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The Tortoise and the Hare: The Race between Vaccine Rollout and New Covid Variants

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Abstract

New variants of the virus are spreading which, together with seasonal effects, are estimated to be able to raise effective reproduction numbers by up to 90%. Meanwhile, many countries are rolling out vaccination programmes, but at varying speeds. Hence the race is on to beat the variants with the vaccines. Vaccination is very powerful at reducing virus transmission: fully vaccinating 20% of the population is estimated to have the same effect as closing down public transport and all-but-essential workplaces; fully vaccinating 50% of the population would have a larger effect than simultaneously applying all forms of containment policies in their most extreme form (closure of workplaces, public transport and schools, restrictions on travel and gatherings and stay-at-home requirements). For a typical OECD country, relaxing existing containment policies would be expected to raise GDP by about 4-5%. Quick vaccination would thus help limit the extent to which containment policies need to be escalated in future epidemic waves, providing huge welfare benefits both in terms of fewer infections and stronger economic activity.

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1. Introduction

The ever-growing body of the literature has been providing insights with regard to the effect of individual lockdown and other public health policies on the reproduction rate and economic outcomes. There is now much research to suggest that containment policies are associated with a reduction in infections, in COVID-19-related deaths and in reproduction numbers (Conyon et al., 2020; Gros et al., 2020). However, there is disagreement as to which interventions are most effective, with different studies emphasising different polices. Some research suggests that stay-at-home requirements are most effective in curbing the propagation of the virus (Esra et al., 2020; Gapen et al., 2020; Spiegel and Tookes, 2020; Chernozhukov et al., 2020). A recent survey concludes that a majority of papers find significant effects of school closure on the spread of the virus (Walsh et al., 2020). School closure is found to be particularly effective by Liu et al. (2020) and Olczak et al. (2020). Chernozhukov et al. (2020) argue the effect is uncertain, whilst Spiegel and Tookes (2020) find no effect. Some studies find that limiting potential 'super-spreader' events -- such as NBA and NHL games in the United States, football matches in England or gatherings more generally -- are a very effective way of reducing the spread of the virus (Ahammer et al., 2020; Chen et al., 2020; Hunter et al., 2020; Olczak et al., 2020; Weber, 2020; Li et al., 2020). Other studies emphasise the importance of travel restrictions, particularly on international flights and at the early stages of the pandemic (Hubert, 2020; Keita, 2020, Leffler et al., 2020).

The elderly population is especially vulnerable to COVID-19 with much higher mortality rates than other demographic groups. A particular concern is that at the early stages of the pandemic, mortality rates were alarmingly high in long-term care facilities (LTCFs) in some OECD countries (ECDC, 2020b; Gandal et al. 2020). Evidence from influenza outbreaks as well as the current pandemic suggests that improving hygiene, including regular hand sanitising and disinfection at the establishment level (Koshkouei et al., 2020), as well as limiting the migration of staff across different care homes, help to reduce infection rates substantially (Koshkouei et al., 2020; Chen et al., 2020), although the latter may be difficult given widespread staff shortages. Recent work at the country level also underlines the importance of protecting the elderly (Égert et al, 2020).

The effectiveness of testing and tracing crucially depends on correctly and speedily identifying contact persons and on compliance with isolation orders (Hellewell et al. 2020). Empirical evidence, exploiting an administrative mistake in contact tracing in England, indicates potentially massive effects from timely contact tracing (Fetzer and Graeber, 2020). Testing and tracing appears to work well in countries with good social security and in particular high coverage of paid sick leave in case isolation is needed. This effect has been shown for earlier influenza episodes as well (Pichler et al., 2020). It has been argued that repeated mass testing coupled with the isolation of the infected could eradicate the virus without reliance on contact tracing (Taipale, Romer and Linnarsson, 2020).[2]

A recent review of about 50 studies on the effectiveness of facial coverings in the community concluded that they have a "*small to moderate effect*" in preventing the spread of COVID-19 (ECDC, 2021). Measuring the health effect of facial coverings in multi-country empirical studies is difficult, because they depend on the take-up rate and it is difficult to account for the greater tendency to wear face masks, regardless of policy pronouncements, in some (mostly Asian) countries prior to the current virus outbreak. Nevertheless, some cross-country studies have identified important negative effects on mortality (Esra et al., 2020, Leffler et al., 2020, Hatzius et al., 2020) and the reproduction number (Égert et al., 2020). Beneficial effects of

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[2] China has demonstrated the potential for mass testing in the city of Wuhan in May 2020, with up to 1.5 million tests being processed in a single day (New York Times, 2020). Mass antigen testing has been considered a success in Slovakia, where the reproduction number declined by 0.3. Nevertheless, such a strategy can work in the longer term only if mass testing is repeated at regular intervals (Kahanec et al., 2021).

mask wearing on mortality are also reported at the regional level in the United States (Hatzius et al., 2020, Welsch, 2020; Spiegel and Tookes, 2020) and Germany (Mitze et al., 2020).

Containment policies are also found to depress economic activity, for example König and Winkler (2020) and Gros et al. (2021) find a strong link between the overall stringency of containment policies and quarterly GDP growth rates. In terms of specific policies, workplace closure is often found to have the strongest link with GDP, with stay-at-home requirements and school closures having weaker links (Chen et al., 2020; Demirguc-Kunt et al., 2020; Kok, 2020). Other containment policies are less often singled out, although it is clear that international travel restrictions have more severely impacted those countries that are more reliant on travel and tourism. The GDP costs of containment measures must be understood in a short-run/immediate sense, because from a longer-run perspective, there may be no cost to containment policies if they prevent an epidemic from spreading, which would lead to larger GDP costs later on via either spontaneous changes in behaviour or the need for harsher containment measures. A recent study that attempts to take epidemiological dynamics into account indeed finds little output costs to additional containment polices that reduce deaths (Arias et al., 2021).

The contribution of the paper is manifold. First, using OECD country experiences from the beginning of 2020 to mid-May 2021 it evaluates policy impacts for a set of policies and not for specific policies in isolation, as it done in much of the literature. Second, the paper studies the importance of vaccination. Many countries around the world are now faced with a race to rollout vaccination programmes against potential upsurges in infections caused by more transmissible COVID-19 variants. While mass vaccination should eventually win the race and bring the pandemic under control,[3] the rapid spread of new variants has the potential to cause new epidemic waves in the meantime, requiring further containment policies, which will slow or delay any economic recovery. In these circumstances, the appropriate policy responses, and their dependence on the speed of vaccine rollout. Third, the paper assesses the relative importance of differential variants of the virus as well as seasonal effects. Finally, the paper looks at the economic costs using the OECD Weekly GDP Tracker-

The empirical analysis consists of two equations estimated at high frequency: the first explains the daily evolution of the effective reproduction number, R (representing the spread of the virus), and the second explains a proxy measure of weekly GDP. The estimations make extensive use of a set of COVID-19 policy trackers maintained by the Oxford Blavatnik School of Government (Hale et al., 2020), as well as data on the scale of vaccinations and the prevalence of different variants of the virus.

These equations are then used to explore alternative scenarios that differ according to the speed of vaccine rollout and the infectiousness of new variants of the virus. A feature of all of the scenarios is that the number of infections is on a downward trajectory (i.e. the reproduction number remains below 1). This is because differing OECD country experiences since the start of the pandemic underline the advantage of suppressing the virus rather than pursuing a strategy of stop-and-go mitigation (Aghion et al, 2021). On that basis, the different scenarios consider whether new lockdown measures may be required to offset the effect of more transmissible variants of the virus and the extent to which this can be avoided by a faster vaccination rollout.

The remainder of the paper is organised as follows. Section 2 provides stylised facts. Section 3 describes the data and the estimation method. for the reproduction number and the proxy measure of GDP, as well as the policies and other explanatory variables that influence them in the estimation framework. In section 4, estimation results for the drivers of the reproduction rate are presented for OECD countries, because

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[3] This assumes that a new variant does not prove to be resistant to existing vaccines, although were this to be the case, the hope is that existing vaccines could be modified relatively quickly.

sensitivity analysis suggests that responses from a wider set of countries are very different.[4]. Section 5 reports the determinants of weekly GDP. In section 6, the estimation results are used to construct a number of stylised scenarios incorporating the prevalence of more transmissible variants, to consider the required setting of containment policies and how this varies with the proportion of the population that are vaccinated. Section 7 summarises the results.

2. Stylised facts

The median R estimate for OECD countries fell rapidly from around 2¼ in early March 2020 to around 0.75 the next month and has since fluctuated in the 0.75 to 1.50 range (Figure 1, panel A). Reasons behind these fluctuations include seasonal effects, the probably premature lifting of restrictions in the summer of 2020 and the delayed and muted policy reaction to the surge of the virus in the Autumn of 2020. Another reason is the ebb and flow of mutations in the virus. For instance, the emergence of the so-called UK or alpha variant (B.1.1.7) in the fall of 2020, first in the United Kingdom and then in many other countries, was a major factor behind the increase in R in the first quarter of 2021 (Figure 1, panel B).
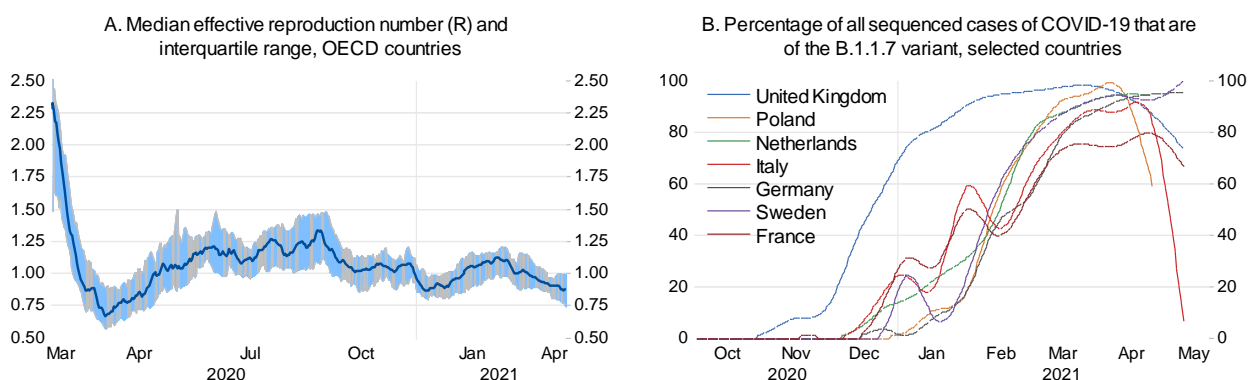
The OECD Weekly Tracker of GDP growth, developed by OECD (2020b) and Woloszko (2020a and 2020b)[5] shows a large drop and quick recovery in 2020. The median weekly GDP tracker for OECD countries also shows that output has been about 5% below the no-pandemic counterfactual in late 2020 and much of 2021 (Figure 2).

The question that needs to be raises is how the typical policy response with regard to containment measures has evolved since the start of the pandemic. A cursory examination would suggest that among OECD countries, more recent responses have been characterised by less resort to the most stringent implementation of school closures, workplace closures, international travel restrictions and stay-at-home requirements, but more stringent restrictions on gatherings (Figure 3). Different waves of the virus have, however, hit countries at different times, so in order to define a typical policy response, a focus here is on all OECD European countries on the assumption that the timing may be more similar. Typically, policy response during the first wave contained hard lockdown measures such as stay-at-home requirements and workplace closures, whereas policies have been shifted towards less binding measures including mandatory mask wearing and to the scaling up test, trace and isolate policies amd the roll-out of vaccination programmes.

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[4] For example, many of the main containment measures (such as workplace closures and stay-at-home requirements) have much weaker effects on the reproduction number in non-OECD countries than OECD countries, perhaps reflecting weaker social security nets and/or more limited possibilities to work remotely.

[5] applies a machine learning model to a panel of Google Trends data, aggregating together information about search behaviour related to consumption, labour markets, housing, trade, industrial activity and economic uncertainty to provide estimates of the growth rate of weekly GDP compared to a year earlier.

Figure 1. Reproduction number and emergence of the B.1.1.7 variant

A. Median effective reproduction number (R) and interquartile range, OECD countries

B. Percentage of all sequenced cases of COVID-19 that are of the B.1.1.7 variant, selected countries

Source: Arroyo Marioli, F. et al. (2020), "Tracking R of COVID-19: A New Real-Time Estimation Using the Kalman Filter"; Hodcroft, E.B. (2021), "CoVariants: SARS-CoV-2 Mutations and Variants of Interest" and authors' calculations.

Figure 2. A weekly measure of OECD GDP

Median and interquartile range, % difference from a no-pandemic counterfactual
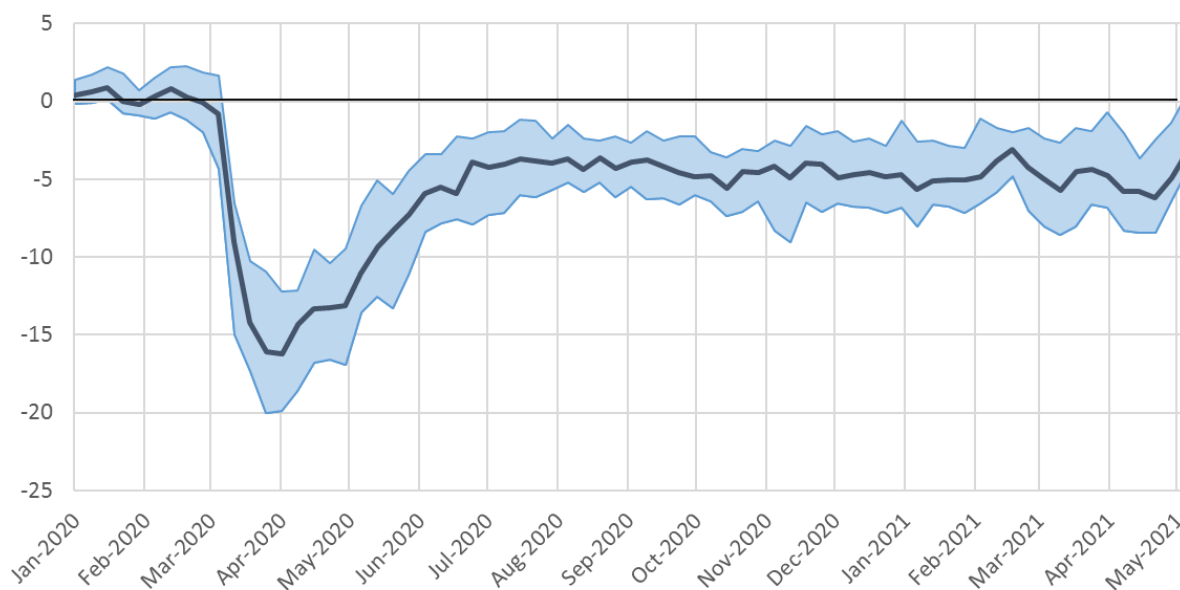
Note: The chart shows the difference between the proxy measure of weekly GDP and a no-pandemic counterfactual projection provided by *OECD Economic Outlook* No. 106 (November 2019).
Source: OECD Weekly Tracker site: http://www.oecd.org/economy/weekly-tracker-of-gdp-growth/

3. Data and estimation issues

The empirical analysis relies on a set of variables representing containment measures maintained by the Oxford Blavatnik School of Government (Hale et al., 2020), which in their original form are scored according to the degree of stringency or comprehensiveness with which they are applied. Eight categories of containment measures are distinguished, being variously scored from 0 to 2, 0 to 3, or 0 to 4 (Table 1). The scoring of measures refers to their design, not necessarily how they have been applied. This

represents a potential weakness as the variables do not capture how enforcement and abidance by regulations has varied across countries.

For the purposes of estimation, the cardinal value of these scores are ignored (as there is no reason, for example, to expect a policy with a stringency value of 3 to have treble the effect of a policy with a value of 1) and instead the same policy at different levels of stringency are included as distinct dummy variables (taking the value of zero or one). Subsequently, if the estimation does not deliver the expected ordinal ranking in coefficients (so that a more stringent application of a policy has a greater effect), the same coefficient may be imposed across different levels of stringency by combining policy variables.[6] For school closures, an indicator produced by UNESCO and measuring whether schools and universities are partially or completely closed due to COVID-19 is used in the empirical analysis instead of the one by the Oxford Blavatnik School of Government.

Table 1. Definition of different stringency levels for containment policies

Containment measure	Scoring of degree of stringency
School closures	1: Partial closure due to COVID
	2: Complete closure due to COVID
Workplace closures	1: Recommend closing (or work from home)
	2: Require closing (or work from home) for some sectors or categories of workers
	3: Require closing (or work from home) all-but-essential workplaces (e.g. grocery stores, doctors)
Cancel public events	1: Recommend cancelling
	2: Require cancelling
Restrictions on gatherings	1: Restrictions on very large gatherings (above 1000 people)
	2: Restrictions on gatherings between 101-1000 people
	3: Restrictions on gatherings between 11-100 people
	4: Restrictions on gatherings of 10 people or less
Close public transport	1: Recommend closing (or significantly reduce volume/route/means of transport available)
	2: Require closing (or prohibit most citizens from using it)
Stay at home requirements	1: Recommend not leaving house
	2: Require not leaving house with exceptions for daily exercise, grocery shopping, and 'essential' trips
	3: Require not leaving house with minimal exceptions (e.g. only once a week, or one person at a time)
Restrictions on internal movement	1: Recommend not to travel between regions/cities
	2: Internal movement restrictions in place
International travel controls	1: Screening
	2: Quarantine arrivals from high-risk regions
	3: Ban on arrivals from some regions
	4: Ban on all regions or total border closure

Note: Not shown in the table, but "No measures" or "No restrictions" are always scored 0.
Source: Oxford COVID-19 Government Response Tracker described in Hale et al. (2020) and UNESCO's School closures caused by Coronavirus (Covid-19) (unesco.org).

The Oxford COVID-19 Government Response Tracker includes the severity of restrictions on visitors to LTCFs, with the most stringent classification reserved for when all non-essential visitors are prohibited (Table 2). In this paper's empirical framework, facial coverings are investigated using the Oxford COVID-19 Government Response Tracker indicators, which denote the strength of government mandates in this regard. The empirical work will investigate the effect of the protection of the elderly.

To capture the effect of test and trace policies, the policy indicators from the Blavatnik School of Government at the University of Oxford (Hale et al., 2020) are used (Table 2). Again, for the purpose of

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[6] Multicollinearity, implying problems in being able to separately identify coefficients on different explanatory variables, is a concern given that containment measures were often introduced simultaneously or very close together. Earlier work, estimating similar equations over a shorter sample to mid-2020 (Égert et al. 2020), suggested there was collinearity between some of the main containment policies associated with lockdown, however this is much less apparent over a longer sample period.

the estimation work, the cardinal values of the trackers are ignored and instead different dummy variables are used to represent test-and-trace variables at different degrees of comprehensiveness. Many aspects of testing and tracing may be easier at low infection levels and this can be readily tested in the empirical framework. However, an important limitation of these indicators is that they do not capture timing or speed, which can be key to a successful strategy: test results must be returned with minimum delay and then contacts need to be traced quickly. A further important limitation of these indicators is there is no information on the extent to which test and trace polices are followed up with measures to isolate those infected or potentially infected.

Table 2. Public health policies against COVID-19

Protection of elderly people
1: Recommendations regarding isolation, hygiene and visitor restrictions in Long-term Care Facilities (LTCFs) and/or elderly to stay at home.
2: Narrow restrictions for isolation, hygiene and visitor restrictions in LTCFs and/or restrictions protecting elderly people at home.
3: Extensive restrictions for isolation, hygiene in LTCFs, all non-essential external visitors prohibted, and/or elderly required to stay at home with minimal exceptions and no visitors.
Testing policy[1]
1: Only those who both (a) have symptoms AND (b) meet specific criteria (e.g. key workers, admitted to hospital, came into contact with a known case, returned from overseas)
2: Testing of anyone showing COVID-19 symptoms
3: Open public testing (e.g. "drive through" testing available to asymptomatic people).
Contact tracing
1: Limited contact tracing - not done for all cases
2: Comprehensive contact tracing - done for all identified cases.
Facial coverings
1: Recommend
2: Required in some specified shared/public spaces or some situations when social distancing not possible
3: Required in all specified shared/public spaces or all situations when social distancing not possible
4: Required outside the home at all times

Note: Not shown in the table, but "No measures" or "No restrictions" are scored 0.
(1) Testing variable relates to policies testing for infection (PCR test), not to policies testing for immunity (antibody tests).
Source: Oxford COVID-19 Government Response Tracker described in Hale et al. (2020).

Data on vaccination rates are taken from Our World in Data. The estimation results do not differentiate between the different vaccines, although there is some evidence to suggest that some vaccines -- such as the SINOVAC vaccine which, among OECD countries, has been approved in Chile, Turkey, Mexico and Colombia – has lower efficacy than other vaccines commonly used in OECD countries, especially after only one shot (Figure 3).[7]

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[7] The speed with which vaccination programmes are being rolled out varies greatly across OECD countries. By end-May, there were five countries where more than 50% of the population had received at least one vaccine done, but also five countries where this share had not reached 20%.

Figure 3. Vaccination rates vary greatly across OECD countries

Per cent of population vaccinated as of end-May 2021
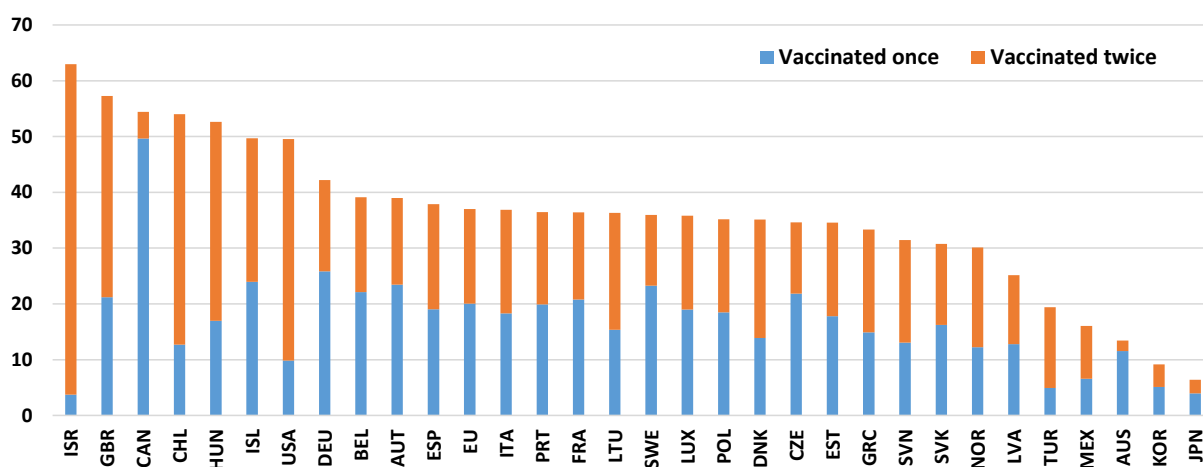
Source: Official data collated by Our World in Data. Some OECD countries are missing because the data do not allow splitting vaccination status between one and two doses.

The empirical work considers mutants of the virus that have had widespread prevalence in the estimation sample as well as the recent Indian variant. Data on the prevalence of different variants are from the GISAID database via the website Covariants.org. The series measure the proportions of all virus sequences (not cases) submitted to GISAID classified as a specific variant. The names for the variants refer to the Pango Lineage nomenclature. B.1.1.7 is commonly referred to as the UK variant. Other variants considered (B.1.258, B.1.160 and B.1.177) have all been highly prevalent in at least a few OECD countries. The more recent Indian variant (B.1.617) is also considered

4. Explaining the reproduction number

Regression analysis is used to relate country-level daily reproduction numbers to several potential explanatory factors, including containment policies, public-health policies, seasonal conditions, the prevalence of variants, vaccination rates as well as proxies for spontaneous behavioural changes and natural immunity. In addition, the estimated equation includes a full set of country fixed effects to account for fixed country characteristics (such as population density, general social habits, etc.) that could affect virus transmission. This means that identification relies on variation of reproduction numbers and other variables in the time dimension.

Unlike many other studies that focus on a single explanatory factor, the approach used here has the advantage of considering all of the above factors at once within the same framework and using a large amount of daily data from several countries. Nevertheless, the approach is not able to identify causal policy effects, as many of the explanatory variables are not independent from the reproduction number. For instance, containment and other policies are taken in response to the evolution of the pandemic. Identifying pure causal effects would require exogenous sources of policy variation (e.g. natural experiments) or the use of instrumental variables, if good instruments could be found.

An important feature of the estimated equation explaining R is that the preferred functional form for the dependent variable is logarithmic; a formal test decisively rejects a linear form in favour of a logarithmic

one.[8] This implies that any policy intervention will have a larger effect when R is initially high than when it is low.

4.1. Containment policies

In the estimation, the coefficients on six containment policies -- workplace and school closures, restrictions on gatherings, stay-at-home requirements, international travel controls and closures of the public transport system -- are found to have a statistically significant effect in reducing R (Table 3, Figure 4).

- The largest effects come from the most stringent application of workplace closures, which reduce logged R by 0.27 (which from an initial R number of 1.5, implies an absolute fall in R of 0.35). Resort to such stringent policies have, however, been very infrequent. Also rare is the accompaniment of workplace closures with a complete closure of the public transport system, which in combination reduces logged R by 0.37.
- Tight restrictions on gatherings and stay-at-home requirements have been widely applied across most OECD countries and are estimated to reduce logged R by up to 0.15 and 0.13, respectively.
- Complete closure of schools, which OECD countries have been more reluctant to impose since their widespread imposition in dealing with the first wave of the virus in the first half of 2020, reduce logged R by 0.13.
- International travel restrictions are estimated to reduce logged R by up to 0.12, although this may underestimate their importance in preventing the spread of new variants of the virus and in sustaining a situation in which the national rate of infections is much lower than in other countries.

The estimated equation suggests that tightening the stringency of policies increases their effectiveness, although not always in a linear fashion (Figure 6). The finding of stronger effects from more stringent application of containment policies contradicts the findings of Bendavid et al. (2021), who conclude that more restrictive containment policies do not have a significantly greater impact on the growth of infections.

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[8] Testing the appropriate functional form of the dependent variable is not as straightforward as testing for the functional form of explanatory variables because the competing models cannot be nested within a general model. The test is therefore conducted by first transforming the dependent variable by dividing by its geometric mean to make the two competing models (log and linear) comparable. A formal test of model equivalence can be performed with the BoxCox statistic by comparing the relative goodness-of-fit of the two models. The test decisively favours the logarithmic form for R over different country samples. Conversely, when a similar test is carried out for the weekly GDP equation, the linear form is decisively preferred to the logarithmic form.

Table 3. The drivers of the effective reproduction number, OECD countries

Sample period: 15 January 2020 to 16 May 2021

Dependent variable: ln(R)	
Constant	0.6999**
Containment policies	
Stay-at-home requirement (=1 & 2)	-0.0755**
Stay-at-home requirement (=3)	-0.1293**
Workplace closures (=1)	-0.1036**
Workplace closures (=2)	-0.1987**
Workplace closures (=3)	-0.2666**
Closure of public transport(=2) & workplaces (=3)	-0.1005**
School closures (=2)	-0.1327**
Restrictions on gatherings (=1 & 2)	-0.0494**
Restrictions on gatherings (=3)	-0.1139**
Restrictions on gatherings (=4)	-0.1481**
International travel controls (=3)	-0.0932**
International travel controls (=4)	-0.1235**
Test and Trace policies	
All Test & Trace combinations	0.0217
All Test & Trace combinations when deaths < 10 per million	-0.0612**
Other non-containment policies	
Facial coverings (=3 & 4)	-0.0157**
Protection of the elderly (=3)	-0.0403**
Seasonal effect	
Hours of daylight	-0.0203**
Death rates (per million population)	
Daily national death rate	-0.0172**
Daily global death rate	-0.1338**
Total national death rate	-0.0001**
Vaccination rates (% of population)	
Vaccinated once(-28)	-0.0054**
Vaccinated twice(-28)	-0.0181**
Prevalence of virus variants (% of cases sequenced)	
B.1.177	0.0014**
B.1.160	0.0009**
B.1.258	0.0043**
B.1.1.7 ('UK variant')	0.0035**
B.1.617 ('Indian variant')	0.0006
Adjusted R-squared	0.476
Daily observations	14167
Countries covered	35

Note: The policy variables are based on the variables described in Table 1and Table 2, but re-normalised to be (0, 1) dummy variables as described in the main text. The notation in brackets "(=n)" after a containment policy variable denotes that the dummy variable is assigned a 1 if the original score for that policy was equal to n, whereas the notation "(>=n)" denotes that the dummy variable is assigned a 1 if the original score for that policy was greater than or equal to n. "**" denotes statistical significance at the 5% level, based on heteroscedasticity-robust standard errors. The equation includes country fixed effects, which are not reported here. The dependent variable (R) has a lead of 12 days relative to the explanatory variables, to account for the delay between infection and case detection.
Source: Authors' calculations.

Figure 4. Estimated effects of policies and natural caution on logged R

A. Effect on logged R
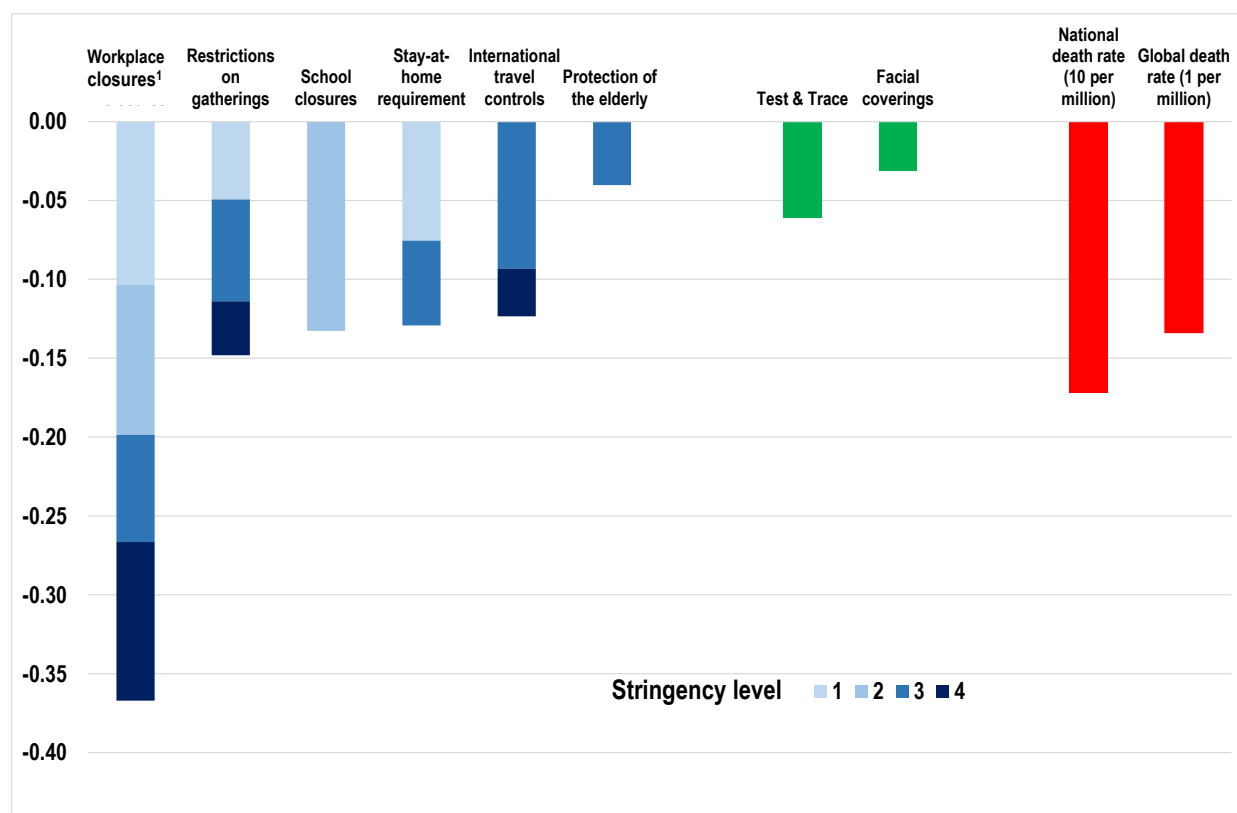
Note: The chart shows the estimated effect on logged R of different containment policies at varying degrees of stringency, the effect of policies relating to test-and-trace and facial coverings as well as the effect of increased natural caution, proxied by the daily death rate. If a particular degree of policy stringency is not shown in the bar chart, then it either means there is no significant effect on GDP (this being the case when bar segments at a higher level of stringency are shown), or that it has the same effect as the policy at the previous level of stringency (when bar segments at a lower level of stringency are shown). The effect of the test-and-trace and facial coverings are the maximum effect, which in the former case depend on a low level of infections.
1) Workplace closures have a maximum stringency level of 3 according to the Oxford taxonomy, but are shown here as having a maximum stringency level of 4 when combined with a complete closure of public transport. Full closure of public transport is not shown separately because it has only rarely been applied and then in combination with full workplace closure and this is also reflected in the estimation.
Source: OECD calculations based on estimations reported in Table 3.

4.2. Public health policies

The implementation of test and trace policies is found to reduce R, but the effects are relatively small. It is also difficult to distinguish the size of effects according to the comprehensiveness of the policy, so in the estimated specification the same coefficient applies to all combinations of test and trace stringencies. This result may be attributable to differences in how quickly and successfully test and trace policies are applied, as explained previously. All test and trace policies are found to be much more effective when the infection rate is low (which in this estimation is taken to be less than ten new daily cases per million population, a rate which many countries had well exceeded already in March and April 2020). This is a rather unsurprising finding, given the difficulties of tracking down all contact persons in a timely manner if the system is overwhelmed with new cases.

Recommendations to make facial coverings mandatory in public are found to reduce the spread of the virus, but the estimated effects are small, lowering logged R by less than 0.02. This result -- possibly explained by inadequate compliance, improper mask wearing and the fact that many infections take place in family settings where masks are impractical -- is consistent with the recent review of about 50 studies, referred to above, that concluded the use of facial coverings in the community have a "*small to moderate effect*" in preventing the spread of COVID-19 (ECDC, 2021).

The most stringent interventions to protect the elderly, involving prohibiting all non-essential visitors from LTCFs, are found to reduce the spread of the virus, but the effects are relatively small, reducing logged R by about 0.04. However, this understates the importance of such measures given that the elderly are much more vulnerable to serious illness once infected.

Vaccination is found to reduce the reproduction number substantially. The percentage of the population having received either one or two doses of vaccine enters the equation with a lag of four weeks, to account for the gradual build-up of immunity after vaccination. The estimated coefficients imply that each percentage point of the total population that is fully vaccinated lowers logged R by 0.018. Hence, fully vaccinating only 7% of the population reduces logged R by the same amount as closing down schools and fully vaccinating 20% of the population is as powerful as closing all-but-essential workplaces and public transport (Figure 53). Once 60% of the population has received two doses, as in Israel at the end of May 2021, then logged R is reduced by about 1.1. The results imply that two doses are much more effective at reducing transmission than a single dose, but the second-dose effect may also include some delayed immunity from the first dose.

Figure 53. The powerful effect of vaccination

Equivalency between estimated effects of selected containment policies and percentage of population fully vaccinated
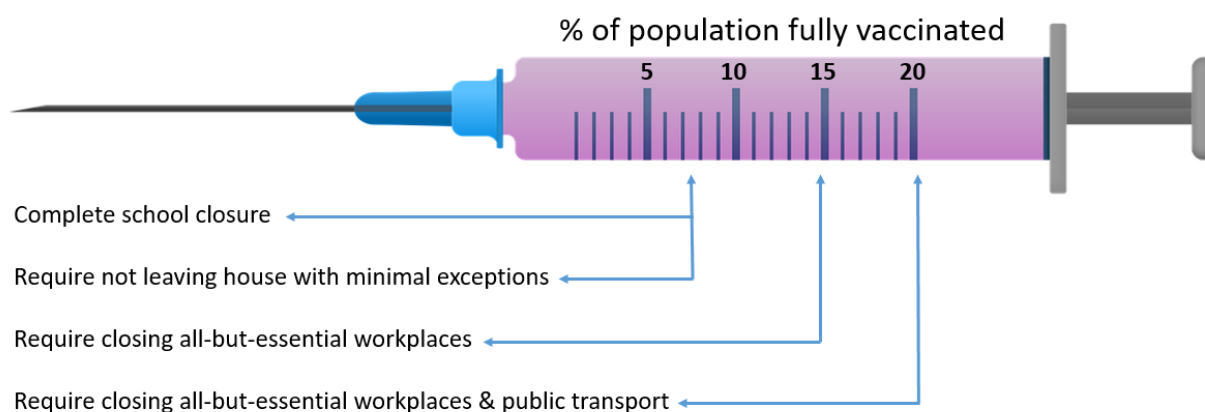
Note: The figure is based on the coefficient estimates reported in Table 3.

4.3. Non-policy effects: Awareness of the virus and transition towards herd immunity

Voluntary social distancing and increased personal hygiene measures, such as increased handwashing, are important in containing the spread of the virus (Caselli et al., 2020). In some cases, voluntary behavioural changes preceded the implementation of containment measures (Audirac et al., 2020) and in some cases their effects might even have been superior to those of official containment policies (Berlemann and Haustein, 2020; Goolsbee and Syverson, 2020; Gupta et al., 2021).

In order to capture voluntary behavioural responses, the regression analysis includes different measures of the death rate from the virus (national and global daily deaths per million population) as proxies for general awareness of the pandemic prompting more cautious behaviour. The importance of these variables is that they substitute for changes in behaviour that are likely to be engendered regardless of government-mandated restrictions.

Total national deaths attributed to the virus, expressed as a share of the population, are also separately included as a proxy for the share of the population that has previously been infected, with the expectation of a negative coefficient: as the share of the population that has been infected rises (and presumably becomes immune), the speed with which the virus spreads should be reduced.

The death rate variables are statistically significant with the expected negative sign and their magnitudes imply they can play an important role in the evolution of R.

- The national daily death rate varies substantially, both across countries and over time, but for some OECD countries it was running at well over 10 per million going into the first lockdown in March 2020 and has exceeded this threshold in some countries in recent months. At such levels, the estimated coefficient implies precautionary behaviour to such an extent that that the reduction in R is larger than most of the containment policies implemented in isolation (Figure 4).
- The global daily death rate has exceeded 1 per million since November 2020, and the estimated coefficient implies this would further supplement this precautionary effect by reducing logged R by about 0.13.
- The coefficient on the total national death rate (i.e. based on cumulative deaths) is surprisingly small, implying that even in those OECD countries which have experienced the highest death rates of over 1 000 per million population, logged R would only be reduced by about 0.1.

4.4. Non-policy effects: Seasonal conditions

The global nature of the pandemic indicates that the virus can spread all over the world irrespective of seasonal conditions. Review papers trying to distil the several hundreds of studies analysing the potential seasonality of Coronavirus transmission struggle to come to a clear conclusion.[9] Some evidence suggests that increased UV light exposure bears a stronger relation to transmission than temperature or humidity (Merow and Urban, 2020).[10] For the purposes of this paper, seasonal effects (whether due to weather, behavioural changes or other factors) are proxied by a measure of daylight hours. For the median OECD country, the number of daylight hours varies by around seven hours between winter and summer and by up to 13 hours in some Nordic countries such as Finland, Norway or Sweden. The estimated coefficient implies that this would produce a seasonal variation in logged R of between 0.15 and 0.25. Climatic variables, including temperature, were found to generate similar seasonal variation, but multicollinearity between the different measures precludes the inclusion of more than one such variable.

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[9] Papers summarised in Mecenas et al. (2020) connect warm and wet weather with reduced virus transmission, the papers reviewed in Briz-Redon and Serrano-Aroca (2020), Shakil et al. (2020) and Paraskevis et al. (2021) provide more mixed evidence.

[10] For European countries, Walrand (2021) identifies UV light as the only climatic factor explaining COVID-19 outbreaks. UV light exposure is strongly correlated with daylight hours, which determines time spent indoors and the emergence of vitamin D deficiency, which is thought to amplify the severity of COVID-19 (Weir et al., 2020).

4.5. Prevalence of virus variants

Relative to the original strain of the virus, to which the estimated constant assigns a basic reproduction number (R0) of about 2.0, four variants are found to increase the effective reproduction number substantially.

- The B.1.177 variant initially expanded in Spain and spread widely across Europe via holiday travel (Hodcroft et al., 2021). In the summer of 2020, it became the most prevalent variant in western Europe.
- The B.1.160 variant became the second most dominant variant in western Europe over the northern-hemisphere summer of 2020, after variant B.1.177.
- The B.1.258 variant first circulated widely in Ireland in August 2020 and later on in central Europe, particularly the Czech Republic and Slovenia.
- The B.1.1.7 variant, commonly referred to as the 'UK variant' because it appears to have arisen and/or initially expanded in the South East of England, became the dominant variant in many European countries during the first quarter of 2021. It has since been found throughout the world, notably the United States where it was the most prevalent variant according to the latest data.

Each of these variants is estimated to raise the logged reproduction number by between 0.01 and 0.04 for each percentage point of all cases sequenced attributable to it. If prevalence of the B.1.1.7 variant became 100%, for instance, then the effective reproduction number would be 2.9 instead of 2.0, a result consistent with Davies et al. (2021), who find that the UK variant is 43% to 90% more transmissible than the original strain of the virus. The B.1.617 (aka Indian) variant is included in the estimated equation but its impact on the reproduction number is not statistically significant, most likely because prevalence was still very low in most OECD countries even toward the end of the estimation period.

5. Explaining weekly GDP over the pandemic period

Estimation results suggest that six of the eight categories of containment policies have a negative short-run effect on GDP and a fiscal stimulus variable is found to have a significant positive effect (Table 4). Sensitivity testing suggests that there has been some decline in the (negative) GDP effects of containment policies over time, distinguishing between the first half of 2020 and the period since then. These differences are most significant for restrictions on gatherings and on internal movement (see the second column of Table 4).

The sensitivity of the estimation results to different sample periods is examined by maintaining a preferred specification estimated over the full sample period as a reference point, but then re-estimating it adding a time dummy (taking the value of 1 after the start of July 2020) interacted with each of the containment policy variables. Most of the interaction terms are found to be positive, although only those that are also statistically significant are reported in the second column of Table 4. A revised (and reduced) policy effect can then be computed over the second half of the sample by summing the coefficients estimated over the full sample with the corresponding coefficient interacted with the period dummy variable. When a similar procedure was followed for the R equation, it was difficult to discern any meaningful systematic pattern in the interaction coefficients, which were more often small and statistically insignificant. So, for this reason, it was decided to retain the R equation estimated over the full sample, not least no minimise problems of multicollinearity.

Focussing on the effect over the last year of the most stringent application of each of the containment policies suggests a clear ranking of policies in terms of their adverse effect on GDP, with workplace closures having the largest effect on GDP (particularly in the extreme case of being accompanied by the

closure of public transport), followed by stay-at-home requirements, with school closures, restrictions on gatherings and internal movement all having a lesser, but significant, cost to GDP (Figure 6).

Table 4. The determinants of weekly GDP

Sample period: Mid-January 2020 to mid-May 2021

	Over entire period	Interacted with dummy from July
Dependent variable: GDP (% difference from counterfactual)		
Constant	-0.0109**	
Containment policies		
Stay-at-home requirement (=1)	-0.0125**	
Stay-at-home requirement (>=2)	-0.0184**	
Workplace closures (=1&2)	-0.0159**	
Workplace closures (=3)	-0.0254**	
School closures (=2)	-0.0116**	
Restrictions on gatherings (>=3)	-0.0257**	0.0146**
Restrictions on internal movement (=1)	-0.0231**	0.0169**
Restrictions on internal movement (=2)	-0.0425**	0.0381**
Closure of public transport (=2) * Workplace closure (=3)	-0.0224**	
Fiscal policy controls		
Structural budget balance (% of GDP)	-0.0015**	
Death rates (per million population)		
Daily national death rate	-0.0075**	0.0079**
Adjusted R-squared	0.656	
Daily observations	2122	
Countries covered	33	

Note: The containment policy variables are based on those summarised in Table 1, but re-normalised to be (0, 1) dummy variables as described in the main text. The notation in brackets "(=n)" after a containment policy variable denotes that the dummy variable is assigned a 1 if the original score for that policy was equal to n, whereas the notation "(>=n)" denotes that the dummy variable is assigned a 1 if the original score for that policy was greater than or equal to n. "**" denotes statistical significance at the 5% level. The structural budget balance variable is taken from the *OECD Economic Outlook* No. 109 database at a quarterly frequency and is converted to a weekly frequency. The coefficients reported in the second column are those that are significant when interacted with a dummy taking the value of 1 from the beginning of July 2020; the effect of these policies from July is then estimated to be the sum of the coefficients in the two columns.
Source: Authors' calculations.

Figure 6. The effect of containment policies on GDP (per cent)

Maximum effect on GDP in period after July 2020
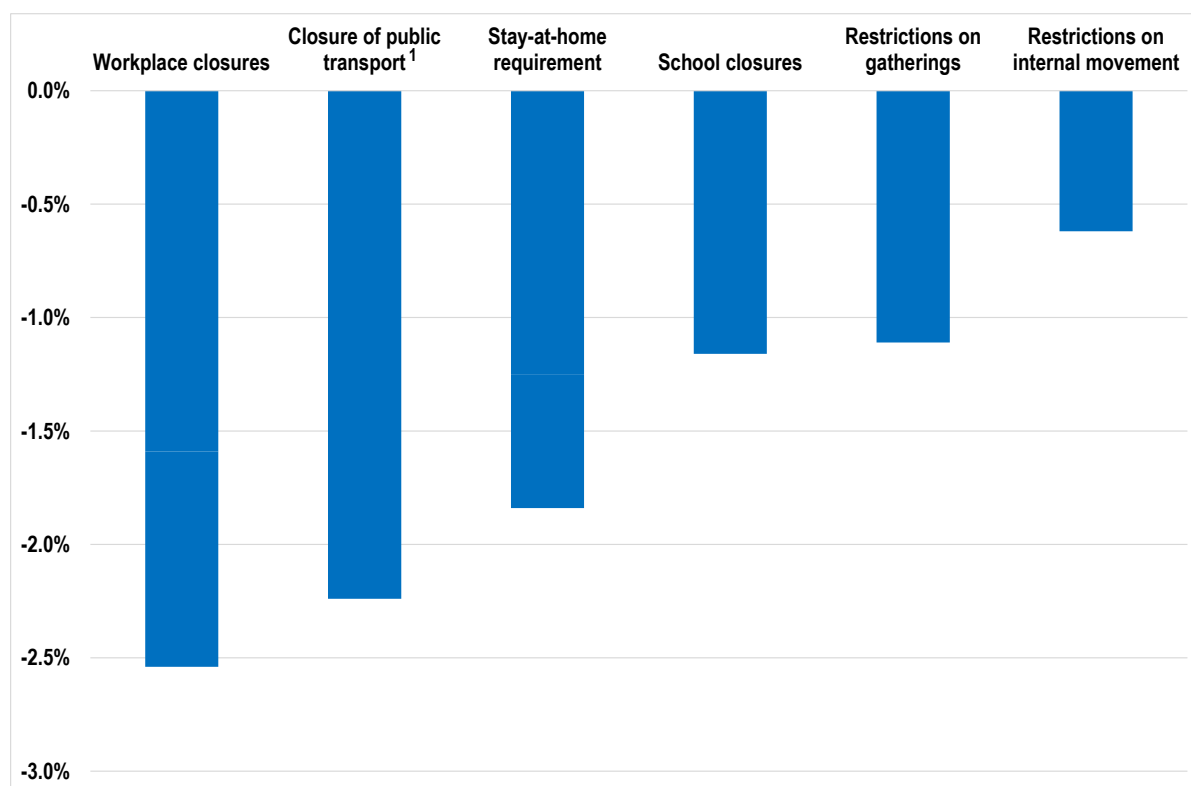
Note: The chart shows the maximum effect on GDP of different containment policies estimated for the period after July 2020.
1) The effect of full closure of public transport is estimated when implemented with full workplace closure.
Source: Authors' calculations based on estimation results in Table 4.

Modelling the effect of international travel restrictions on GDP is more difficult because it depends not only on restrictions imposed by the country in question, but also on the restrictions imposed on travellers by other countries. While international travel restrictions are not included in the equation reported in Table 4, alternative equations suggest the effect on GDP of international travel restrictions is proportional to the importance of tourism in the country.

Fiscal measures are also found to play a role in supporting GDP through the inclusion of the structural budget balance (expressed in per cent of GDP).[11] The estimated coefficient is highly statistically significant and implies a multiplier of about 0.2, which is consistent with much of the fiscal support having taken the form of income support and subsidies.

6. Scenario analysis

The estimations described earlier in the paper are used to construct scenarios that illustrate the benefits of a rapid vaccination rollout, particularly in the face of more contagious strains of the virus. The

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[11] The structural budget balance is a measure of the cyclically-adjusted primary fiscal balance (expressed as a percentage of GDP) and is taken from the most recent quarterly *OECD Economic Outlook* database and is converted to a weekly frequency with interpolation.

assumptions are highly stylised, but nevertheless highlight some of the policy implications of different speeds of vaccination rollout.

### 6.1. Baseline scenario prior to vaccination rollouts and new variants

An initial baseline scenario is constructed to be representative of the position of a typical OECD country during the first quarter of 2021, before either vaccines or new variants were having any significant effect on the spread of the virus, on the following assumptions:

- Containment measures are applied at the median level of stringency observed across all OECD countries during the first quarter of 2021. This implies maximum stringency as regards restrictions on public events, gatherings and internal movement. It also implies some workplace closures as well as stay-at-home requirements, partial school closures and restrictions on international travel, although all these latter measures remain one stringency notch below the maximum specified by the Oxford taxonomy. The overall cost of these measures to the economy is estimated to be about 5% of GDP, which corresponds roughly with the hit to GDP in the median OECD country since the start of 2021.

- All public health measures, including test and trace policies and mandating facial coverings, which might help reduce the spread of the virus, have already been implemented and cannot be made more effective. However, protection for the elderly remains below the maximum level of stringency, so although there are some restrictions on visitors to long-term care facilities, these fall short of prohibiting all non-essential visitors.

- A 'fear factor', proxied by the global and national daily death rates (here assumed to be running at 1 per million and 2 per million, respectively), induces more cautious behaviour which further reduces the reproduction number.

Using the estimation results described in the previous section, the reproduction number implied by the combination of these assumptions is only just below 1.0 (equivalent to log R being below 0) as summarised in Figure 74. The situation represented by the scenario is, however, precarious, with many factors, including seasonal influences, having the potential to push the reproduction number above 1 and so lead to a surge in infections.

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Figure 74. An initial baseline scenario before vaccinations and more transmissible variants

Effect on the logged reproduction number R
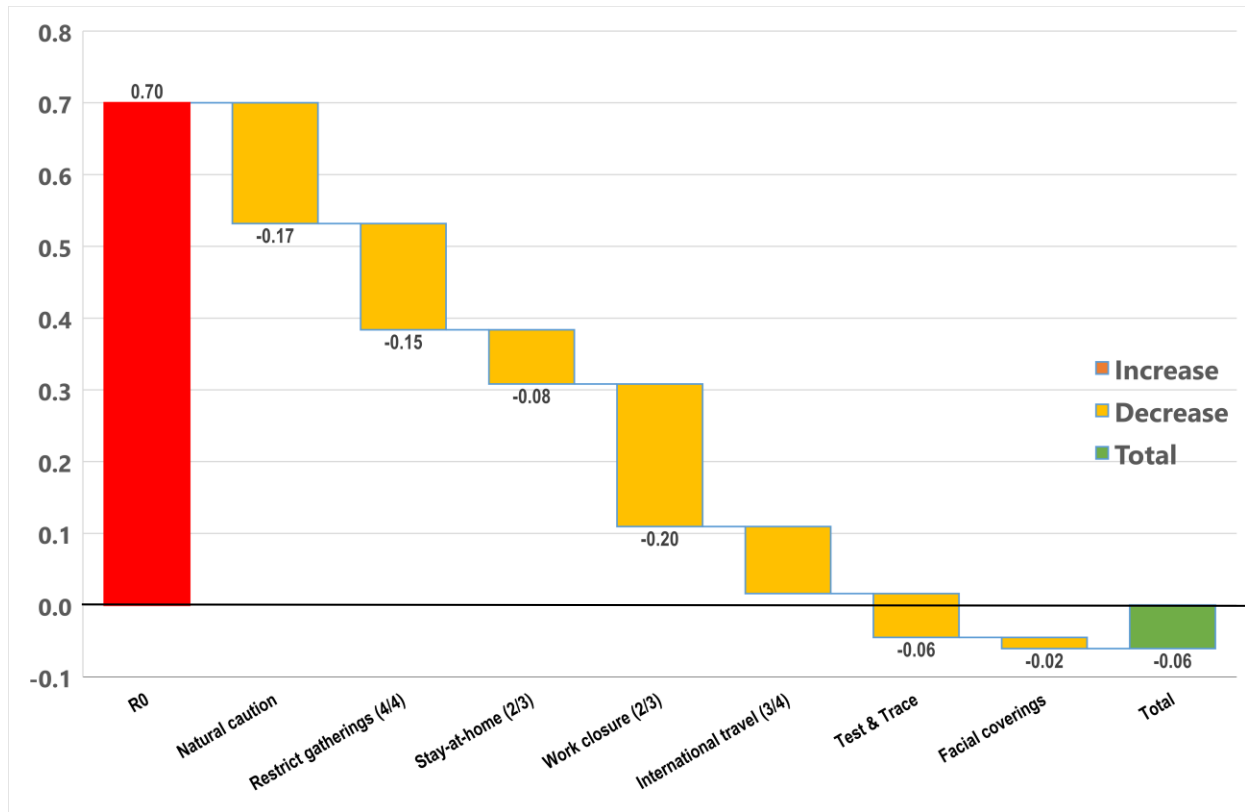
Note: The waterfall chart illustrates the component effects on logged R. The sum of the initial R0 (red bar) and the negative effects of natural caution and policies (yellow bars) give a total estimate for the logged reproduction number (green bar). The (small) negative number for the total logged R implies that R is (just) less than 1. The numbers in brackets after each containment policy (n/N) indicates that corresponding containment policy is assumed to be at stringency level n, compared to a possible maximum stringency level of N. The natural caution effect assumes a global daily death rate of 1 per million and a national daily death rate of 2 per million.
Source: Authors' calculations based on the estimation results in Table 3.

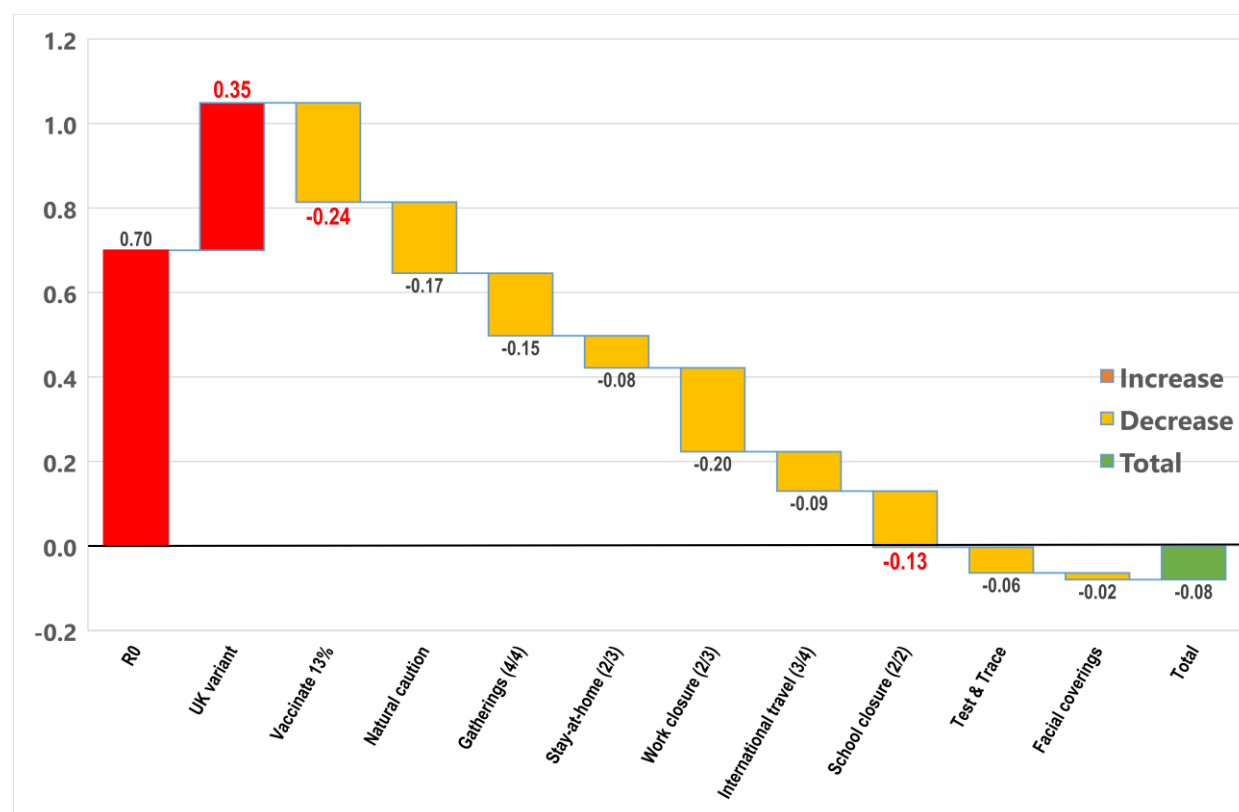### 6.2. Scenario with more contagious new variant and moderate vaccination rollout

The scenarios that follow build on the initial baseline scenario by considering how the situation might develop in response both to more contagious variants and the rollout of vaccination programmes. For this purpose, all scenarios assume that the so-called 'UK variant' becomes predominant, leading to an increase in transmissibility of the virus by 35%. If only 13% of the population have been fully vaccinated, which corresponds to the OECD median in mid-May, then vaccinations would be insufficient to keep the reproduction number below 1. Policy-makers would then face difficult choices about which containment policies to tighten further, given the raft of containment policies already implemented in the baseline scenario. In the scenario summarised in Figure 10, it is assumed that all schools are closed full-time, which would be just sufficient to keep the reproduction number below 1.

Of course, there is considerable uncertainty around the parameter estimates used to construct the scenarios as well as the assumptions underlying them. On the positive side, seasonal factors for many European countries coming into summer could serve to lower the reproduction number, by approximately 15% for a central European country relative to winter. Alternatively, the test, trace and isolation policy now operating in a particular country could be more effective than captured by the average estimate for all countries over the whole pandemic period. On the other hand, a slower vaccination rollout (some OECD

countries had only vaccinated around 5% of the population by mid-May) or even more transmissible variants would only exacerbate the dilemma about which containment policies to tighten; given lockdown fatigue, policy-makers might hesitate to implement the most stringent forms of stay-at-home requirements and the closure of all-but-essential workplaces that might then be required to keep the reproduction number below 1 (Figure 8).

Figure 8. UK variant with limited vaccine rollout

Effect on the logged reproduction number R

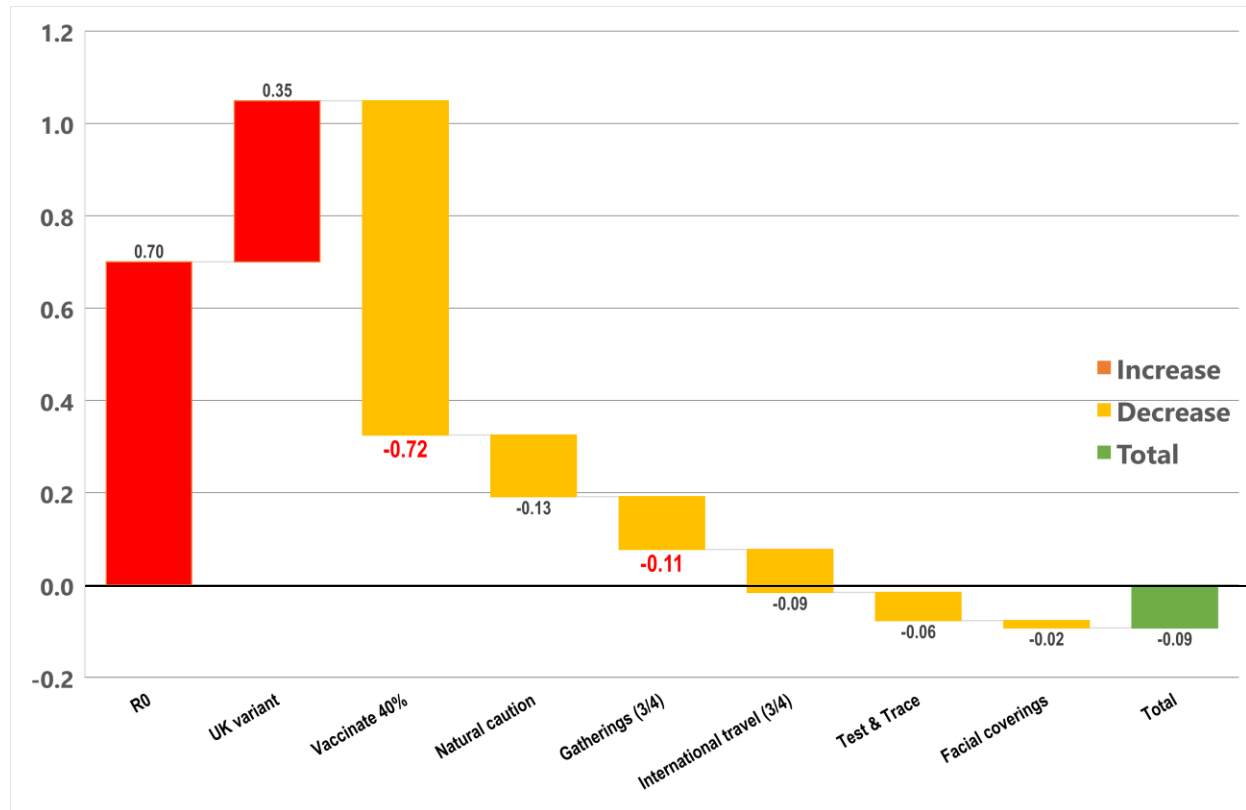Note: See the note to Figure 9. Changes relative to the baseline scenario are highlighted by the red bolded numbers.
Source: Authors' calculations based on the estimation results in Table 3.

6.3. Scenario with more contagious new variant and faster vaccination rollout

A faster vaccine rollout would not only avoid the need to tighten containment polices, but also enable containment policies in the baseline scenario to be progressively relaxed. For example, if 40% of the population were fully vaccinated (which is close to the shares in the United States and United Kingdom at end-May), then there might be no need for any stay-at-home requirements or closure of workplaces and restrictions on gatherings could start to be relaxed, which would raise GDP by 4% relative to the baseline scenario (Figure 9).

Figure 9. UK variant with quick vaccine rollout

Effect on the logged reproduction number R

Note: See the note to Figure 9. Changes relative to the previous scenario illustrated in Figure 10 are highlighted by the red bolded numbers, in addition there is no need for stay-at-home requirements and closure of workplaces, which are consequently excluded from the chart
Source: Authors' calculations based on the estimation results in Table 3.

6.4. Scenario with comprehensive vaccination rollout

The estimates also suggest that, in the absence of any supporting measures, roughly 70% of the population would need to be vaccinated to ensure the reproduction number remains below 1 (Figure 10). While much of the focus has recently been on the speed with which vaccines have been rolled out, achieving such a high overall level of vaccination is likely to be a challenge in many countries, given that some vulnerable groups (such as young children) will not be vaccinated and given the observed slowdown in take-up when vaccination rates reach high levels. Moreover, if other more transmissible variants of the virus become predominant, then the overall required level of vaccination would rise further. This suggests that in some countries, it may be necessary to continue with some public health measures and limited containment measures over the longer term even after large shares of the population have been fully vaccinated.

Finally, it is important that policy-makers are not complacent over the summer as seasonal factors may temporarily contribute to suppressing the reproduction rate and so reduce the urgency to rollout vaccinations. For example, for a typical Central European country, seasonal factors could lower the reproduction rate by about 15%, which would mean that it could be kept below 1 with about 10 percentage points less of the population vaccinated. However, without further progress in vaccination, there could be a subsequent surge in the virus as seasonal factors reverse.

Figure 10. Comprehensive vaccination rollout

Effect on the logged reproduction number R
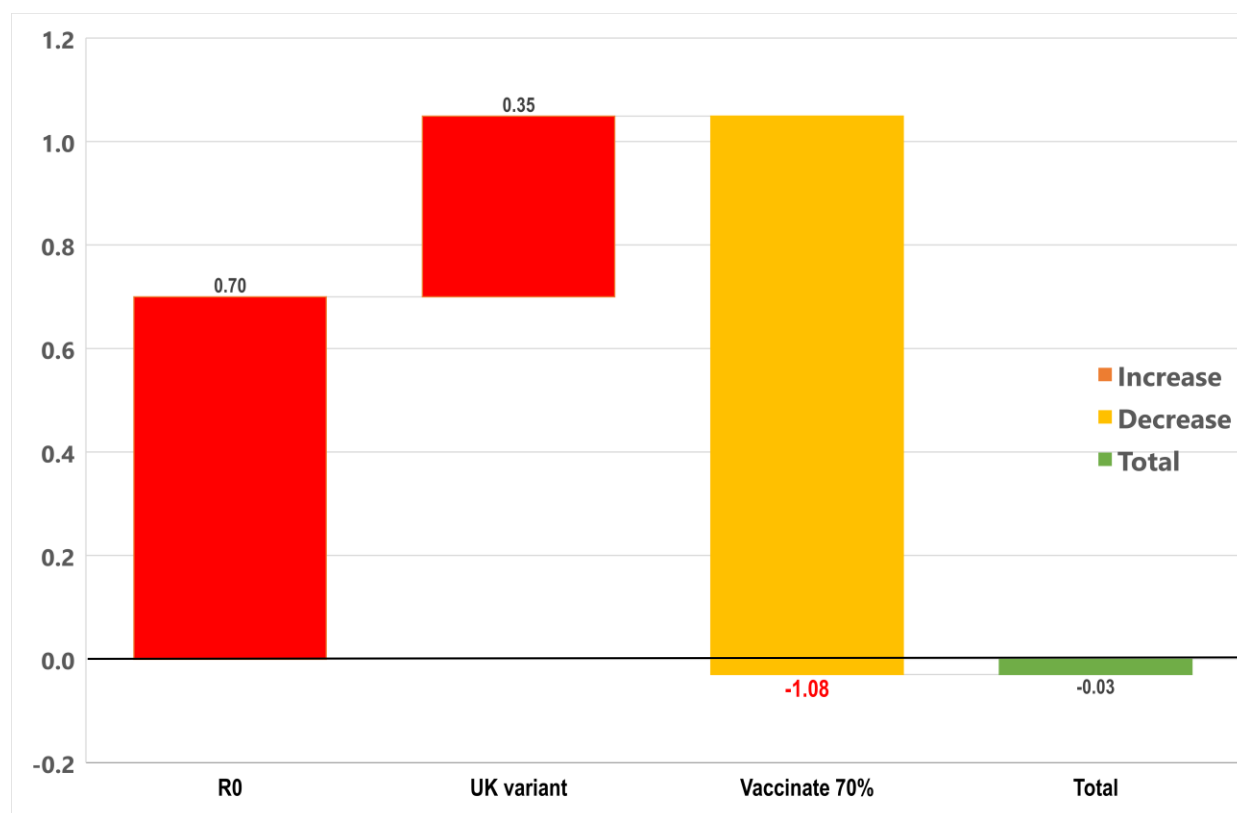
Note: See the note to Figure 9. Changes relative to the previous scenario are highlighted by the red bolded numbers.
Source: Authors' calculations based on the estimation results in Table 3.

7. Conclusions

This paper analysed empirically the impact of policies on the reproduction rate and the OECD Weekly GDP Tracker using high-frequency data for a set of OECD countries, based on which scenario analysis is carried out. The main findings of the paper can be summarised as follows.

First, some new variants of the virus are estimated to be able to boost the effective reproduction number by up to 50%. Seasonal effects are also found to increase the effective reproduction number in fall/winter, in some countries by up to 25% relative to summer. The rapidity of these adverse shocks represent a major challenge to policy-makers because they can coincide and take full effect over a matter of a few months. The two effects together can potentially boost reproduction numbers by up to 90%.

Second, vaccination is found to powerfully reduce the spread of the virus. Using the estimated equation, the effects can be stated in intervention-equivalent terms. Fully vaccinating…

- o 7% of the population is equivalent to either complete school closure, requiring people not to leave the house with minimal exceptions, or banning all public gatherings;
- o 15% of the population is equivalent to closing down all-but-essential workplaces;
- o 20% of the population is equivalent to closing down all-but-essential workplaces as well as public transport.

- ○ 50% of the population is equivalent to simultaneously applying all of the above restrictions as well as closing all international borders.

Third, scenarios based on the estimation results suggest a rapid rollout of vaccinations is needed to compensate for the pressure from more infectious variants, and so avoid an escalation of lockdown measures as well as the risk of the perpetuation of a cycle of stop-and-go mitigation policies. For a typical OECD country, fully vaccinating more than 40% of the population allows most containment policies to be either eliminated or substantially eased, typically raising GDP by 4-5%.

Finally, for those countries now going into summer, it is also important that policy-makers are not lulled into a false sense of security by the temporary decline in reproduction numbers due to seasonal factors, as in the summer of 2020. Failure to vaccinate a sufficient share of the population could then lead to a resurgence of the virus in the winter as seasonal factors reverse.

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Annex A. The importance of timeliness in introducing containment measures

The timing of the introduction of containment policies is very important for the control of the virus. It takes time for measures to become effective (Li et al., 2020) due to the disease's incubation period and the fact that some of the infected are asymptomatic. Moreover, the non-linear transmission of the virus implies that curbing it earlier on may lead to better outcomes than intervening after the spread has reached high growth rates.

To test whether an early timing of containment measures helped limit the spread of the epidemic, the total number of COVID-19-related deaths per million of population as of 15 July 2020 is regressed on the number of days between the local start of the epidemic (the day the country reached the first 100 cases per million) and the implementation of a typical or a maximum stringency of a package of containment measures for a cross-section of up to 148 countries. The stringency of the policy package is calculated as the sum of the scores of the following Oxford policy variables (thresholds for a typical policy in parentheses): stay-at-home requirements (1), workplace closures (2), school closures (2), restriction on public gatherings (3), international travel restrictions (1), testing (3) and tracing (2).[12] The median country reached typical policy levels 25 days and maximum policies four days before the start of the epidemic, reflecting the anticipation effect based on other countries' experience. In addition, the analysis controls for the age and density of the population, which may be associated with COVID-19 mortality and its speed of transmission.

The results suggest that delayed policy interventions lead to a significantly higher number of deaths relative to population by mid-2020 (Annex Table A.A.1). The median country reached the maximum level of polices four days before the local start of the epidemic, which saved five lives per million, relative to the death toll of a country fully intervening only on the first day of the local epidemic outbreak. The fastest-acting (top 25%) countries saved about 80 lives per million more than the slowest-acting (bottom 25%) countries (Annex Figure A.A.1)[13]. Countries which are relatively younger (top 25%) and less urbanized (bottom 25%), lost 30 and 22 lives per million less, respectively, than those with average population structure (Annex Figure A A.1).

These results are in line with other empirical studies which found that countries that implemented containment measures earlier, had a lower number of infections and/or deaths after a certain period than countries, that acted later (Deb et al., 2020; Caselli et al., 2021). While some authors find an effect of timing for a wide range of policies, including restrictions on public events, public transportation or mobility (Blanco

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[12] This means that a package of the same overall strength could have consisted of various combinations of different instruments and their stringencies.

[13] The results are robust to a number of robustness checks: 1) restricting the sample to countries with a minimum number of deaths (50) by mid-July 2020, 2) defining the local start of the epidemic as the date of the first death per million (rather than 100 new cases), 3) defining the end of the first wave as two months from the local start (instead of the fixed end-date of 15 July 2020). 4), controlling for the level (defined as either maximum or range) and/or duration of policies. Qualitatively similar results hold for a group of 28 European countries, except the share of older people does not play a role for mortality there.

et al.,2020), others find timing mostly matters for specific lockdown-type measures (Koh et al., 2020), or school closures and bans on mass-gatherings (Piovani et al., 2021; Haug et al.,2020).

Figure A A.2. Lives saved (or lost [-]) by mid-July depending on population structure

per million, relative to a country acting on the day when 100 cases were reached
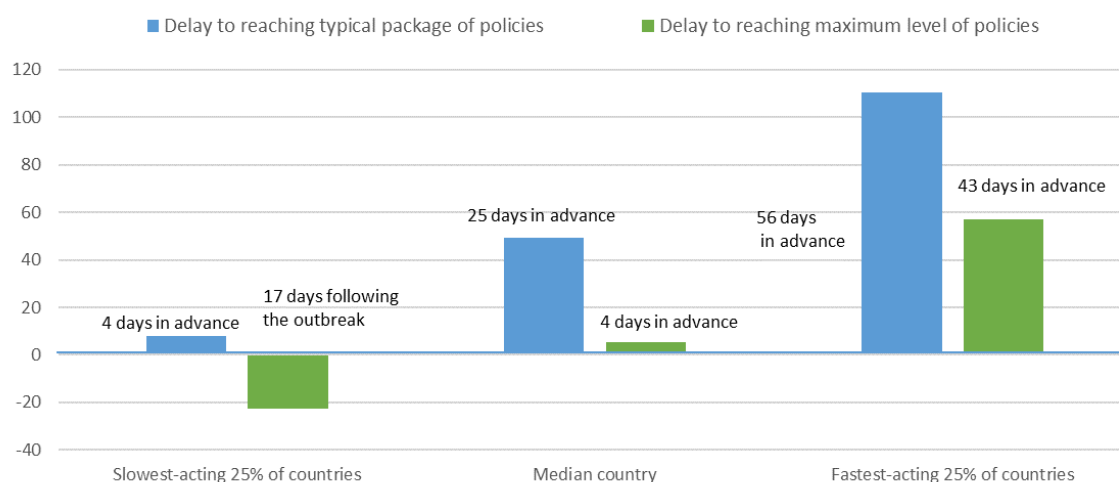
Note: The day of the outbreak is the day when the country reach 100 cumulative cases per million of inhabitants.
Source: Authors' calculations.

Figure A A.3. Lives saved (or lost [-]) by mid-July depending on population structure

per million, relative to median-acting country in terms of policy swiftness with average age and urban structure
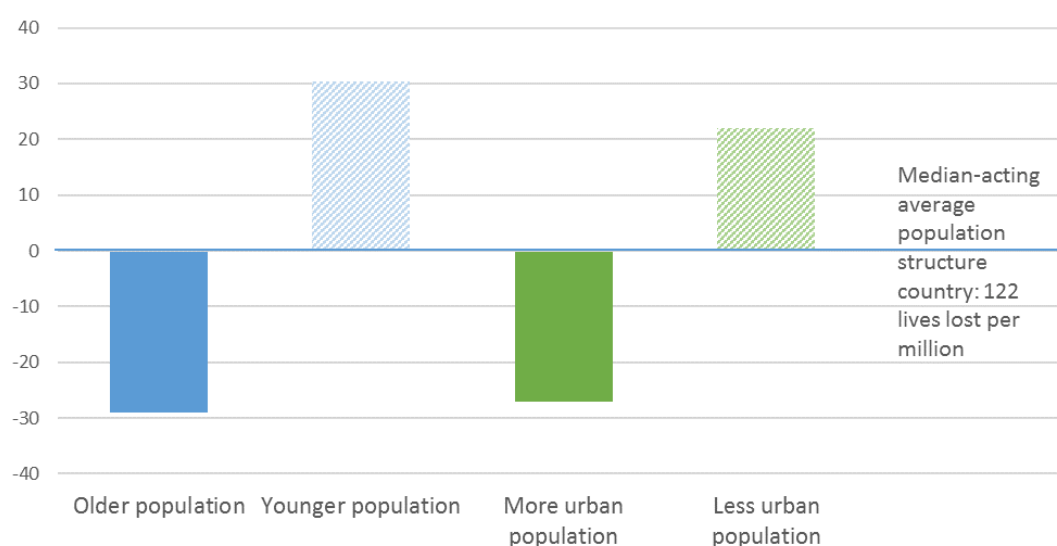
Note: Older population means a median-acting country, with relatively older (top 25%) population and average urbanicity. Younger population means a median-acting country, with relatively younger (top 25%) population and average urbanicity. More urban population means a median-acting country, with relatively high (top 25%) urbanicity and average age structure. Less urban population means a median-acting country, with relatively low (bottom 25%) urbanicity and average age structure.
Source: Authors' calculations.

The effect of policy timing can be investigated relative to the local start of the epidemic as defined by some initial low number of cases or deaths (e.g. 1 or 100), as is commonly done in the literature. It could also be potentially assessed relative to the peak of new cases or deaths. While both points are not exogenous, the local start mainly due to anticipation effects and learning from other countries' experience, the peak is even less of an independent event, as policies directly affect its timing, severity, as well as the profile of the epidemic around the peak, so the former approach is used. The results are robust to choosing an alternative definition of the start of the local epidemic (one death per million) and even with this definition, the majority of countries implemented containment polices in advance of this event. Nevertheless, countries that acted faster than others had fewer deaths by mid-2020 than those acting relatively later.

Table A A.1. Mortality and timing of policies regression results

Dependent variable: total deaths per million population

	(1)	(2)	(3)
Constant	157.212**	113.965**	-56.348
Policy response: time from first 100 cases per million to reach maximum policy		1.345**	0.804**
Policy response: time from first 100 cases per million to reach typical policy	1.973***		
Share of 65+			3.645#
Urban share			1.392*
Share of 65+ X policy (max) response			0.112*
Urban share X policy (max) response			0.022*
Number of countries	129	148	143
Adjusted R squared	0.165	0.124	0.257

Notes: Results from an OLS cross-section regression. * and ** denote statistical significance at the 5 and 1% levels, respectively. # indicates that the coefficient estimate is statistically significant at the 10% level. Variables used in the interaction terms are demeaned.
Source: Authors' calculations.