, the Omicron variant, began spreading on a large scale.

Governments have been responding to the unprecedented COVID-19 pandemic with a combination of strong measures such as urban lockdowns and relatively loose measures such as requests to refrain from various activities in daily life. Infection control measures have many variations, but why do they differ from one country to the next? Of course, there are underlying differences in political systems and cultural contexts, but it is thought that such variations arise from *the struggle between infection control and economic reopening*, as symbolized by the hammer and the dance. The differences among countries in terms of infection control, including vaccination, seem to be significant. In the midst of these responses, the infection situation has fluctuated substantially in a relatively short period of time, accompanied by the emergence of newly mutated virus strains that start new cycles of infection.

In this paper, we focus on factors other than those intrinsic to the virus itself, which should be comprehensively explored by virology, and examine the dynamics of infection in each country from an economic perspective using a relatively large and aggregated data set constructed based on publicly available data.[1] As discussed in detail later, one of the features of this paper is the

[1] In particular, the nature of the Delta variant, which caused serious infections in mid- to late-2021, remains largely unexplored. Specifically, in Japan, the Delta variant expanded rapidly and then declined dramatically, at least superficially, without much linkage to government or public responses. It is difficult to fully explain this phenomenon by the influence of government policies. It has been hypothesized that errors occur in the copying process of the virus and then the virus self-destructs, but many aspects remain unclear. The relationship between the nature of the virus itself and the infection situation needs to be clarified scientifically.

appropriate adaptation of information at the state, province, and prefecture levels in each country used in the analysis to the extent possible, although the data are aggregated. While the analysis naturally explores the determinants of infection status, in this case the number of positive polymerase chain reaction (PCR) tests, it also takes into account the basic nature of infectious disease, which is simply the fact that the virus itself is immobile. In other words, the mobility of people, which is often discussed, is still an important factor to be considered here. Therefore, in addition to the infection situation, this paper attempts to take a multifaceted approach by focusing on this point as well.

Looking back, in the early stages of the pandemic, especially in 2020, mobility control was almost the only intervention for infection control. Hence, lockdowns were implemented in China, Europe, and other countries, and schools were closed altogether. Some countries took a relatively moderate intervention policy, monitoring infection and economic statuses. In Japan, for example, no lockdown was implemented, but instead the government declared a state of emergency and asked people to refrain from business and social activities voluntarily to confront the repeated waves of infection.[2] A change in this mobility control policy occurred in 2021 as a result of the remarkably rapid development of vaccines and the progress of vaccination in many countries. While the effectiveness of the vaccine in controlling infection and preventing sever disease has been confirmed in clinical trials, its effectiveness against new variants is unclear. Although the efficacy of the vaccines is expected to be clarified gradually, this paper assumes a certain level of efficacy and quantitatively examines the associated effects based on the actual infection situation in the medical field to date. Namely, in addition to the issue of mobility mentioned earlier, we consider the positive effect of the progress of vaccination as a second factor affecting the infection situation.

[2]It should be noted that Japan's emergency declarations were substantially different from those in Europe and the United States. For an overview, see Hosono (2021) and Masuhara and Hosoya (2021).

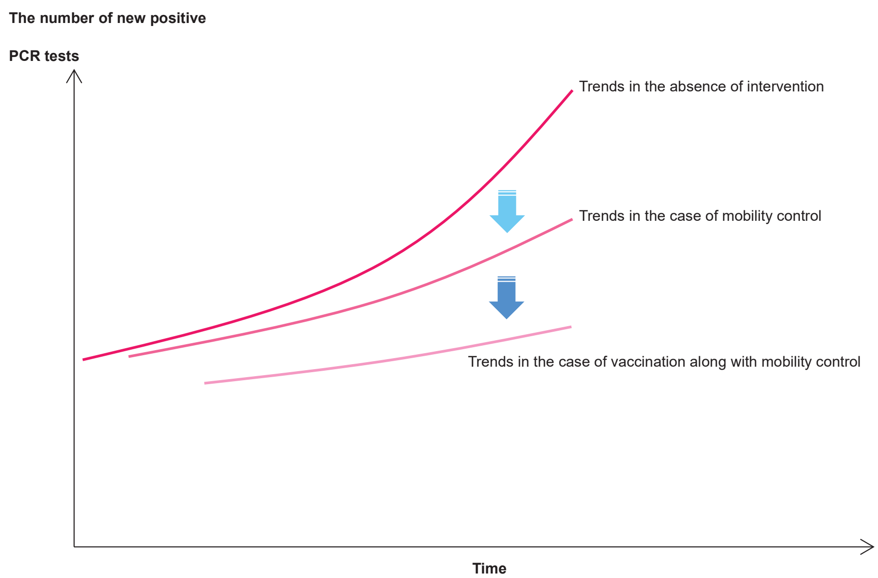

Figure 1: Infection trends in different situations

Let us now consider the above issues in an organized manner. Figure 1 shows infection trends in different situations. We pay special attention to the relative position of the curves, given their importance. We assume a given period of time when the COVID-19 infection was spreading. The top curve is a hypothetical representation of the infection trend in a situation where there are no government interventions, and therefore no individual restraint in behavior. As already observed in practice, in the absence of any interventions, new infections show an exponential upward trend. This corresponds to the very early stage of the actual pandemic. Next, we consider the situation in which there is neither a vaccine nor an effective therapeutic, and the government imposes various types of restrictions on individual behavior with varying degrees of intensity, and people refrain from certain activities in accordance with these restrictions. These efforts can be expected to slow down the increase in the number of infections by interrupting the chain of infection. This situation is depicted by the middle curve in Figure 1, which shows a downward shift from the case of nonintervention, and roughly corresponds to the situation in mid-2020. Next, we add the progress of vaccinations to this situation. For simplicity, it is assumed that the behavioral restrictions described above remain unchanged. Then, the downward pressure to increase the number of new infections is simply the sum of the vaccinations and the mobility-reducing effects of the behavioral restrictions. This pushes the middle curve further downward, and the relative position is assumed to be as shown in the bottom curve of Figure 1.[3] This corresponds to the situation in 2021, especially from the middle of the year. At any given point in time, when the three curves are viewed in a cross-sectional manner from top to bottom, the vertical differences can be read as the infection control effects of mobility control and vaccination, respectively.

Basically, the actual trend of infection (the number of new positive cases) is defined by the interaction of the complex factors described above. Still considering Figure 1, the following is also possible: it is not necessarily the case that the situation shown in the bottom curve holds for a while after vaccination has progressed to a considerable extent. When the vaccination rate increases, the government usually relaxes restrictive measures to a certain extent (this moves in the direction of increasing mobility), and above all, people themselves feel relieved after they have been vaccinated, which reduces their fear of acquiring an unknown infectious disease and leads them to go out more actively. In this case, the infection suppression effect of mobility control, which should have already been obtained, shrinks, pushing the new infection curve upward. Typically, this would be somewhere between the middle and bottom curves. In reality, mobility control is not the only way for governments to control the spread of infectious disease, so the intensity of overall infectious disease control, as expressed by the stringency index described below, is also relevant.

The remainder of this paper is organized as follows. Section 2 presents a

[3]As the vaccination rate increases, the population is expected to come closer to acquiring herd immunity and become less susceptible to infection; however, such practical effects are not discussed here.

review of existing studies that are relevant to this paper. All contributions were made during the period from 2020 to 2022. In Section 3, we first examine the broad macroeconomic conditions before and after the pandemic for the four countries included in our empirical study, and then observe the trends in the infection situation and other data relevant to the analysis. Section 4 describes the details of the data used in the empirical study, including descriptive statistics. The main part of this paper is Section 5, where the estimation results of the econometric studies are presented and evaluated. In Section 6, we examine the effect of vaccination using mobility data, which can be a proxy variable for economic activity. Section 7 summarizes the policy implications from the viewpoint of vaccination. Besides, we wish to present our views on infectious disease and economic activity taking the situation in each country to date into account. Finally, Section 8 concludes.

2. Related literature

Although the factors included in the present paper are familiar with those in studies conducted after 2020, those investigations were conducted under circumstances in which vaccination had progressed considerably, and therefore, contain many important findings. Nevertheless, it is important to review the previous studies related to this paper because they were conducted under different analytical perspectives.

First, some studies examine the diverse effects of the pandemic in detail and present suggestive insights into the post-pandemic world. The study by Alvarez et al. (2021), which has already become the basic reference in COVID-19 research, integrates the Susceptible–Infectious–Recovered (SIR) epidemiological and economic model and theoretically investigates the optimal lockdown policy assuming a social planner. The intensity of the lockdown depends on the COVID-19 fatality rate and the assumed value of statistical life (VSL).[4] Eichenbaum et al. (2021), another prominent theoretical study similar to Alvarez et al.

[4]VSL also plays an important role in Hall et al. (2020), who analyzed the issue of trade in

(2021), highlighted the difficulties of a trade-off between containing infectious disease and maintaining economic activity. Regarding these trade-offs, studies involving nonbehavioral SIR macroeconomic models, such as Fujii and Nakata (2021) and Fukao and Shioji (2022), have also presented interesting results. Fujii and Nakata (2021) examined possible guidelines for infectious disease control measures that the Japanese government could take, and found a clear trade-off between infectious disease control measures involving mobility control and economic activities. Another important finding is that the marginal effect of this control depends on the scale of economic loss. Fukao and Shioji (2022) drew on the former debate over the Phillips curve and focused on the trade-off between infection and production. Fukao and Shioji (2022) developed a reaction function that takes the level of economic activity as a function of the state of infection, and evaluated the situations in Tokyo, New York, and London.

Tisdell (2020) critically examined the validity of lockdown policies and presented interesting findings. Gordon et al. (2021) empirically examined the significance of border closures, focusing on Organisation for Economic Co-operation and Development (OECD) countries in Europe, especially the Nordic countries. Padhan and Prabheesh (2021) argued that not only domestic, but also international coordination is essential to overcome the negative economic impacts of a pandemic.[5] In terms of post-pandemic economic conditions, expectations for a recovery in consumption are high above all else. Hodbod et al. (2021) conducted a survey to examine future trends in household consumption, noting that the long and painful experience of the COVID-19 pandemic may have lasting effects on consumer preferences. In their study, they found that in the Nordic countries, a change in preferences was mainly observed in higher income

regard to avoiding death from infectious disease and sacrificing consumption.

[5]Rungcharoenkitkul (2021) and Taylor (2021) also conducted a comprehensive investigation with important implications. Rungcharoenkitkul (2021) provided an interim assessment of the macroeconomic impact of the pandemic for the period up to 2020 and presented findings for future planning. Taylor (2021) discussed the economic relationship between private and government sectors during a pandemic.

groups, whereas consumer confidence in the future was greatly shaken in the Southern European countries. These facts suggest that, despite expectations of a V-shaped recovery in consumption, major changes in household consumption behavior can be predicted.

Similar to the present study, a number of reports have focused on human mobility. In particular, in the period up to 2020, controlling mobility in the broad sense was about the only interventional policy measure. Mendolia et al. (2021) provided a detailed and comprehensive analysis of mobility around the world in the early stages of the pandemic. In their analysis, they distinguished between the voluntary suppression of mobility through information dissemination and mandatory suppression by government edict. The primary result was that mobility responded significantly to information about the spread of the pandemic. Velias et al. (2022) focused on the case of changes in curfew times in Greece and examined its impact on mobility using a difference-in-differences approach. They speculated that many people may have come to grocery stores and pharmacies during the shortened hours of operation in an overlapping manner, which may have increased the risk of infection. Lockdowns may be necessary at times from the viewpoint of infection control, but they should be implemented effectively with careful consideration of human behavioral characteristics. Carroll and Prentice (2021) and Habib et al. (2021) examined the impact of mobility factors on the spread of infectious disease in the United States and in 10 countries (United States, Brazil, Mexico, United Kingdom, Spain, Italy, France, Germany, Canada, and Belgium), respectively, and raised the importance of ensuring social distancing. Masuhara and Hosoya (2021) pointed out the importance of mobility control in Japan, where infection trends has remained relatively stable.[6] Kephart et al. (2021) conducted an empirical study of 314 cities in Latin America. They also confirmed that the incidence of COVID-19 decreases with low mobility, and that result was even more important than the results in de-

[6] Jung et al. (2021), also relying on Japanese data, utilized mobility data to calculate the effective reproduction number in real time, and confirmed that it performs well.

veloped countries because the importance of nonmedical interventions is much greater in countries including the cities analyzed, where access to vaccines is more limited.[7]

While vaccination is an ongoing medical intervention against infection in both developed and developing countries, a number of studies have already been published. Andersson et al. (2021) carried out a valuable experimental study on the possible adverse effects of COVID-19 vaccines through changing individual behaviors. They pointed out that heightened expectations of vaccine efficacy may lead to lower adherence to public health guidelines for infection control, which may in turn, cause the greater spread of COVID-19. In other words, it can be interpreted as a reduction in the effectiveness of social distancing policies. Chu and Liu (2021) examined how COVID-19 vaccine availability and intention to get vaccinated influence public attitudes toward the vaccine through a survey-based conjoint analysis. Differences among people in attributes such as availability were found to produce significant differences in their concerns about the vaccine. For example, those with low availability and low willingness to be vaccinated tended to be more concerned about safety and more skeptical about the efficacy of the vaccine. Because inequalities exist in the distribution of the COVID-19 vaccine, public health authorities and others in charge of distribution need to issue appropriate messages according to differences in population demographics to promote vaccination effectively. This is an interesting finding that can be applied immediately. Janiak et al. (2021) developed an extended SIR model that generalizes the heterogeneity of firms and industrial sectors to analyze numerically the relationship between infection trends and economic activities. Their analysis was set in Chile and incorporated the vaccination of the entire population. It was found that a strict application of infection control

[7] Some studies have also been conducted on mobility in COVID-19 in the field of spatial statistics. Slater et al. (2021), for example, found that the actual number of trips between regions explains the variation in COVID-19 positive cases better than the physical proximity between regional spaces.

protocols to a small number of sectors is preferable to a broad and shallow application to many sectors, in terms of both infection control and the economy. Morikawa (2021) examined the relationship between COVID-19 vaccination and consumption behavior based on an independent survey conducted in Japan in 2021. Although many people were willing to increase their consumption after the end of the pandemic, fewer people were willing to do so after vaccination. While these results may vary by country, it is interesting to suggest that progress in vaccination may not necessarily be the key factor for economic reopening.

A recent study in Japan by Inoue and Okimoto (2022) comprehensively evaluated the relationship between human mobility, vaccination, and the number of infected people. The results indicated that measures to control the mobility of people visiting retail and entertainment establishments and the state of emergency declaration had the effect of pushing down the rate of change in the number of new infections, and that vaccination suppressed the increase in the number of new infections despite an increase in mobility.

One of the features of this paper is its analysis at the state, province, and prefecture levels. We would like to consider a stringency index at such levels, as well as vaccine and mobility data, but the index is only available at the national level, excluding Canada, and therefore, as described at the beginning of Section 5, it is not used in the actual regression analysis. However, the stringency index is very useful for gaining a comprehensive understanding of response measures against COVID-19, and has been used in national-level analyses in some previous studies, such as Dzator et al. (2021), Giofré (2021), Gordon et al. (2021), Lee et al. (2021), Nanda et al. (2021), and Yang et al. (2021). Among these, Gordon et al. (2021), mentioned at the beginning of this section, examined the impact of stringency in detail, especially from the perspective of economics. They paid particular attention to Sweden, which took a unique approach to the pandemic among the Western countries by aiming for herd immunity. They pointed out that Sweden's public health performance in regard to COVID-19 was quite different from its Nordic neighbors, concluding that Sweden could have reduced the number of cases and deaths if it had closed its borders as its neighbors had in the first half of 2020. Moreover, they reported a statistically significant negative correlation between COVID-19 deaths and economic performance in terms of GDP growth for all OECD countries in Europe.

In Section 7, derived from the empirical results, we summarize the policy implications both directly and indirectly while citing some of the existing studies mentioned above.

3. An overview of the situation in each country under the pandemic: Canada, Germany, Italy, and Japan

As explained in Section 1, this paper examines how vaccination, which is considered to be the key factor in the recent measures against COVID-19, is related to economic recovery after the pandemic, and to what extent it has been effective. One of the factors that accelerate the spread of infectious disease, given its nature, is mobility, which has been the focus of previous studies, such as Carroll and Prentice (2021) and others. The present paper attempts to clarify comprehensively the relationship between the combined effects of vaccination and mobility, the number of positive PCR test cases, and economic activity. A typical scenario is that vaccination decreases the speed of the increase in the number of positive PCR tests, which in turn, stimulates mobility and economic reopening. The present paper aims to reveal the details of these relationships empirically.

While the present paper uses aggregate data, it constructs a fairly large-scale data set. In view of the availability of part of the data, we select a total of four countries for our analysis: Canada, Germany, Italy, and Japan. We review the economic status of these countries before and after the COVID-19 pandemic, and then examine the daily infection situation and other related data.

First, we look at the status of consumption and production activities at the macro level. The data are obtained from OECD.Stat (`https://stats.oecd.org/`) and presented on a quarterly basis. The period is from Q1 2019 to Q3 2021. For consumption, we use P31DC, a private final domestic consumption

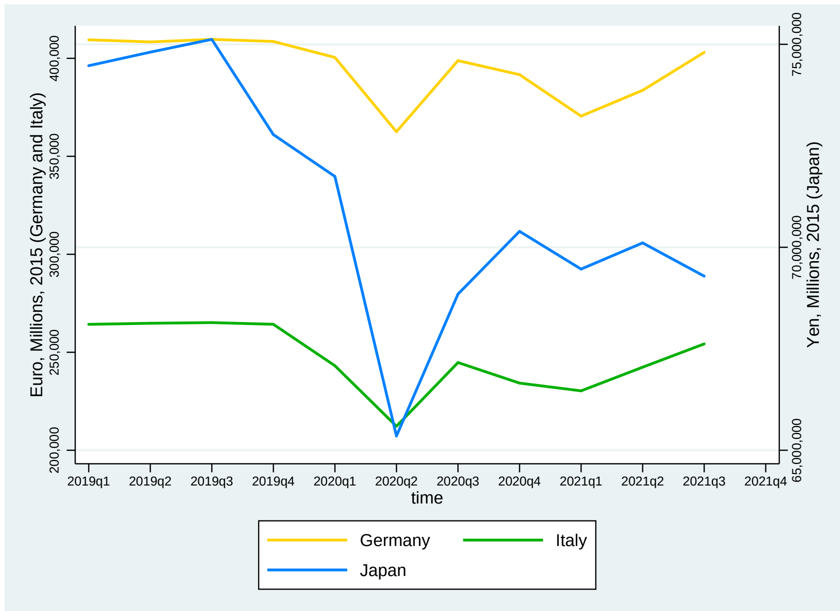

Figure 2: Trends in household final consumption expenditure–Germany, Italy, and Japan

expenditure.[8] Taking Japan as a reference country, we check the differences in consumption *trends* among countries.

Figure 2 shows the status in Japan and the Eurozone countries of Germany and Italy (a direct comparison can be made for Germany and Italy). As there are differences in the measurement units, we focus on the transition patterns rather than the numbers themselves (the left and right axes are in Euro and Yen terms, respectively). Since before and after 2020, the novel coronavirus spread quickly around the world, starting in Wuhan City, Hubei Province, China, and the damage to the economy began to be pronounced in Q1 2020. This was followed by the enacting of a variety of infection prevention measures in each country, as exemplified by urban lockdowns. As a direct result, each country

[8]The measure is LNBQRSA: national currency, chained volume estimates, national reference year, quarterly levels, seasonally adjusted. The measurement units are in national currencies.

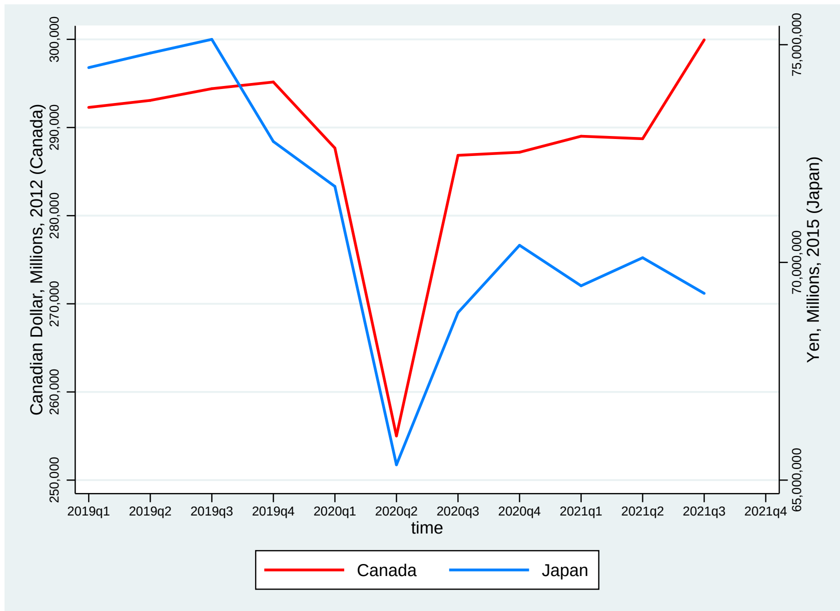

Figure 3: Trends in household final consumption expenditure–Canada and Japan

experienced a serious recession in Q2 2020, including consumption. In Figure 2, broad trends in household consumption expenditure can be observed. While both Germany and Italy were recovering to pre-pandemic levels by 2021, the status in Japan remained severe and recovery appeared to have little resilience. We must keep a close watch on future trends, but the status in Japan may be reminiscent of the "Italianization" observed after the global financial crisis, as it seems difficult to recover to the previous level even after a certain period of time.[9]

Figure 3 shows a comparison between Japan and Canada. Similar to in Germany and Italy, in Canada, a recovery close to the pre-pandemic level in Q3 2020 can be seen. As pointed out earlier, the household consumption trends in Japan show an unusual pattern compared with other developed countries. It can be seen that the negative impact of the pandemic has been particularly pro-

[9]As of 2020, Italy had not yet recovered to its 2008 GDP level.

nounced in the Japanese economy, but another aspect, the infection situation, should not be forgotten. As explained in more detail later, it is well known that the infection situation in Japan has been relatively calm, even from a global perspective (see Masuhara and Hosoya, 2022). By looking at the economic status and infection situation in tandem, it should be possible to make a comprehensive assessment of the impact of the pandemic. One way of looking at Japan might be to say that it is paying the cost of a relatively prolonged economic decline to contain the outbreak. However, a proper assessment requires the consideration of other important issues facing Japan (e.g., the declining birthrate and aging population), as well as factors such as risk attitudes and social norms specific to the people living in Japan. There seems to be considerable variation among countries in regard to how people behave and to what extent they comply with government requests when faced with risk.

Next, let us review the trends in production in the targeted countries. While there are extremely important economic policy issues regarding whether the present pandemic is a supply shock or a demand shock, it is obvious that, at least as an *outcome*, parts of both supply and demand have been severely affected.[10] When workers are restricted from engaging in production activities because of lockdowns or requests for self-restraint, and factory operations are suspended, this can be viewed as a supply shock. On the other hand, when people (workers) face great risk, such as *fear* of infection, and restrain their consumption expenditure on service goods, this corresponds to a demand shock.

In addition to consumption, we examine the period from Q1 2019 to Q3 2021. From Production and Sales (Main Economic Indicators), we focus on the "Production of total industry sa (seasonally adjusted) Index.[11]" This index is measured with 2015 as 100. Unlike consumption expenditure, it is appropriate to show the four countries together (see Figure 4). First, regarding the production

[10] For a discussion of the nature of shocks, see, for instance, Baldwin (2020), Guerrieri et al. (2020), and Kubota (2021).

[11] https://stats.oecd.org/

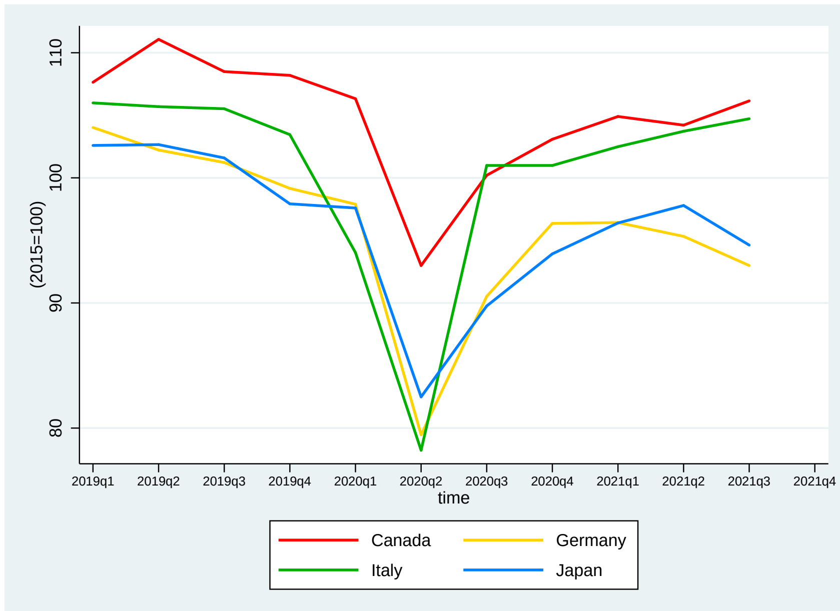

Figure 4: Trends in production from the total industry index–Four countries

index, it bottomed out in Q2 2020 and started to recover in Q3 2020, which is a common feature among the four countries. Japan, Germany, and Italy experienced particularly large declines. While Japan's unusual status stands out in terms of consumption, the time series trends in production are relatively similar. Among them, it is curious that the patterns in Japan and Germany are quite similar. This may be related to the similarity of their industrial structures in which the manufacturing industry, including automobiles, holds a competitive edge. On the other hand, it is interesting that Italy has shown surprisingly strong resilience in terms of production, even though it is still fresh in our minds that Italy's serious infection situation and drastic medical conditions were being reported daily in 2020.

The findings in Figure 4 indicate that the recovery from the decline in production was relatively rapid. As for the supply side, most of the industries directly affected by the COVID-19 pandemic were *services*, and thus, the impact on the non-services industries was relatively light, which is consistent with

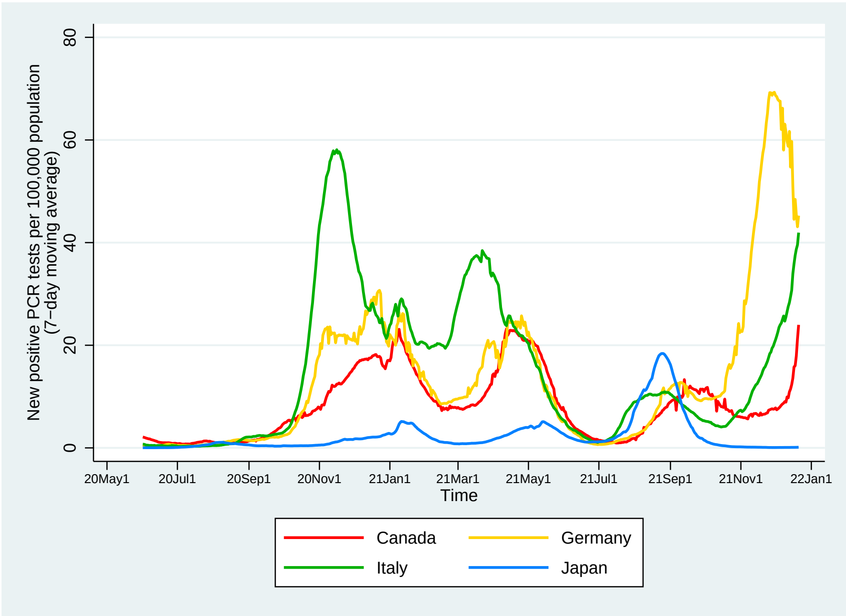

Figure 5: Trends in the number of new positive PCR tests per 100,000 population

the trends in the production index of each country. In relation to the nature of economic shocks mentioned above, the effects of this pandemic have been substantial, but more pronounced in terms of both supply and demand in specific industries than in the macroeconomy as a whole.

Following our review of the macroeconomic data, and let us now focus on the infection situation and related data in the four countries. Figure 5 shows the trends in the number of new positive PCR tests per 100,000 population (daily average increases in the numbers of new positive tests per week) in Canada, Germany, Italy, and Japan from June 1, 2020 to December 21, 2021. The data are described in detail in Section 3. We used the COVID-19 Data Repository compiled by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University to obtain the number of positive PCR tests, Google's COVID-19 Community Mobility Report (2020 and 2021) for residential data, Our World in Data[12] for vaccination status, and the stringency index from the Oxford COVID-19 Government Response Tracker (OxCGRT), which is a composite measure that takes values from 0 to 100 (100=strictest). For Figures 5, 7, and 8, we use the cross-country panel data published by Our World in Data.

The number of new positive PCR tests per 100,000 population among the four countries exhibited common and different features, as shown in Figure 5. The common feature is that the number of new positive cases in each country fluctuated over time. All countries experienced a sharp increase in the number of new infections, followed by a decrease as a result of the success of some infection control measures and policies such as lockdowns, but then another sharp increase. The different feature is that the number of infections in each wave varied by country: in 2020, Canada and Japan were successful in controlling the number of infections, but by May 2021, Canada had about the same number of new infections as Germany and Italy. Even Japan, which had successfully controlled the number of new infections until July 2021, temporarily experienced the most severe outbreak among the four countries in August and September 2021.

The backgrounds to the rapid spread of COVID-19 are thought to be related to the mobility of individuals, the strictness of government regulations, and vaccination status. Let us now examine trends in the data related to these factors. Figure 6 plots the change in residential status obtained from Google's COVID-19 Community Mobility Report. As this index indicates time spent at home, the negative direction means that people left their homes. From Figure 6, we find that there is a difference in residential status among countries, and that Germany and Italy had a more active period for going outside, from June 2020 to December 2021, than did Japan and Canada. Figure 7 shows trends in the stringency index (until December 17, 2021), revealing that overall, government regulations in Japan were less stringent than those in the other three countries. Figure 8 shows vaccination status, representing the percentage of the population

[12] `https://github.com/owid/covid-19-data/tree/master/public/data`

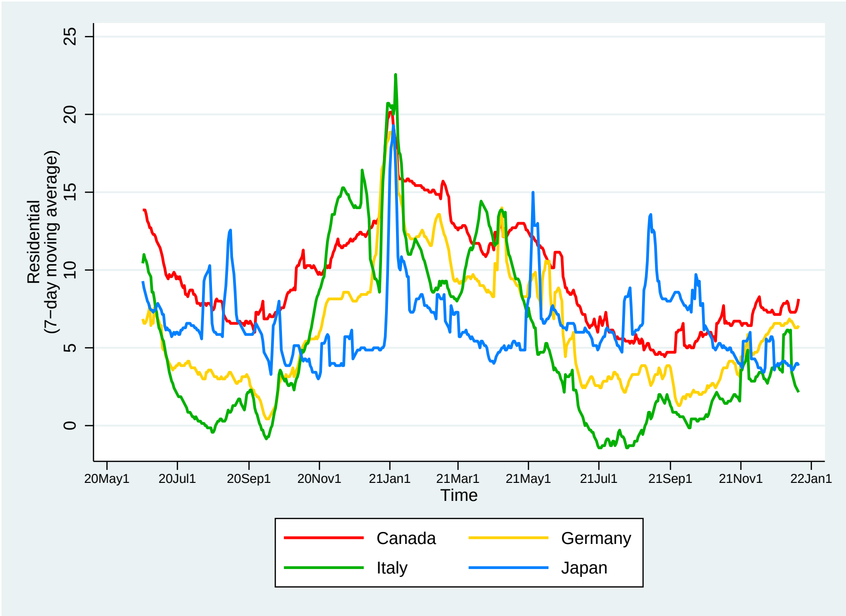

Figure 6: “Residential” mobility

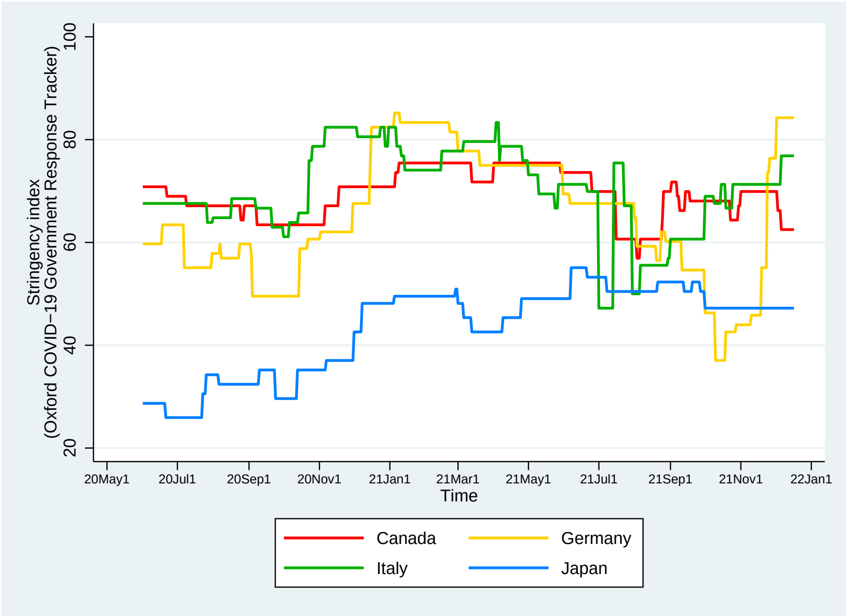

Figure 7: Stringency index

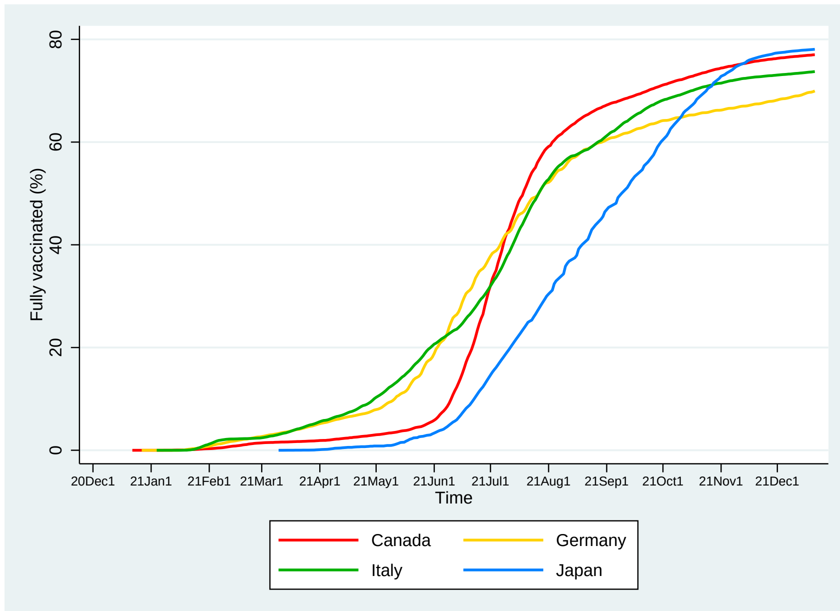

Figure 8: Percentage of population fully vaccinated (two doses)

that has received the second dose of vaccine, not including the so-called booster (i.e., third dose). Among the four countries, Germany was the first to start vaccination, but their vaccination rate was the lowest as of December 2021. The residential and stringency indices are naturally affected by vaccination status and the number of new positive PCR tests. The data series from Figures 5 to 8, overlaid by country, are shown in the Appendix. From these country-specific observations, we can confirm that the number of new positive PCR tests is linked to the stringency index, and that the index is also linked to residential status. Furthermore, as the vaccination rate increases, the degree of linkage becomes less pronounced, indicating that people become less likely to refrain from activities.

4. Description of data

This section explains the details of the data. We construct daily panel data at the state, province, or prefecture levels for Canada, Germany, Italy, and Japan. We chose these four countries because the variables listed below are available on a daily basis, and their vaccination status is similar. For the number of COVID-19-positive PCR tests, we calculated the average daily increase in the number of new positive PCR tests per week per 100,000 population according to those "confirmed" by the CSSE at Johns Hopkins University.

The following population data were used for standardization. For Canada, we use "How to cite: Statistics Canada. Table 17-10-0009-01 Population estimates, quarterly." For Germany, population estimates by province as of December 31, 2020 were made using Bevolkerungsstand Lander, Retrieved 2 July 2021.[13] For Italy, population by province as of January 2021 was obtained from Population Italian Regions, and for Japan, population by prefecture as of January 1, 2021 was obtained from the 2021 Basic Resident Register by age group (by city, ward, and town).[14]

Vaccination status was collected as follows. For Canada, we used state-level daily panel data on COVID-19 cases, deaths, recoveries, examinations, and vaccinations, collected daily by the COVID-19 Canada Open Data Working Group (Berry et al., 2021),[15] who constructed a database from publicly available information such as government reports and releases, news media, etc. For vaccines, values from official state government websites, press releases, and press conferences were used.[16] For Germany, we used the daily panel data published by Mathias Bynens as COVID-19 vaccination doses administered per state.[17] In Italy, we used the vaccine data published by the "Commissario straordinario

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[13] https://doi.org/10.25318/1710000901-eng

[14] https://cio.go.jp/c19vaccine_dashboard

[15] https://github.com/ccodwg/Covid19Canada

[16] https://docs.google.com/spreadsheets/d/1zebsxvOPw8gJ-38r9Wbs_tYOSk5lvfr0khun9_p3gmY/htmlview

[17] https://github.com/mathiasbynens/covid-19-vaccinations-germany

per l'emergenza Covid-19—Presidenza del Consiglio dei Ministri.[18]" These daily panel data are provided by state, which enables us to grasp the vaccination situation fully. For Japan, we used the "Vaccination Count Details by Prefecture (NDJSON, line-separated JSON format)" from the "Vaccination Status of the New Coronary Vaccine (including the elderly)" published by the Government of Japan CIO Portal (`https://cio.go.jp/c19vaccine_dashboard`). We adopted these data because they can be constructed as prefectural panel data, but caution is needed. In Japan, prior vaccination was conducted for medical personnel (doctors, pharmacists, nurses, other professionals, and hospital staff), and for these personnel, no prefectural data have been published. As of January 2022, booster vaccinations are underway in many countries, but the present report uses the vaccination status for the first two doses (or one dose if sufficient).

For mobility, we used Google's COVID-19 Community Mobility Report data (2020 and 2021) for Canada, Germany, Italy, and Japan, which we refer to as the "Google activity" indicator in this paper, following Fernández-Villaverde and Jones (2020). The Google activity indicator is a daily panel data set that shows changes in visitors (or time spent in a location) to "retail and recreation," "grocery and pharmacy," "parks," "transit stations," "workplaces," and "residential" (hereinafter referred to as Retail & Recreation, Grocery & Pharmacy, Parks, Transit Stations, Workplaces, and Residential, respectively) relative to a day-of-week baseline. However, three points need to be added when using these data. First, there is the issue of the reference value: in publishing the data, Google uses the day-of-week reference value as the median value for each day of the week for the 5 weeks from January 3 to February 6, 2020. Therefore, seven reference values are used for each day of the week, and comparisons between days of the week, such as between weekends and weekdays, are meaningless. Second, national holidays other than Saturdays and Sundays may become outliers. In Japan, there are 16 national holidays designated by the government other than Saturdays and Sundays in 2020 and 2021. In Figure 6, the smooth-

[18]`https://github.com/italia/covid19-opendata-vaccini`

Table 1: Variable definitions

Variable	Definition
DailyNewPositives	Average daily increase in the number of new positive PCR tests per week per 100,000 population from the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University
log(DailyNewPositives)	(logarithmic value)
FullyVaccinated	The rate of people fully vaccinated against COVID-19 (%)
Residential	Activity of "Residential" from Google's COVID-19 Community Mobility Report
Canada	Dummy for Canada
Germany	Dummy for Germany
Italy	Dummy for Italy

ing of residential time spent in Japan is weaker than that in the other three countries. This is because it captures outliers caused by national holidays, especially in regard to Mondays, which are used as substitute holidays. Third, there are large variances in some categories. As pointed out by Google, people spend a large part of the day in Residential, for which the change is small. In Sections 4 and 5, mobility is specified as Residential for data stability. However, other mobility variables can be proxies for economic activity and are discussed in Section 6, which describes their properties again.

Tables 1 and 2 show the variable definitions and the results of the summary statistics for the daily panel data (Wednesday and Saturday). To analyze weekday and weekend behavior, we use data from Wednesdays and Saturdays, which are less affected by national holidays; the details are discussed later. Note that the results of the summary statistics show an unbalanced panel for some of the variables. In particular, the series of the Google activity indicator Residential has a noticeable missing value in Canada. The logarithm of the average daily increase in the number of new positive PCR tests per week per 100,000 population (added to 1) was also rarely missing. A negative value for the average daily increase in the number of new positive PCR tests per 100,000 population occurred when the number of positive PCR tests was mistakenly overreported

Table 2: Summary statistics

Variable		Wednesday Mean	Std. Dev.	Min	Max	Observations
DailyNewPositives	Overall	7.142	14.070	−6.674	308.167	7,803
	Between		6.897	0.353	30.582	$N = 97$
	Within		12.279	−23.307	284.726	$\bar{T} = 80.443$
log(DailyNewPositives)	Overall	1.280	1.190	0.000	5.734	7,803
	Between		0.766	0.240	2.550	$N = 97$
	Within		0.913	−1.145	4.936	$\bar{T} = 80.443$
FullyVaccinated	Overall	0.188	0.272	0.000	0.855	$N = 7{,}857$
	Between		0.035	0.130	0.328	$N = 97$
	Within		0.270	−0.140	0.831	$T = 81$
Residential	Overall	5.704	4.590	−4.000	35.000	7,533
	Between		2.257	1.580	13.790	$N = 93$
	Within		4.004	−2.333	34.716	$T = 81$
Canada	Overall	0.134	0.341	0.000	1.000	7,857
	Between		0.342	0.000	1.000	$N = 97$
	Within		0.000	0.134	0.134	$T = 81$
Germany	Overall	0.165	0.371	0.000	1.000	7,857
	Between		0.373	0.000	1.000	$N = 97$
	Within		0.000	0.165	0.165	$T = 81$
Italy	Overall	0.216	0.412	0.000	1.000	7,857
	Between		0.414	0.000	1.000	$N = 97$
	Within		0.000	0.216	0.216	$T = 81$

Variable		Saturday Mean	Std. Dev.	Min	Max	Observations
DailyNewPositives	Overall	7.208	14.202	−6.721	304.759	7,850
	Between		7.039	0.348	30.978	$N = 97$
	Within		12.356	−23.662	280.989	$\bar{T} = 80.928$
log(DailyNewPositives)	Overall	1.281	1.195	0.000	5.723	7,850
	Between		0.777	0.238	2.579	$N = 97$
	Within		0.911	−1.196	4.949	$\bar{T} = 80.928$
FullyVaccinated	Overall	0.192	0.275	0.000	0.858	7,857
	Between		0.034	0.134	0.331	$N = 97$
	Within		0.273	−0.140	0.833	$T = 81$
Residential	Overall	4.360	4.549	−9.000	28.000	7,520
	Between		1.334	1.432	7.580	$N = 93$
	Within		4.352	−7.541	28.681	$\bar{T} = 80.860$

and subsequently corrected. Theoretically, the number of new positive PCR tests per 100,000 population is greater than zero, so when taking the logarithm, we assigned zero to the negative values in the original series (the excess was treated as no change) and then added one.

Next, we present the results of the unit root test for the average daily increase in the number of new positive PCR tests per week per 100,000 population and Residential. Let N be the number of samples in the cross section and T be the sample size of the time series. Theoretically, the data used in this paper are panel data, where N is finite and T is infinite. Therefore, the Harris–Tzavalis test (Harris and Tzavalis, 1999), the Breitung test (Breitung and Das, 2005), the Im–Pesaran–Shin test (Im et al., 2003), and the Hadri Lagrange multiplier test (Hadri, 2002), which require a balanced panel, are not applied. In addition, the Levin–Lin–Chu test (Levin et al., 2002) is not strictly applicable because it is also an unbalanced panel. Therefore, we used the Fisher-type (Choi, 2001) unit root test, which can be applied even with an unbalanced panel and is applicable when T is infinite and N is finite.

The results of the Fisher-type unit root test are shown in the Appendix. In most of the test results, the null hypothesis that all panels would contain unit roots was rejected at the 5% significance level. This indicates that the log of the average daily increase in the number of new positive PCR tests per week per 100,000 population and the Residential series are limited, if they exist at all. However, the null hypothesis could not be rejected for the Phillips–Perron tests, which included a trend term for the log of the average daily increase in the number of new positive PCR tests per week per 100,000 population, because although the augmented Dickey–Fuller test rejected it, the Phillips–Perron tests are robust to heteroskedasticity. The number of new positive PCR tests per 100,000 population starts at zero, with amplitude, but converges to zero again when T is infinite, which is self-evident owing to the nature of infectious diseases, and does not diverge to infinity with a trend. The number of new infections is not likely to be a stochastic process like a random walk, as its amplitude is clearly affected by the past values. Residential, due to the nature of the data, is also based on the median value for each day of the week for the 5 weeks from January 3 to February 6, 2020, and shows a deviation. When T is infinite, it is expected to converge to the median of January 3 to February 6 again if it is in January or early February. Of course, the existence of seasonality and changes in the global environment may cause drastic changes in behavioral patterns, but at least in the data used in the present paper, we could not confirm the existence of unit roots. Therefore, we can assume that no critical problem will occur even if we use the original series to estimate the number of Google activity indicator Residential and new positive PCR tests per 100,000 population.

5. Estimated results

Tables 3 and 4 show the estimated results for the Google activity indicator Residential, and Tables 5 and 6 the estimated results for the average daily increase in the number of new positive PCR tests per week per 100,000 population (logarithmic values) for Wednesday and Saturday. We use a lag variable for vaccination coverage to analyze the behavioral change (Residential) caused by the coronavirus and the final outcome, i.e., the number of new positive PCR tests. As it has been reported that it takes 2 weeks to acquire antibodies from the vaccine, we used the vaccination rate of 2 weeks prior for Residential. In addition, because there is a time lag between the onset of COVID-19 symptoms and the time when a positive test result is obtained, the vaccination rate 3 weeks prior to the onset of COVID-19 symptoms was used to estimate the number of new positive PCR tests results. As for the stringency index used in Section 3, data for Canada are available as a panel by state, but for Germany, Italy, and Japan, there are no panel data by state, province, or prefecture, only national data. Therefore, we do not use it as an explanatory variable.

In this paper, we present estimation results for Saturday and Wednesday, and the reasons for choosing these 2 days are as follows. It was necessary to analyze behavior on Saturday or Sunday, when people are expected to go out more frequently for shopping. However, due to the existence of the holiday law in

Table 3: Estimated results for Residential (Wednesday)

Residential	(1)	(2)	(3)	(4)
Wednesday	FE	FE	FE	FE
FullyVaccinated	-1.111***	-0.200*	-0.411	-0.367
	(-6.464)	(-1.674)	(-1.155)	(-1.053)
FullyVaccinated × Canada	-6.976***	-6.941***	-6.508***	-6.162***
	(-15.56)	(-10.62)	(-15.47)	(-9.792)
FullyVaccinated × Germany	-5.775***	-9.144***	-4.836***	-7.770***
	(-24.71)	(-22.93)	(-18.74)	(-18.19)
FullyVaccinated × Italy	-7.747***	-10.22***	-7.016***	-9.142***
	(-32.46)	(-32.19)	(-28.27)	(-26.86)
2020 dummy	-1.426***	-0.464***	-0.724***	-0.280
	(-9.243)	(-6.505)	(-3.565)	(-1.511)
Canada × 2020 dummy		0.125		0.348
		(0.392)		(1.107)
Germany × 2020 dummy		-3.238***		-2.831***
		(-17.79)		(-14.72)
Italy × 2020 dummy		-2.427***		-2.111***
		(-12.28)		(-10.54)
February dummy			-2.091***	-2.083***
			(-7.885)	(-7.867)
March dummy			-3.122***	-3.096***
			(-15.80)	(-15.78)
April dummy			-3.301***	-3.248***
			(-15.80)	(-15.77)
May dummy			-1.603***	-1.513**
			(-2.648)	(-2.524)
June dummy			-4.404***	-4.096***
			(-10.27)	(-9.957)
July dummy			-5.135***	-4.736***
			(-10.06)	(-9.577)
August dummy			-3.570***	-3.113***
			(-6.273)	(-5.644)
September dummy			-4.795***	-4.299***
			(-9.190)	(-8.568)
October dummy			-4.401***	-3.882***
			(-12.14)	(-11.10)
November dummy			-2.128***	-1.599***
			(-7.064)	(-5.427)
December dummy			-0.0439	0.459*
			(-0.169)	(1.707)
constant	7.104***	7.207***	9.882***	9.882***
	(80.67)	(153.9)	(29.31)	(35.54)
Observations	7,440	7,440	7,440	7,440
R^2	0.118	0.138	0.282	0.297
Number of states	93	93	93	93

Notes: FullyVaccinated takes a 14-day lag in Residential. Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Germany, behavior on Sunday is different from that in other countries. Therefore, Saturday was adopted first. As for weekday behavior, we used Wednesday, the middle of the week. In the data period, we fixed the vaccination coverage

Table 4: Estimated results for Residential (Saturday)

Residential Saturday	(5) RE	(6) FE	(7) RE	(8) FE
FullyVaccinated	−4.302***	−3.185***	−5.764***	−5.654***
	(−24.37)	(−28.77)	(−11.98)	(−12.52)
FullyVaccinated × Canada	−3.623***	−4.235***	−2.474***	−2.841***
	(−7.278)	(−5.688)	(−4.851)	(−3.986)
FullyVaccinated × Germany	−5.465***	−8.232***	−3.946***	−6.338***
	(−24.72)	(−24.53)	(−14.81)	(−15.15)
FullyVaccinated × Italy	−8.474***	−12.13***	−7.250***	−10.54***
	(−33.42)	(−29.60)	(−24.51)	(−23.43)
2020 dummy	−2.792***	−1.510***	−2.785***	−2.078***
	(−15.80)	(−19.96)	(−11.92)	(−10.51)
Canada × 2020 dummy		−0.868***		−0.747***
		(−2.771)		(−2.639)
Germany × 2020 dummy		−3.109***		−2.748***
		(−18.27)		(−15.66)
Italy × 2020 dummy		−3.581***		−3.315***
		(−15.01)		(−14.10)
February dummy			−3.702***	−3.690***
			(−18.36)	(−18.34)
March dummy			−3.790***	−3.759***
			(−15.50)	(−15.26)
April dummy			−4.084***	−4.026***
			(−23.33)	(−22.62)
May dummy			−4.719***	−4.610***
			(−17.70)	(−17.81)
June dummy			−5.753***	−5.369***
			(−15.62)	(−15.48)
July dummy			−6.379***	−5.926***
			(−14.56)	(−14.24)
August dummy			−5.026***	−4.469***
			(−10.08)	(−9.411)
September dummy			−4.829***	−4.230***
			(−12.94)	(−12.08)
October dummy			−3.805***	−3.177***
			(−16.81)	(−13.65)
November dummy			−1.561***	−0.919**
			(−4.116)	(−2.222)
December dummy			−0.512	0.106
			(−1.287)	(0.245)
constant	6.722***	6.843***	10.72***	10.72***
	(44.53)	(142.0)	(47.45)	(70.36)
Observations	7,427	7,427	7,427	7,427
R^2		0.219		0.404
Number of states	93	93	93	93

Notes: FullyVaccinated takes a 14-day lag in Residential. Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

at the end of November, so Residential is Wednesdays (Saturday) from June 1, 2020 to December 14, 2021, and the number of new positive PCR tests is Wednesdays (Saturday) from June 1, 2020 to December 21, 2021.

Tables 3 and 4 show the estimation results for the vaccine dummy, the 2020 dummy, the monthly dummy, and the cross-dummies between these and the country. We also attempted to use monthly and cross-country dummies, but the results are not shown because of the instability of the estimation results. The reason for including the 2020 dummy is to control for the effect of COVID-19 variants in 2020 and 2021. Because the effects of the Alpha and Delta variants were basically nonexistent in 2020 and the baseline of the number of infected people differs, it is reasonable to include a cross-dummy between the 2020 dummy and the country. In addition, because vaccinations started in earnest after 2021, the vaccination rate is basically a variable that rises steadily and functions as a trend variable. Therefore, the inclusion of cross-dummies between the monthly and country dummies leads to the problem of multicollinearity. As a result, in this paper, we focus on the country dummy, the 2020 dummy, and the monthly dummy, and limit the cross-dummy to those that do not cause the effect of multicollinearity.

In Tables 3 and 4, the results of the standard F-test, Breusch–Pagan test, and Hausman test show that only (5) and (7) for Saturdays cannot be rejected as random effects models, while the fixed effects models dominate in all the remaining cases. The tables show some interesting facts. We are most interested in whether people's behavior and the number of positive PCR tests would change if the vaccination rate were to reach 100%. This can be confirmed by the coefficient of FullyVaccinated, which takes values from 0 to 1. The coefficient of FullyVaccinated is positive to encourage people to stay at home, and negative to encourage people to go out.

In Tables 3 and 4, the coefficients of FullyVaccinated in Residential were significant at least at the 10% level for equations (1) and (2), excluding the monthly dummy, but not for (3) and (4), including the monthly dummy, although the signs of the coefficients were negative, but not significant, with respect to Japan. We cannot confirm the strong result that the vaccination encouraged active going out in Japan. However, the coefficients of FullyVaccinated in equations (5) to (8) for the Saturday data are negative and significant at the 1% level in

Japan, confirming that vaccination encouraged people to go out. Interestingly, the cross-dummies for FullyVaccinated are significantly negative at the 1% level for Canada, Germany, and Italy, indicating a stronger effect of vaccination compared with Japan. The results are stable even when the variables are switched, and the Wednesday data show that going out is promoted even more than in Japan: 6.162 to 8.976 percentage points in Canada, 4.836 to 9.144 percentage points in Germany, and 7.016 to 10.22 percentage points in Italy. The same trend was observed on Saturdays, so we can conclude that vaccination had a stronger effect on encouraging people to go out in Canada, Germany, and Italy than in Japan.

Tables 5 and 6 provide the estimated results of the effect of vaccination on the average daily increase in the number of new positive PCR tests per week per 100,000 population (logarithmic values). The magnitude of the FullyVaccinated coefficient differs depending on the presence or absence of the monthly dummy, but the trend is negative and significant at the 1% level. This means that vaccination reduces the average daily increase in the number of new positive PCR tests in Japan by 0.639 to 2.951% when the vaccination rate reaches 100%. In Japan, it can be said that the vaccine has indeed reduced the number of positive cases. It is interesting to note that in Canada and Germany, the vaccine has not been as effective in reducing the number of positive cases as in Japan. The cross-dummies with the FullyVaccinated variable were positive and significant at the 1% level in all estimating equations, and the effect on the number of positive cases was -1.229 to 0.562% in Canada and -1.548 to 0.674% in Germany, resulting in an increase in the number of positive cases in some cases. In Italy, the absolute value of the coefficient of the cross-dummy was smaller than that of the coefficient of FullyVaccinated, indicating that the vaccine had a suppressive effect on the number of positive cases. Of course, it cannot be denied that this result picks up the effect of the spike in the number of positive cases caused by the Delta and Omicron variants in Germany. However, it would be difficult to deny the effect of the vaccine in reducing the number of positive cases.

Table 5: Estimated results of new positive PCR tests per week per 100,000 population (Wednesday)

log(DailyNewPositives)	(1)	(2)	(3)	(4)
Wednesday	RE	FE	RE	FE
FullyVaccinated	−0.839***	−0.639***	−2.951***	−2.898***
	(−14.59)	(−10.72)	(−16.12)	(−16.37)
FullyVaccinated × Canada	1.200***	1.201***	1.722***	1.720***
	(3.787)	(3.016)	(4.569)	(3.897)
FullyVaccinated × Germany	1.513***	1.064***	1.798***	1.350***
	(25.75)	(11.02)	(26.14)	(11.79)
FullyVaccinated × Italy	0.402***	−0.335***	0.624***	−0.107
	(3.943)	(−2.737)	(6.183)	(−0.855)
2020 dummy	−0.733***	−0.652***	−1.560***	−1.516***
	(−24.73)	(−23.18)	(−20.19)	(−21.05)
Canada × 2020 dummy		0.105		0.0552
		(0.942)		(0.512)
Germany × 2020 dummy		−0.182**		−0.256***
		(−2.462)		(−3.540)
Italy × 2020 dummy		−0.387***		−0.478***
		(−6.476)		(−8.177)
February dummy			−0.396***	−0.395***
			(−8.719)	(−8.690)
March dummy			−0.336***	−0.331***
			(−6.149)	(−6.021)
April dummy			0.0282	0.0386
			(0.586)	(0.802)
May dummy			−0.00797	0.00976
			(−0.118)	(0.147)
June dummy			−0.637***	−0.577***
			(−8.654)	(−8.197)
July dummy			−0.379***	−0.301***
			(−4.704)	(−3.864)
August dummy			0.446***	0.538***
			(4.625)	(5.656)
September dummy			0.594***	0.695***
			(7.678)	(8.906)
October dummy			0.683***	0.789***
			(9.539)	(10.26)
November dummy			1.199***	1.307***
			(11.88)	(12.01)
December dummy			1.404***	1.509***
			(14.63)	(14.48)
Constant	1.593***	1.616***	1.920***	1.925***
	(17.94)	(81.38)	(16.56)	(44.96)
Observations	7,802	7,802	7,802	7,802
R^2		0.161		0.448
Number of states	97	97	97	97

Notes: FullyVaccinated takes a 21-day lag in DailyNewPositives. Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

6. Effects of vaccination on economic activity

In Section 5, we analyzed the relationship between vaccination and mobility using the Google activity indicator Residential. The reason for this is that,

Table 6: Estimated results of new positive PCR tests per week per 100,000 population (Saturday)

log(DailyNewPositives)	(5)	(6)	(7)	(8)
Saturday	RE	FE	RE	FE
FullyVaccinated	−0.860***	−0.668***	−2.892***	−2.841***
	(−15.02)	(−11.14)	(−16.11)	(−16.36)
FullyVaccinated × Canada	1.225***	1.236***	1.752***	1.739***
	(3.912)	(3.111)	(4.738)	(3.975)
FullyVaccinated × Germany	1.593***	1.146***	1.886***	1.420***
	(26.21)	(12.20)	(26.89)	(12.83)
FullyVaccinated × Italy	0.471***	−0.235*	0.710***	−0.0110
	(4.623)	(−1.932)	(6.987)	(−0.0885)
2020 dummy	−0.746***	−0.669***	−1.525***	−1.475***
	(−25.00)	(−23.23)	(−20.50)	(−21.16)
Canada × 2020 dummy		0.118		0.0398
		(1.014)		(0.357)
Germany × 2020 dummy		−0.186**		−0.285***
		(−2.457)		(−3.866)
Italy × 2020 dummy		−0.368***		−0.487***
		(−6.135)		(−8.328)
February dummy			−0.400***	−0.398***
			(−8.567)	(−8.523)
March dummy			−0.323***	−0.318***
			(−5.921)	(−5.790)
April dummy			0.0234	0.0331
			(0.498)	(0.701)
May dummy			−0.0119	0.00633
			(−0.185)	(0.101)
June dummy			−0.563***	−0.497***
			(−7.296)	(−6.744)
July dummy			−0.420***	−0.344***
			(−5.051)	(−4.317)
August dummy			0.451***	0.546***
			(4.637)	(5.744)
September dummy			0.574***	0.678***
			(7.493)	(8.886)
October dummy			0.675***	0.784***
			(9.875)	(10.69)
November dummy			1.223***	1.334***
			(12.46)	(12.56)
December dummy			1.392***	1.502***
			(14.87)	(14.68)
Constant	1.595***	1.613***	1.890***	1.891***
	(17.95)	(80.89)	(16.22)	(44.55)
Observations	7,850	7,850	7,850	7,850
R^2		0.167		0.435
Number of states	97	97	97	97

Notes: FullyVaccinated takes a 21-day lag in DailyNewPositives. Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

as Google also points out, Residential is the most stable indicator in daily life because of the nature of the time spent at home, which accounts for nearly half of the day. However, as mentioned in Section 4, Google activity includes variables other than Residential. Fukao and Shioji (2022) used Google activity as a proxy variable for economic activity and analyzed the trade-off between COVID-19 and economic activity in data from three cities. In this paper, we also use the Google activity indicator to confirm the impact of vaccination on economic activity indirectly.

Table 7 shows descriptive statistics for Google activities other than Residential. Compared with Residential in Table 2, the standard deviations and the absolute values of the minimum and maximum values are larger, which can be seen immediately. These are especially large for Parks, where the base time for Google activity is from January 3 to February 6, 2020, suggesting that the demand for Parks was small because of seasonal factors. In addition, when the number of visitors staying in Parks is extremely small, Google does not disclose the data from the viewpoint of privacy protection. As Transit Stations are public transportation stations, the behavior patterns in urban and nonurban areas are expected to be structurally different. Moreover, the characteristics of Transit Stations differ significantly between areas such as urban areas in Japan, where people use railroads for daily commuting, and areas where people use airplanes for multiple trips per year. Therefore, while the analysis is suitable for urban areas, it is not appropriate for all areas. With these considerations in mind, Parks and Transit Stations are also excluded in subsequent analyses.

Retail & Recreation, Grocery & Pharmacy, and Workplaces are the remaining variables. However, as Workplaces has a trade-off relationship with Residential on weekdays, it can be excluded from the analysis. Therefore, we use Grocery & Pharmacy, which represents daily shopping, and Retail & Recreation, which includes even nonroutine shopping and has the character of an extravagant good. By analyzing these two mobilities, we examine the impact of consumption recovery in Canada, Germany, and Italy, as shown in Figures 2 and 3, and the slump in consumption in Japan, based on their proxy variables.

Figures 9 and 10 show the changes (7-day moving averages) since June 2020 for Retail & Recreation and Grocery & Pharmacy, respectively. The charac-

Table 7: Summary statistics other than Residential

		Wednesday				
Variable		Mean	Std. Dev.	Min	Max	Observations
Retail & Recreation	Overall	−8.674	17.236	−85.000	119.000	$N = 7{,}674$
	Between		7.978	−28.210	12.091	$n = 95$
	Within		15.312	−85.699	111.252	$\bar{T} = 80.779$
Grocery & Pharmacy	Overall	4.926	12.829	−92.000	119.000	$N = 7{,}517$
	Between		5.067	−6.704	21.704	$n = 93$
	Within		11.797	−90.358	111.926	$\bar{T} = 80.828$
Parks	Overall	33.254	72.197	−72.000	672.000	$N = 7{,}282$
	Between		41.686	−33.358	211.286	$n = 92$
	Within		59.264	−210.031	618.722	$\bar{T} = 79.152$
Transit Stations	Overall	−20.138	17.890	−79.000	164.000	$N = 7{,}486$
	Between		12.091	−53.679	7.568	$n = 93$
	Within		13.279	−85.644	136.356	$\bar{T} = 80.495$
Workplaces	Overall	−16.971	14.126	−86.000	10.000	$N = 7{,}764$
	Between		8.716	−41.049	−3.395	$n = 96$
	Within		11.148	−79.761	6.239	$\bar{T} = 80.875$

		Saturday				
Variable		Mean	Std. Dev.	Min	Max	Observations
Retail & Recreation	Overall	−15.394	17.398	−90.000	81.000	$N = 7{,}685$
	Between		8.491	−37.738	3.359	$n = 95$
	Within		15.216	−94.381	76.001	$\bar{T} = 80.895$
Grocery & Pharmacy	Overall	1.108	13.782	−95.000	105.000	$N = 7{,}531$
	Between		4.923	−12.800	10.691	$n = 94$
	Within		12.943	−99.176	95.898	$\bar{T} = 80.117$
Parks	Overall	31.281	72.846	−82.000	491.000	$N = 7{,}375$
	Between		45.981	−43.333	181.256	$n = 93$
	Within		57.099	−169.976	425.718	$\bar{T} = 79.301$
Transit Stations	Overall	−20.654	23.812	−82.000	242.000	$N = 7{,}500$
	Between		13.231	−46.348	26.000	$n = 93$
	Within		19.870	−119.148	196.852	$\bar{T} = 80.645$
Workplaces	Overall	−11.599	11.100	−74.000	29.000	$N = 7{,}715$
	Between		5.463	−26.128	2.654	$n = 96$
	Within		9.686	−69.328	14.746	$\bar{T} = 80.365$

teristics of the figures are summarized as follows. First, Retail & Recreation changed in response to government regulations, as indicated by the stringency index in Figure 7. Correspondingly, mobility declined after November in Figure

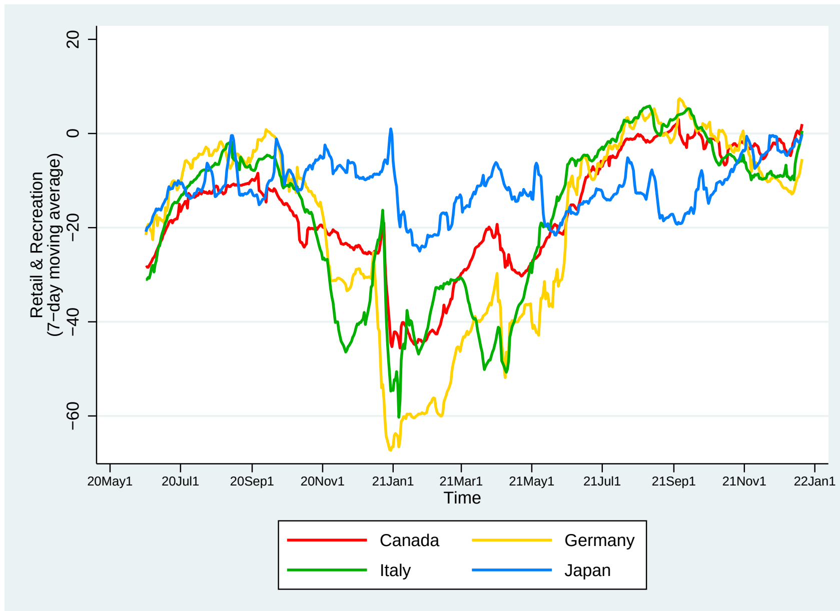

Figure 9: Mobility in Retail & Recreation

9. In particular, in Germany, the tightening of regulations from December 2020 strongly contributed to the decline in mobility in Retail & Recreation. Second, the change in mobility in Grocery & Pharmacy, where people go out to purchase necessities, is milder than that in Retail & Recreation; until October 2020, Italy is somewhat exceptional, but in 2020, the change in mobility in Canada, Germany, and Japan is much smaller than that in Germany. No significant difference is observed in changes in mobility. Third, an increase in mobility is seen in Canada, Germany, and Italy in response to vaccination after January 2021. One interpretation for this is that the increase in mobility is due to the fact that consumers stop buying in bulk and start buying daily necessities. Fourth, there is a peculiarity in Japan. Although stringency was low in Japan, there was neither a marked drop in mobility nor a marked increase due to the progress of vaccination. Compared with the other three countries, no significant change is observed. This may be related to the spread of the Delta strain that Japan faced in the summer of 2021, but nevertheless, it can be regarded as a unique

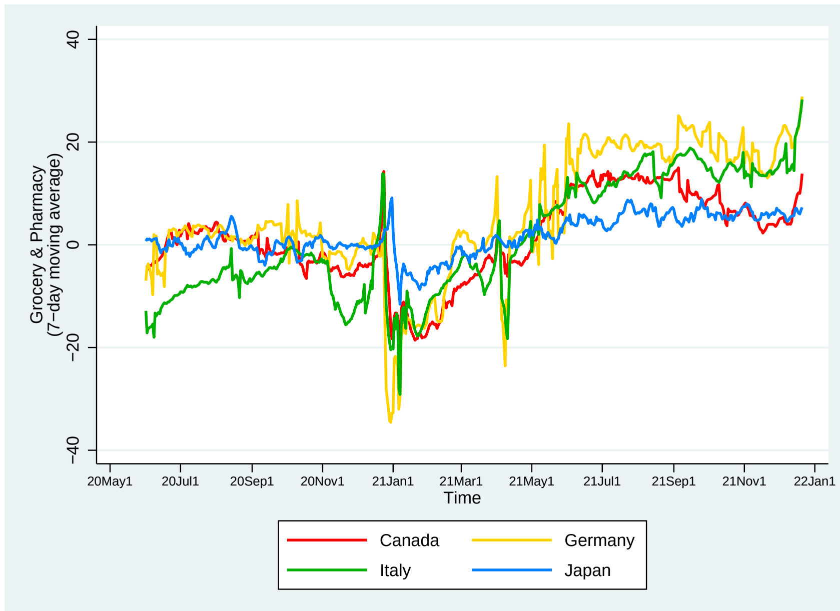

Figure 10: Mobility in Grocery & Pharmacy

situation.

Finally, the results of a regression analysis confirmed the effects of vaccination on Retail & Recreation and Grocery & Pharmacy (the results of the unit root test are shown in the Appendix). The estimation method is the same as that used for the Residential data in Tables 3 and 4. Tables 8 and 9 show the estimated results for Retail & Recreation on Wednesdays and Saturdays, and Tables 10 and 11 show the estimated results for Grocery & Pharmacy on Wednesdays and Saturdays. The most important coefficients are FullyVaccined and its cross-term. The signs of these coefficients are basically the same as those of the Residential coefficients in Tables 3 and 4, although a positive sign is expected given that vaccination encourages going out (note that for Residential, a negative sign on the coefficient encourages going out).

The estimation results in Tables 8 and 9 show that the coefficient of Fully-Vaccined and its cross-term are significant at the 1% level for both Wednesday and Saturday, confirming that vaccination promotes mobility in Retail & Recre-

Table 8: Estimated results for Retail & Recreation (Wednesday)

Retail & Recreation	(1)	(2)	(3)	(4)
Wednesday	RE	FE	FE	FE
FullyVaccined	17.18***	11.98***	10.48***	10.12***
	(17.56)	(23.18)	(6.795)	(6.608)
FullyVaccined × Canada	33.06***	55.04***	30.12***	48.07***
	(15.43)	(17.97)	(16.87)	(16.40)
FullyVaccined × Germany	19.26***	19.25***	17.59***	14.43***
	(8.611)	(8.580)	(7.049)	(5.157)
FullyVaccined × Italy	28.56***	40.86***	26.18***	35.20***
	(19.83)	(19.05)	(20.26)	(16.79)
2020 dummy	10.53***	5.692***	4.949***	2.706***
	(12.72)	(22.39)	(5.045)	(2.976)
Canada × 2020 dummy		19.47***		17.16***
		(16.73)		(14.34)
Germany × 2020 dummy		-1.471		-3.126**
		(-1.167)		(-2.510)
Italy × 2020 dummy		10.90***		9.049***
		(10.31)		(8.496)
February dummy			3.779***	3.740***
			(4.964)	(4.923)
March dummy			12.78***	12.66***
			(14.93)	(14.95)
April dummy			11.01***	10.77***
			(14.40)	(14.41)
May dummy			14.92***	14.52***
			(11.54)	(11.51)
June dummy			18.26***	16.80***
			(9.576)	(9.267)
July dummy			23.13***	21.24***
			(10.24)	(9.922)
August dummy			26.58***	24.41***
			(9.351)	(8.930)
September dummy			17.52***	15.18***
			(7.791)	(7.083)
October dummy			15.00***	12.56***
			(9.310)	(8.264)
November dummy			10.88***	8.397***
			(9.171)	(7.167)
December dummy			11.10***	8.740***
			(8.993)	(6.598)
Constant	-18.39***	-18.93***	-30.22***	-30.23***
	(-14.33)	(-74.16)	(-23.46)	(-31.54)
Observations	7,579	7,579	7,579	7,579
R^2		0.319	0.438	0.472
Number of states	95	95	95	95

Notes: Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

ation. The cross-term with the country dummy (the reference is Japan) is also positive and significant, meaning that vaccination promotes more mobility in Retail & Recreation in Canada, Germany, and Italy than in Japan. If vac-

Table 9: Estimated results for Retail & Recreation (Saturday)

Retail & Recreation	(5)	(6)	(7)	(8)
Saturday	FE	FE	RE	FE
FullyVaccined	20.04***	14.84***	17.95***	17.65***
	(20.35)	(29.46)	(13.01)	(13.44)
FullyVaccined × Canada	39.19***	62.25***	35.72***	57.00***
	(18.40)	(22.22)	(18.06)	(20.99)
FullyVaccined × Germany	17.99***	17.19***	15.65***	13.05***
	(7.443)	(6.190)	(5.722)	(3.986)
FullyVaccined × Italy	29.95***	42.01***	27.06***	37.63***
	(28.35)	(26.03)	(25.45)	(23.55)
2020 dummy	11.08***	6.698***	8.082***	6.452***
	(13.64)	(22.34)	(9.814)	(9.116)
Canada × 2020 dummy		19.22***		17.87***
		(22.50)		(20.75)
Germany × 2020 dummy		-2.902***		-3.906***
		(-2.838)		(-3.623)
Italy × 2020 dummy		9.735***		8.645***
		(8.358)		(7.576)
February dummy			9.191***	9.133***
			(15.40)	(15.30)
March dummy			13.90***	13.75***
			(15.19)	(15.01)
April dummy			13.01***	12.74***
			(16.33)	(16.02)
May dummy			13.85***	13.35***
			(14.23)	(14.10)
June dummy			19.26***	17.38***
			(15.37)	(15.48)
July dummy			21.05***	18.80***
			(13.48)	(13.40)
August dummy			16.97***	14.23***
			(8.661)	(7.869)
September dummy			17.12***	14.20***
			(10.40)	(9.513)
October dummy			15.17***	12.13***
			(13.99)	(11.84)
November dummy			10.33***	7.228***
			(8.447)	(5.727)
December dummy			6.243***	3.250***
			(6.059)	(2.733)
Constant	-25.97***	-26.51***	-38.19***	-38.18***
	(-17.08)	(-113.5)	(-21.19)	(-60.27)
Observations	7,590	7,590	7,590	7,590
R^2		0.408		0.522
Number of states	95	95	95	95

Notes: Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

cination were to reach 100%, this would imply an increase of 10.12 to 17.18 percentage points in Retail & Recreation mobility in Japan. For Canada, Germany, and Italy, this value would be the sum of FullyVaccined and the value

Table 10: Estimated results for Grocery & Pharmacy (Wednesday)

Grocery & Pharmacy	(1)	(2)	(3)	(4)
Wednesday	RE	RE	RE	RE
FullyVaccined	10.17***	10.10***	-3.117**	-2.894**
	(19.08)	(21.58)	(-2.047)	(-2.000)
FullyVaccined × Canada	14.38***	12.99***	12.55***	9.016***
	(8.040)	(5.226)	(7.641)	(3.841)
FullyVaccined × Germany	10.40***	9.305***	11.13***	9.145***
	(3.739)	(4.396)	(3.711)	(3.953)
FullyVaccined × Italy	25.61***	27.84***	24.22***	24.71***
	(12.56)	(10.23)	(12.78)	(9.703)
2020 dummy	0.664**	0.576**	-7.667***	-7.134***
	(2.052)	(2.402)	(-8.512)	(-8.962)
Canada × 2020 dummy		-1.417		-3.650***
		(-1.602)		(-4.149)
Germany × 2020 dummy		-1.411		-2.496**
		(-1.184)		(-2.161)
Italy × 2020 dummy		2.344**		0.413
		(2.451)		(0.441)
February dummy			4.434***	4.437***
			(5.118)	(5.120)
March dummy			11.94***	11.96***
			(12.29)	(12.28)
April dummy			12.05***	12.08***
			(11.93)	(11.92)
May dummy			17.15***	17.19***
			(11.39)	(11.37)
June dummy			18.37***	18.55***
			(12.96)	(12.90)
July dummy			19.96***	20.21***
			(12.01)	(12.13)
August dummy			24.00***	24.28***
			(10.91)	(11.15)
September dummy			18.86***	19.16***
			(10.89)	(10.95)
October dummy			17.69***	17.99***
			(10.87)	(10.90)
November dummy			16.19***	16.50***
			(10.54)	(10.55)
December dummy			22.71***	23.00***
			(11.87)	(11.81)
Constant	1.169***	1.150***	-10.25***	-10.25***
	(2.775)	(2.738)	(-10.65)	(-10.65)
Observations	7,424	7,424	7,424	7,424
R^2				
Number of states	93	93	93	93

Notes: Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

of its cross-term. We therefore conclude that vaccination promoted Retail & Recreation, which is considered to have an luxurious character.

Tables 10 and 11 present the Grocery & Pharmacy estimation results for

Table 11: Estimated results for Grocery & Pharmacy (Saturday)

Grocery & Pharmacy	(5)	(6)	(7)	(8)
Saturday	FE	FE	FE	FE
FullyVaccined	10.31***	11.97***	6.326***	6.727***
	(20.12)	(30.50)	(6.650)	(7.105)
FullyVaccined × Canada	21.30***	16.42***	19.34***	12.98***
	(11.65)	(7.656)	(11.32)	(6.527)
FullyVaccined × Germany	4.421*	2.260	3.929*	1.301
	(1.939)	(1.138)	(1.668)	(0.609)
FullyVaccined × Italy	23.50***	19.46***	21.88***	16.55***
	(13.62)	(8.668)	(13.44)	(7.913)
2020 dummy	-1.539***	0.292	-4.650***	-3.162***
	(-4.342)	(0.911)	(-8.231)	(-5.714)
Canada × 2020 dummy		-4.891***		-6.401***
		(-6.601)		(-8.844)
Germany × 2020 dummy		-2.424***		-3.234***
		(-4.002)		(-5.067)
Italy × 2020 dummy		-4.143***		-5.511***
		(-4.102)		(-5.537)
February dummy			9.348***	9.374***
			(26.14)	(26.17)
March dummy			12.00***	12.06***
			(27.14)	(27.20)
April dummy			14.81***	14.93***
			(33.15)	(33.01)
May dummy			11.87***	12.09***
			(16.47)	(17.03)
June dummy			16.44***	17.23***
			(30.79)	(33.27)
July dummy			16.28***	17.23***
			(21.26)	(23.56)
August dummy			14.43***	15.57***
			(13.16)	(15.02)
September dummy			14.20***	15.44***
			(19.89)	(21.73)
October dummy			12.88***	14.17***
			(11.48)	(12.81)
November dummy			13.38***	14.69***
			(17.22)	(18.33)
December dummy			9.857***	11.12***
			(10.86)	(12.57)
Constant	-1.886***	-1.727***	-12.68***	-12.68***
	(-8.583)	(-8.614)	(-26.95)	(-28.61)
Observations	7,438	7,438	7,438	7,438
R^2	0.229	0.234	0.308	0.315
Number of states	94	94	94	94

Notes: Robust t-statistics are in parentheses. FE and RE denote the fixed effects model and the random effects model, respectively. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Wednesday and Saturday. An interesting fact is that the coefficient of Fully-Vaccined is negative and significant in Models 3 and 4 for Wednesday only. Even if vaccination were 100% in Japan, the mobility of Grocery & Pharmacy would increase by −2.894 to 10.17 percentage points. This means that vaccination does not necessarily promote the mobility of Grocery & Pharmacy, which is considered to have a necessity character. Although the results are unstable, as discussed in the next section, the combination of vaccination and the spread of the Delta strain in Japan may have suppressed Grocery & Pharmacy on Wednesdays. In addition, as the majority of Japanese shoppers do not buy daily necessities in bulk, we cannot rule out the possibility that this may also have had an effect. However, in the other three countries, the coefficients are positive and significant, indicating that vaccination promotes mobility in Grocery & Pharmacy. Table 11 shows that the coefficient of FullyVaccined is positive and significant on Saturdays in Japan only. If vaccination were to reach 100%, the mobility of Grocery & Pharmacy on Saturdays would be increased by 6.326 to 11.97 percentage points.

Based on these estimates, it can be said that vaccination promotes both Retail & Recreation and Grocery & Pharmacy mobility on Saturdays in all four countries. The policy implications of these estimates, together with the effects of vaccination on the number of positive PCR tests and residential use analyzed in Section 5, are examined in Section 7.

7. Policy implications of vaccination

In this paper, we first analyzed the effect of vaccination on the Google activity indicator Residential and the number of new positive PCR tests per week per 100,000 population (logarithmic values) using state, provincial, or prefectural panel data from Canada, Germany, Italy, and Japan. We found that vaccination strongly encouraged people to go outside the home, except for in Japan, and that vaccination reduced the number of new positive PCR tests in Japan and Italy. It is necessary to add mobility to the explanatory variables in the estimation of the number of new positive PCR tests per week per 100,000 population and to try to estimate the endogenous effect. However, as we could not find appropriate instrument variables that affect only mobility, not the number of new positive PCR tests, we did not estimate the number of new positive PCR tests using the instrumental variable method, only the reduced form. Next, we analyzed the effects of vaccination on the Google activity indicators Retail & Recreation and Grocery & Pharmacy as proxy variables for economic activity. Fukao and Shioji (2022) also performed an analysis under the same assumption. The results showed that for Saturdays, vaccination increased mobility in Retail & Recreation and Grocery & Pharmacy in all four countries. Canada, Germany, and Italy showed stronger effects on promoting outings than did Japan.

In Canada, Germany, Italy, and Japan (Saturday only), vaccination increased outings and, especially in Canada, Germany, and Italy, outings were more strongly encouraged than in Japan. On Wednesdays in Japan, vaccination did not lead to an increase in outings, and at the same time, the number of new positive PCR tests decreased. Almost the same results were obtained when mobility was considered from Retail & Recreation and Grocery & Pharmacy. In Canada and Germany, vaccination increased the number of new positive PCR tests. The simultaneous increase in mobility due to vaccination and the increase in the number of infected persons in Canada and Germany is consistent with the predictions of Andersson et al. (2021). They found that vaccine information reduced people's willingness to socially distance themselves, adhere to public health guidelines, and stay at home voluntarily. This means that increased attention to vaccines may accelerate the spread of infectious diseases by increasing optimism and decreasing adherence to public health guidelines, thereby reducing the effectiveness of policies aimed at social distancing. The results of this paper are based on state, provincial, and prefectural panel data, but even panel data show that access to vaccine information did not promote social distancing (Eichenbaum et al., 2021), but rather, encouraged more outings in Canada and Germany. As pointed out by Masuhara and Hosoya (2022), in-line with the SIR model, the vaccination shifts the parameters that contain information on the encounter and infection rates downward, but this is offset or magnified by optimism, as predicted by Andersson et al. (2021).

On the contrary, the fact that only a limited increase in Wednesday outings was observed in Japan and that Saturday outings were more restrained compared with the other three countries, suggests the possibility that the vaccine information pointed out by Eichenbaum et al. (2021) may lead to social distancing. However, considering that vaccination coincided with the period of COVID-19 spread in Japan, it is highly possible that the "voluntary and request-based lockdowns" proposed by Hosono (2021), or actions based on fear with suppressed optimism, may have had an impact. Fukao and Shioji (2022), which was introduced earlier, is similar to Hosono (2021) in terms of its analytical framework, although it does not consider individual optimization behavior. In 2020, Hosono (2021) found that the two lockdowns did not lead to a significant explosion of positives, but paid for it with a reduction in consumption. Similar precautionary self-restraint behavior was also noted by Cronin and Evans (2021), who used cell phone location data in the U.S. and found that the reduction in foot traffic in high-risk establishments such as restaurants and bars was not the result of stay-at-home orders, but rather, to precautionary behavior. In August 2021, Japan had more positive PCR tests than did Canada, Germany, and Italy, as well the lowest vaccination rate among the four countries. Although a state of emergency in Japan was declared by the government, it is more likely that the voluntary and request-based lockdown, precautionary actions, or suppressed optimism during the August Obon season led to people staying home, which in turn, led to social distancing and suppressed the number of positive PCR tests. In the present study, we examined mobility and infections from a different perspective. Carroll and Prentice (2021), using county-level mobility data for the U.S. from March 23, 2020 to March 7, 2021, found that in the early stages of the pandemic, the number of positive PCR tests declined with decreasing mobility, and in the later stages of the pandemic, the number of positive PCR tests increased with decreasing mobility. They speculated that the reason for this was a function of the government's stay-at-home orders and self-restraint in the early stages of the pandemic and the result of vacation gatherings in the later stages. However, the results of the present paper did not find such a trend in Canada and Germany, where the increases in mobility and positive cases occurred simultaneously.

Considering these results and the mechanism of infection, it can be said that to reduce the increase in optimism caused by vaccination, the continued use of stay-at-home orders, which is based on voluntary preventive behavior, is crucial for controlling infections. Based on the nature of infectious diseases, the results of this study suggest that infection cannot occur without contact. As Velias et al. (2022) point out, forced lockdowns can lead to overlapping visits to grocery stores and pharmacies, which can result in the further spread of infection. Therefore, it is desirable to stay at home with voluntary preventive behaviors that suppress the rise of optimism. It is at least undeniable that vaccination was a key factor in controlling infection before the Omicron variant, and based on the estimated results for Japan, where optimism was low and Saturday outings were observed at a lower level than that in the other three countries, if vaccination coverage were to reach 100%, it would reduce the number of new positive PCR tests by 0.639–2.951%. In Italy, the number of new positive PCR tests tended to decrease, although not as much as in Japan, suggesting that optimism may offset the effect. In other words, as shown in Figure 1, if the principal policy target is to reduce the number of new positive PCR tests, it would be desirable to implement mobility control and vaccination concurrently. In particular, mobility suppression and vaccination are likely to be effective against the Delta variant, which tended to cause more severe cases.

We contrast our estimates with epidemiological results to analyze the results in more detail. Haas et al. (2022) estimated total averted burden using an age–sex group, the cumulative proportion of age–sex groups that received at least one dose of vaccine, the incidence rate among the unvaccinated, and the incidence rate among those who received at least one dose of vaccine. In Israel, Haas et al. (2022) reported that from January 3 to April 10, 2021, the actual number of positive cases was 316,772, but if the vaccine had not been administered, the number would have reached 475,437. This means that in 13 weeks, the number of cases was reduced to 66.617%, giving a reduction rate of 33.383%. Correcting this to per week, we have $1 - \exp\left(\log\left(0.666\right)/13\right)$, so solving this gives us a reduction effect of 3.076% per week. For a comparison in the same country as the data used in this paper, the estimate for Japan by Nishiura (2021) is instructive: from March 2 to September 25, 2021, the actual number of positive cases in Japan was 1,140,661, but if the vaccine had not been given, the number of new positive PCR tests would have been 1,792,153. This means that the number of new positive PCR tests was reduced to 63.647% in 30 weeks, which is a reduction of 36.352%. Correcting this to per week, we have $1 - \exp\left(\log\left(0.636\right)/30\right)$, which we solve to get 1.495%. In the present paper, it was confirmed that if the vaccination rate were to reach 100%, it would reduce the number of new positive PCR tests by 0.639–2.951%. If we recalculate this result by applying it to the vaccination coverage in Japan on September 25, 2021, which was approximately 70%, it would result in a reduction of 0.447% to 2.066% per week. Interestingly, the estimation results in this paper are similar to the epidemiological results, and the estimation results that take seasonality into account and include monthly dummies confirm a slightly higher reduction effect compared with Nishiura (2021). However, no large discrepancy is seen between the epidemiological results and the results of this paper, which supports the robustness of the estimation results.

Of course, the results from Japan may also be due to the fact that the policy or voluntary lockdown of outings overlapped with the Obon vacation in August, which limited the increase in outings, and that the vaccination program was also promoted during this period, but the explosion of infections suppressed an outbreak of optimism. In addition, Japan was the only one of the four countries that did not experience a recovery in consumption, a side effect that had a negative impact on GDP. A slow recovery in consumption was indirectly observed in Japan, as the increase in Retail & Recreation and Grocery & Pharmacy was less pronounced than that in the other three countries. Inoue and Okimoto (2022) also showed that measures to control mobility to Retail & Recreation and the state of emergency declaration had a negative effect on the rate of change in the number of new infections, and that vaccination suppressed the increase in the number of new infections, even though mobility increased. However, in a relative analytical environment that includes other countries, the results may give a different picture. That is, Wednesday outings in Japan are not promoted, and even on Saturdays, the increase in mobility is not as substantial. The difference from the other three countries is striking. In sum, in our framework, the impact of vaccination on mobility was less forceful in Japan than in the other three countries. The results of this paper, while supporting the findings of Inoue and Okimoto (2022), also indicate that Japan had a relatively small increase in mobility compared with the other three countries, and, as in Fukao and Shioji (2022), can simultaneously explain the slow recovery of consumption in Japan when Google activity is considered a proxy variable for economic activity.

On the other hand, as pointed out by Andersson et al. (2021), successful vaccination may have discouraged social distancing and accelerated the spread of infection in the other countries, which did not face a decline in consumption. Canada, Germany, and Italy seem poised to coexist with COVID-19, but this is not the case in Japan, which faces a situation that could be interpreted as a recession caused by COVID-19. One of the reasons for this is the delay in switching to the noncontact "new normal" and the inability to break away from the face-to-face based business model that existed before COVID-19. The rise of optimism, as pointed out by Andersson et al. (2021), leads to greater losses from infectious diseases, and the government needs to use stay-at-home orders to control excessive optimism while concurrently implementing policies to avoid a decline in consumption; however, the balance between the two is difficult to achieve. In the case of Japan, the low level of optimism suppressed mobility compared with the other three countries, and while vaccination may have been successful, it came at a cost in terms of lost GDP. As shown in the analysis by Fukao and Shioji (2022) with the background of the pandemic Phillips curve, in the early stages of a pandemic, each country prioritizes containment over the economy. As time goes by, however, the public may experience stay-at-home fatigue and turn to economic reopening (New York and London), though the situation in Japan (Tokyo) still seems to be different. We can envision a scenario where foreign countries are moving toward living with COVID-19, and while Japan continues to experience economic stagnation despite a certain degree of suppression of COVID-19, it is important to note that this is only a short-term trend. Although the lack of economic recovery is a problem, so is the loss of many lives. These influences are likely to appear in a variety of forms in the future. It is therefore essential to continue considering issues related to infectious disease and the economy from a long-term perspective.

What we can learn from this experience is that in areas where noncontact is equally effective (e.g., office work, university education), a society that can immediately switch to noncontact upon any sign of the spread of infection should be built. In the case of eating and drinking, as long as it is possible to avoid the 3 Cs (i.e., closed spaces, crowded spaces, and closed-contact settings), citizens should be encouraged to use such facilities actively and to help prevent the closure of restaurants by ordering take-out. As it is possible to control infection if a business is based on individuals rather than on an unspecified number of people, the tourism industry may be required to break away from business aimed at an unspecified number of people and shift to a model based on individuals who recognize each other. By making these preparations, we can build a society able to live with infectious diseases and minimize their negative impacts. In the wake of the recent pandemic, Japanese people have been *cautious* for better or worse in terms of both economic activities and their response to infectious disease. What is behind this? The unique historical, cultural, and spiritual contexts may not be irrelevant, and their current behavior may be dictated by their expectations about the country's future (i.e., future trends). Accordingly, future efforts to discuss differences in preference formation by country based on studies such as Falk et al. (2018) and to feed the results back into COVID-19 research would also be of great significance.

In the era of living with infectious diseases, the role of the government should be to control optimism, issue appropriate alerts, raise awareness of the need to move away from the traditional face-to-face society, and provide support for the non-face-to-face society. It is necessary to inform the public that there is a limitation to the effectiveness of vaccination in reducing the number of positive cases, to keep the public informed of who is at risk and who is not, and to provide appropriate risk control and alerts. By doing both at the same time, forced lockdowns can be avoided, people can stay-at-home voluntarily, and an explosion of positive cases can be avoided while simultaneously controlling over-optimism. However, these efforts may cause a decline in consumption. Therefore, if we cannot go back to a society that assumes face-to-face contact for a while, we need to use COVID-19 as an opportunity to appeal to the public for change. In Japan, in particular, the movement is slow, and society is still stuck on the premise of face-to-face interaction, not only in business, for instance, but also in education. If there are insufficient financial resources for the transition to a non-face-to-face society, then the government has a rationale to provide subsidies actively in the future.

8. Concluding remarks

In this paper, we have analyzed the effects of vaccination on the Google activity indicator Residential and the number of new positive PCR tests per 100,000 population (logarithmic values), using Canada, Germany, Italy, and Japan as examples, where vaccination statuses are similar and the number of infections temporarily increased, but remained relatively under control until mid-2021. The results indicated that vaccination strongly encouraged people to go outside in Canada, Germany, and Italy. The macro data support the findings of Andersson et al. (2021) that vaccination leads to a reduction in voluntary social distancing, adherence to hygiene guidelines, and willingness to stay at home. Vaccination suppressed the number of new positive PCR tests in Japan and Italy, but was likely to increase the number of new positive PCR tests in Canada and Germany, as Andersson et al. (2021) had feared. Considering the nature of infectious diseases, where the number of positive cases increases with increased contact with people outside the home, and the fact that breakthrough COVID-19 infections may occur, the results obtained in this paper are within the expected range. However, it will be difficult to achieve a reduction in the number of positive cases without suppressing people's optimistic behavior through vaccination. As Hosono (2021) pointed out, when analyzing the impact of voluntary lockdowns, we may need to further refine our explanatory variables. One factor that could influence voluntary lockdowns is the importance of information about the status of the pandemic, and proxy variables for this information could be the growth rate in the number of positive PCR tests in a week or the logarithm of the number of positive PCR tests. However, this paper does not employ these proxies because country-specific effects are highly influential. As shown in Figure 5, the number of positive PCR tests differs greatly among countries. In Japan in particular, the number of positive PCR tests was often small or close to zero, and only in the summer of 2021 was it higher than in the other three countries. If the analysis were limited to Japan, it would be better to use a lagged variable as a proxy variable, but because of the large country-specific effects in this study, we could not find an appropriate method for treating the lagged variable, and this issue will need to be addressed in the future.

Based on the results in Japan, where vaccination-induced outreach was relatively low, we estimate that the effect of 100% vaccine uptake on suppressing the number of new positive PCR tests in society would be 0.639–2.951%. This estimate is slightly higher than the epidemiological estimates of Haas et al. (2022) and Nishiura (2021), even after accounting for seasonality, but the deviation is not large. At least for the COVID-19 vaccine, it is difficult to deny its effectiveness strongly. However, for everyone to enjoy the benefits of the vaccine, it is necessary to control over-optimism and encourage voluntary mobility control over forced lockdowns. In other words, the government needs to suppress optimism by letting people know that there is a limitation to the effectiveness of the vaccine in suppressing new positive cases, to continue to send out appropriate risk controls and alerts to avoid forced lockdowns, and to promote ongoing voluntary stay-at-home behavior to avoid an explosion of positive cases. However, too much voluntary restraint could lead to a decline in consumption, which would give the government an extremely difficult task in making the public aware that they cannot return to a society based on face-to-face contact while providing necessary assistance. Google activity indicators other than Residential were also used to examine the relationship between the present COVID-19 pandemic and macroeconomic status, as mentioned in Section 3. One of the striking findings was that the economic reopening in Japan was less forceful than that in other countries. After examining the details of this relationship, we found that even though vaccination has progressed in Japan, the growth of outings has been sluggish, which may have dampened the economic recovery. However, a comprehensive analysis that takes the expansion of e-commerce and other related factors occurring in the background into account is needed in the future.

It is nearly impossible to leave behind the means of communication that we have been accustomed to since birth, face-to-face communication with others, which our daily consumption activities still rely on heavily. Having the means to achieve high economic growth while respecting the right-to-life of people of all ages to the maximum extent possible will be necessary for future infection control and be a policy tool pursued by governments around the world.

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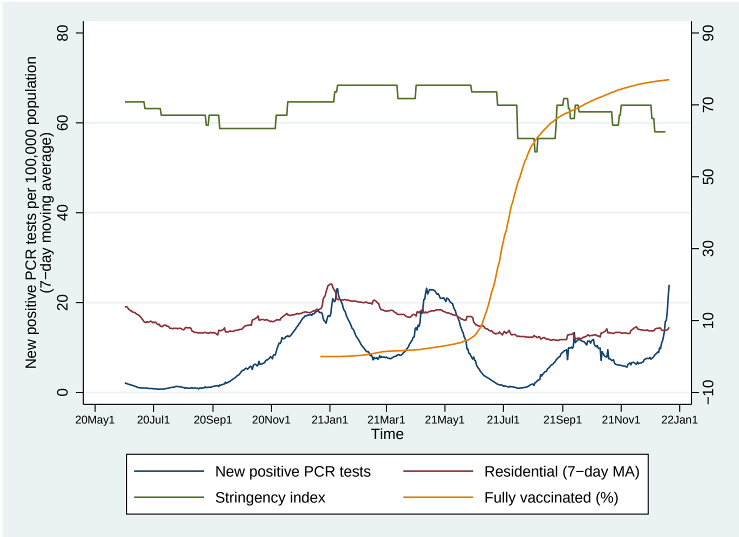

Figure A.1: Canada

Appendix A. Figures by country

In the Appendix, graphs of the average daily increase in the number of new positive PCR tests per week per 100,000 population, the Google activity indicator Residential, the stringency index, and the vaccination rate for the four countries shown in Section 3 are presented. This process makes it possible to understand the impact of the stringency index and vaccination on the number of positive cases in Residential and new positive PCR tests in a time series. Figure A.1 presents the situation in Canada, where the number of new positive PCR tests is shown on the left axis and that in the other three indicies is shown on the right axis; the maximum value on the axis of the number of new positive PCR tests is set at 8,000 to keep the scales consistent among the four countries. Figures A.2 to A.4 show the situations in Germany, Italy, and Japan, respectively.

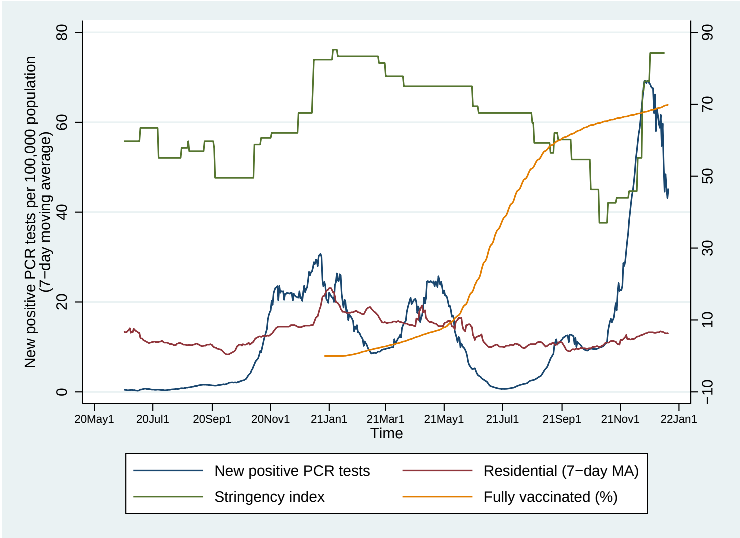

Figure A.2: Germany

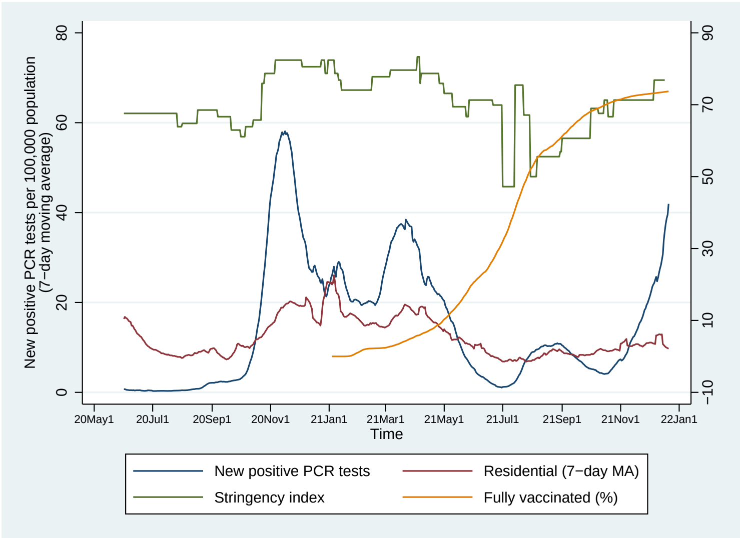

Figure A.3: Italy

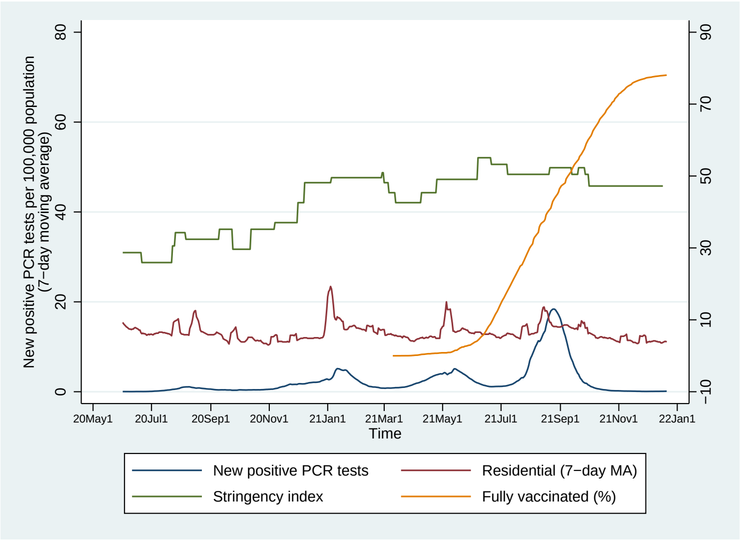

Figure A.4: Japan

Appendix B. The results of the unit root tests

Table B.1: Unit root tests for Wednesday

Wednesday			Residential	log(DailyNewPositives)	Retail & Recreation	Grocery & Pharmacy
Augmented Dickey–Fuller tests						
Constant	Inverse chi-squared (186)	P	1,461.863***	523.911***	1,503.575***	1,981.623***
	Inverse normal	Z	−28.001***	−12.379***	−26.842***	−38.189***
	Inverse logit t (469)	L^*	−41.308***	−13.131***	−41.529***	−56.684***
	Modified inv. chi-squared	Pm	66.150***	16.749***	67.385***	93.099***
Constant + trend	Inverse chi-squared (186)	P	1,146.943***	346.202***	1,255.115***	2,523.251***
	Inverse normal	Z	−22.110***	−6.322***	−21.884***	−43.988***
	Inverse logit t (469)	L^*	−31.458***	−6.614***	−33.268***	−72.151***
	Modified inv. chi-squared	Pm	49.823***	7.727***	54.639***	121.181***
Phillips–Perron tests						
Constant	Inverse chi-squared (186)	P	2,963.699***	238.117**	844.525***	1,003.026***
	Inverse normal	Z	−43.715***	−3.231***	−17.657***	−24.424***
	Inverse logit t (469)	L^*	−84.583***	−3.253***	−22.444***	−28.594***
	Modified inv. chi-squared	Pm	144.017***	2.240**	33.576***	42.361***
Constant + trend	Inverse chi-squared (186)	P	2,529.604***	120.003	637.920***	1,367.823***
	Inverse normal	Z	−38.581***	5.162	−12.068***	−29.683***
	Inverse logit t (469)	L^*	−71.757***	4.477	−15.045***	−39.018***
	Modified inv. chi-squared	Pm	121.510***	−3.757	22.978***	61.275***

Note: Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B.2: Unit root tests for Saturday

Saturday			Residential	log(DailyNewPositives)	Retail & Recreation	Grocery & Pharmacy
Augmented Dickey–Fuller tests						
Constant	Inverse chi-squared (186)	P	683.786***	508.403***	574.446***	2,144.656***
	Inverse normal	Z	−14.633***	−12.400***	−14.180***	−39.216***
	Inverse logit t (469)	L^*	−17.758***	−12.960***	−15.281***	−61.015***
	Modified inv. chi-squared	Pm	25.809***	15.961***	19.722***	100.907***
Constant + trend	Inverse chi-squared (186)	P	465.506***	331.134***	418.814***	2,713.516***
	Inverse normal	Z	−7.610***	−6.326***	−9.252***	−45.012***
	Inverse logit t (469)	L^*	−9.134***	−6.531***	−9.796***	−77.605***
	Modified inv. chi-squared	Pm	14.492***	6.962***	11.738***	130.244***
Phillips–Perron tests						
Constant	Inverse chi-squared (186)	P	1,307.700***	241.961**	373.736***	945.736***
	Inverse normal	Z	−24.162***	−3.435***	−8.896***	−22.889***
	Inverse logit t (469)	L^*	−36.295***	−3.502***	−8.880***	−26.856***
	Modified inv. chi-squared	Pm	58.157***	2.435***	9.426***	39.391***
Constant + trend	Inverse chi-squared (186)	P	1,027.692***	126.959	239.843***	1,242.647***
	Inverse normal	Z	−17.737***	4.882	−3.359***	−27.002***
	Inverse logit t (469)	L^*	−26.561***	4.084	−3.348***	−35.296***
	Modified inv. chi-squared	Pm	43.640***	−3.404	2.557***	54.785***

Note: Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.