FAST TRACK

Physical distancing interventions and incidence of coronavirus disease 2019: natural experiment in 149 countries

Nazrul Islam,[1,2] Stephen J Sharp,[2] Gerardo Chowell,[3] Sharmin Shabnam,[4] Ichiro Kawachi,[5] Ben Lacey,[1] Joseph M Massaro,[6] Ralph B D'Agostino Sr,[7] Martin White[2]

For numbered affiliations see end of the article.

Correspondence to: N Islam nazrul.islam@ndph.ox.ac.uk (ORCID 0000-0003-3982-4325)

Additional material is published online only. To view please visit the journal online.

Cite this as: *BMJ* 2020;370:m2743

http://dx.doi.org/10.1136/bmj.m2743

Accepted: 8 July 2020

ABSTRACT

OBJECTIVE

To evaluate the association between physical distancing interventions and incidence of coronavirus disease 2019 (covid-19) globally.

DESIGN

Natural experiment using interrupted time series analysis, with results synthesised using meta-analysis.

SETTING

149 countries or regions, with data on daily reported cases of covid-19 from the European Centre for Disease Prevention and Control and data on the physical distancing policies from the Oxford covid-19 Government Response Tracker.

PARTICIPANTS

Individual countries or regions that implemented one of the five physical distancing interventions (closures of schools, workplaces, and public transport, restrictions on mass gatherings and public events, and restrictions on movement (lockdowns)) between 1 January and 30 May 2020.

MAIN OUTCOME MEASURE

Incidence rate ratios (IRRs) of covid-19 before and after implementation of physical distancing interventions, estimated using data to 30 May 2020 or 30 days post-intervention, whichever occurred first. IRRs were synthesised across countries using random effects meta-analysis.

RESULTS

On average, implementation of any physical distancing intervention was associated with an overall reduction in covid-19 incidence of 13% (IRR 0.87, 95% confidence interval 0.85 to 0.89; n=149 countries). Closure of public transport was not associated with any additional reduction in covid-19 incidence when the other four physical distancing interventions were in place (pooled IRR with and without public transport closure was 0.85, 0.82 to 0.88; n=72, and 0.87, 0.84 to 0.91; n=32, respectively). Data from 11 countries also suggested similar overall effectiveness (pooled IRR 0.85, 0.81 to 0.89) when school closures, workplace closures, and restrictions on mass gatherings were in place. In terms of sequence of interventions, earlier implementation of lockdown was associated with a larger reduction in covid-19 incidence (pooled IRR 0.86, 0.84 to 0.89; n=105) compared with a delayed implementation of lockdown after other physical distancing interventions were in place (pooled IRR 0.90, 0.87 to 0.94; n=41).

CONCLUSIONS

Physical distancing interventions were associated with reductions in the incidence of covid-19 globally. No evidence was found of an additional effect of public transport closure when the other four physical distancing measures were in place. Earlier implementation of lockdown was associated with a larger reduction in the incidence of covid-19. These findings might support policy decisions as countries prepare to impose or lift physical distancing measures in current or future epidemic waves.

WHAT IS ALREADY KNOWN ON THIS TOPIC

In the absence of evidence for effective treatment regimens or a successful vaccine for coronavirus disease 2019 (covid-19), the most pragmatic recommendation has been to advise physical distancing to minimise transmission

The broader aim of this recommendation was to reduce the burden from covid-19 on public health and healthcare services, and to allow time for the prevention and management of the disease

Evidence on the effectiveness of these interventions to date is largely based on modelling studies, and empirical population level data on effectiveness is scarce globally

WHAT THIS STUDY ADDS

Data from 149 countries showed that the incidence of covid-19 decreased by an average of 13% in association with physical distancing interventions

No evidence was found of additional benefits from closure of public transport when four other physical distancing measures (school closures, workplace closures, restrictions on mass gatherings, and lockdown) were in place

Earlier implementation of lockdown was associated with a larger reduction in the incidence of covid-19

Introduction

As of 8 June 2020, the coronavirus disease 2019 (covid-19) pandemic has been responsible for more than seven million confirmed cases worldwide, including more than 400 000 deaths. In many countries, healthcare facilities have been overwhelmed by a surge in cases, especially patients requiring intensive care. In the absence of evidence for effective treatment regimens or a successful vaccine, the most pragmatic recommendation has been to advise physical distancing (referred to by some as social distancing) to minimise person-to-person transmission[1] with a view to flattening the epidemic curve.[2-4] The main aim of physical distancing is to prevent more rapid spread of covid-19 and to allow more time for public health and healthcare services to become better prepared for the prevention and management of the disease.[4 5] Although most countries have implemented some policy interventions aimed at physical distancing (eg, closure of schools, workplaces, and public transport, and cancellation of public events), data on the effectiveness of, and adherence to, those policy interventions is scarce. To date, little evidence exists on the comparative effectiveness of specific combinations or sequences of interventions.

Most of the evidence on the postulated effectiveness of physical distancing interventions comes from modelling studies.[2-4] A recent Cochrane systematic review[6] reported that all evidence of physical distancing interventions on covid-19 related morbidity and mortality comes from modelling studies, and only four observational studies focused on severe acute respiratory syndrome and Middle East respiratory syndrome. The UK Department of Health also highlighted the limited availability of robust data on the effectiveness of these measures on influenza.[7] Two recent studies from Wuhan, China[8] and Hong Kong[9] reported a reduction in the number of confirmed cases and transmission of covid-19 associated with physical distancing policy interventions. The data on global effectiveness of these interventions are, however, limited.

Given the impact of the covid-19 pandemic on health and economies worldwide, evidence is urgently needed to inform policy responses. In this natural experimental study across 149 countries we used interrupted time-series analyses to compare the change in incidence of covid-19 before and after implementation of policy interventions for physical distancing.

Methods

Data sources

We obtained data on policy interventions for physical distancing from the Oxford covid-19 Government Response Tracker, a study that tracks national government policy measures in response to the covid-19 pandemic globally (to 30 May 2020).[10] The details of this database, the first such initiative in the context of the covid-19 pandemic, have been described in a working paper.[10] Briefly, a dedicated team of public policy and governance experts based at the University of Oxford collects official data on public policy measures adopted by governments around the world to deal with the covid-19 global pandemic, including physical distancing policies and economic and other healthcare related measures. Our primary interventions of interest were those aimed at physical distancing. These include closures of schools and workplaces, restrictions on mass gatherings (a combination of two variables: cancellation of public events and restrictions on gathering), public transport closure, and lockdown (a combination of two variables: stay at home regulations and restrictions on movements within a country). We merged similar variables related to restrictions on mass gatherings and lockdown because effectively the same concepts are measured and because in most of the countries these restrictions were implemented together, or within a short interval, making it difficult to separate the individual effects. To check the robustness of our primary analysis, we conducted a sensitivity analysis with the seven variables separately.

From the European Centre for Disease Prevention and Control, we collected data on the number of reported cases of covid-19 (to 30 May 2020), as well as the 2019 population estimates.[11] Other population and demographic data—for example, percentages of populations aged 65 years or older (2018 estimates) were from the World Bank data portal.[12] Gross domestic product (GDP) per capita (2018 estimates) were from the International Monetary Fund.[13] The 2019 Global Health Security Index (HSI), a measure of a country's emergency pandemic preparedness developed by the Johns Hopkins University, was from the official report.[14] Data on covid-19 testing (per million) were collected from a variety of sources (see appendix, pp6-7).

Statistical analysis

We used an interrupted time series analysis of each country's data to model the population incidence of covid-19 over time and to estimate the impact of each intervention on the change in incidence of covid-19. This approach allows each country to act as its own control (pre-intervention being the control). Counts of covid-19 cases were modelled using Poisson regression, with the log of the total population size as an offset. The model was used to estimate the incidence rate ratio for development of covid-19 after versus before each intervention within each country.

In this analysis we used an interrupted time series regression model, using the equation:

$$log(Y_t)=\beta_0+\beta_1 T+\beta_2 X_t+\beta_3 Z+\beta_4(log(total\ population))$$

where Y_t represents the number of covid-19 cases at time t, T represents the number of days since the start of follow-up (ie, days since first reported case), X_t is a dummy variable that equates to 0 for the pre-intervention period and 1 for the post-intervention period, and Z represents days since the intervention (equates to 0 for the pre-intervention period). Here, β_0 represents the baseline level of the outcome (number of covid-19 cases) at t=0, β_1 represents the change in the outcome each day pre-intervention, β_2 represents the change in the level of outcome immediately post-intervention, and β_3, our primary parameter of interest, represents the difference in the slope post-intervention (slope B in appendix, pp2-3) compared with the pre-intervention period (slope A in appendix, pp2-3).

Since these policy interventions are not expected to have immediate effects,[15] we hypothesised a seven day lag time (decided a priori) for each intervention to take effect, to coincide with the approximate incubation period of severe acute respiratory coronavirus 2 (SARS-CoV-2),[16] the virus responsible for covid-19, and a recent empirical study.[17] Therefore, we considered the first seven days of the implementation of the intervention as part of the pre-intervention period along with any period before the policy intervention (see appendix, pp2-3). To be eligible for the analysis, countries had to have seven days or more of data after the reported date of intervention implementation, and 30 cases or more by 30 May 2020 (for model convergence).

doi: 10.1136/bmj.m2743 | BMJ 2020;370:m2743 | the bmj

Because the epidemic curves are different across the countries studied, use of specific calendar time (eg, 30 May) in the statistical analysis will result in some countries having a substantially longer post-intervention follow-up time than others. As the incidence inevitably decreases with the decline in the epidemic curve, such an approach might show the efficacy of the intervention with greater certainty but could also overestimate the intervention effect. We therefore restricted the post-intervention follow-up time to 30 days since the implementation of a policy, or 30 May 2020, whichever occurred first. This analytical approach also maintains comparability across the countries analysed in meta-analysis.

We also added a scale parameter to the regression equation set as the Pearson χ^2 statistic divided by the residual degrees of freedom,[18] to deal with overdispersion (when the variance is larger than the mean, which is a violation of an assumption of Poisson regression) associated with count data.[19] Models were also checked for autocorrelation.

Random effects meta-analysis was then used to combine these rate ratios (the incidence rate of covid-19 post-intervention compared with the incidence rate pre-intervention) estimated for individual countries.[20] This analysis ascertains whether implementation of any of the physical distancing interventions was associated with an effect on the incidence of covid-19.

Since many country level characteristics might affect both the policy intervention and the incidence of covid-19, we assessed several of these factors in meta-regression, including days between the first reported case and implementation of the first intervention (representing a delay in introduction of the policy), GDP per capita (representing a measure of economic standing, as it is known that covid-19 disproportionately affects those in lower income groups),[21 22] percentage of population aged 65 years or older (to account for population demographics, given the substantially increased risk shown with age),[23] and diagnostic testing rate for covid-19 (because testing has varied within individual countries, and across countries at the same time).

We used random effects meta-analysis to examine the comparative effectiveness of different combinations and sequences of policy interventions. Because the combinations and sequence of interventions do not differentiate between being implemented together or apart, we considered interventions to occur together only if they were implemented within a seven day timeframe. The eligibility criteria to be included in this analysis are the same as those for the primary analysis (ie, at least seven days of data after the intervention and at least 30 cases of covid-19 by 30 May 2020). Additional inclusion criteria include at least a seven day interval between two successive interventions (or combinations of interventions) for valid estimation of the incidence rates and corresponding 95% confidence intervals. We also expanded our time series model to separate out the intervention effects (see appendix, pp2-3). By separating out the effects of interventions implemented in a staggered way, this model also allowed us to examine the comparative effectiveness of early compared with late lockdown. For each specified policy intervention, we report the effect measures as rate ratios comparing the rates of development (slope) of covid-19 before and after each intervention.

All statistical analyses were performed using Stata statistical software (version 14.2)[24] or Python (version 3.6).[25]

Sensitivity analysis

We tested the robustness of our primary analysis using a series of sensitivity analyses. Firstly, we conducted a sensitivity analysis with all seven components of physical distancing interventions separated (as opposed to merging related variables). Then we examine the robustness of our primary seven day lagged analysis, using two additional sensitivity analyses for a five day and a 10 day lagged time frame. Finally, as larger countries might have greater within country variability in the implementation of these interventions, we conducted a sensitivity analysis excluding Brazil, Canada, China, India, Russia, the United Kingdom, and the United States.

Patient and public involvement

This study did not involve patients and the public directly and, given the rapidity of the research, patient and public involvement was not considered viable in this case. However, our findings will be widely disseminated to the public through official (press release, institutional websites, and repositories), personal, and social communication tools.

Results

Overall, 149 countries implemented at least one of the five physical distancing policies between 1 January and 30 May 2020 (flowchart in appendix, p9), with at least seven days of data on incidence of covid-19 post-intervention available for analysis. Figure 1 shows each country and its physical distancing policies. The appendix provides the trajectory of confirmed covid-19 incidence, along with the timeline of policy implementation for each country, as well as the model predicted covid-19 incidence rates for individual countries (pp33-330). In most countries there was little evidence of residual autocorrelation.

Overall impact of physical distancing interventions

All the countries included in the analysis (except Belarus and Tanzania) had implemented at least three of the five physical distancing measures by 30 May 2020. All five measures were in place in 118 countries, whereas 25 countries had four policy measures and four countries had three. On average, policies were first implemented 9 days (SD 13 days) after the first reported case. Countries with the longest interval until first implementation of any of the physical distancing policies were Thailand (58 days), Australia (51 days), Canada (46 days), Sri Lanka and the UK (45 days), Finland and Malaysia (42 days), and Cambodia, Sweden, and the US (40 days).

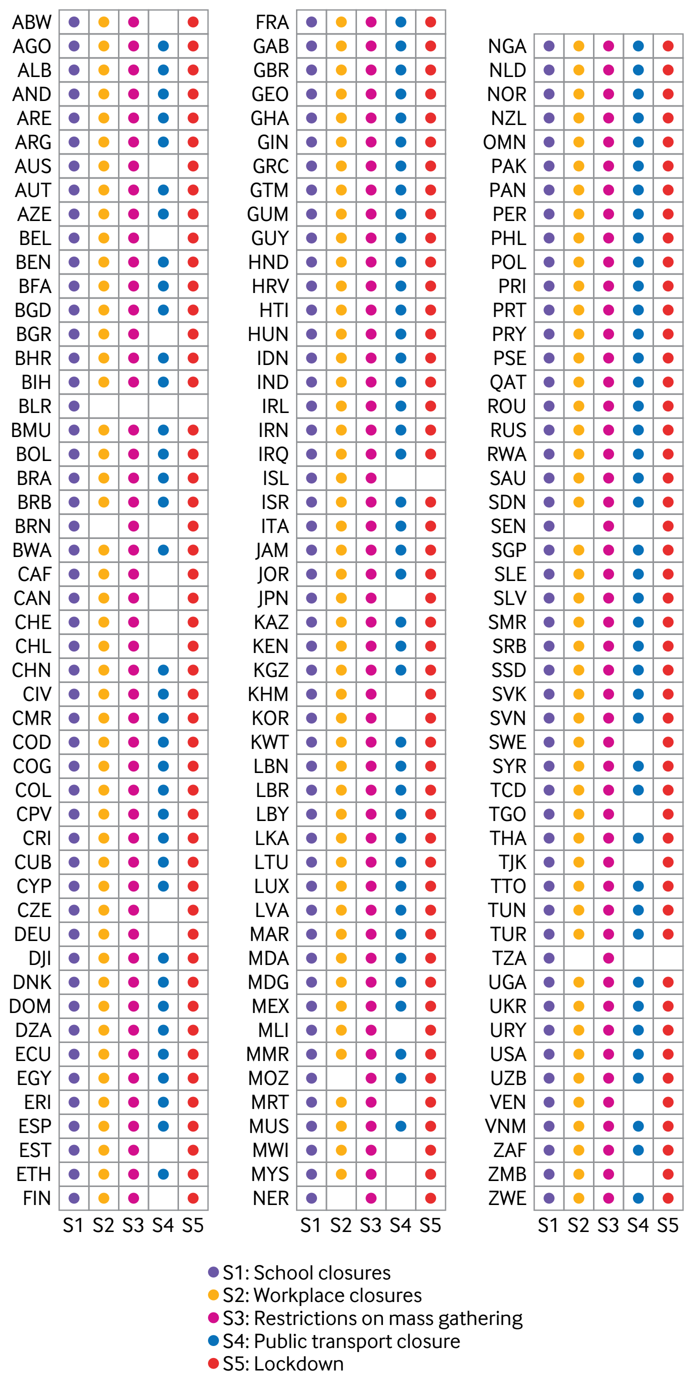

Fig 1 | Physical distancing policies implemented by countries globally. Country codes used are based on the Alpha-3 codes by International Organization for Standardization (see appendix, pp4-5)[25]

The pooled estimates from 149 countries showed an overall decrease of 13% (pooled incidence rate ratio (IRR) 0.87, 95% confidence interval 0.85 to 0.89; P<0.001) in the incidence of covid-19 associated with implementation of any of the physical distancing policies (fig 2). Heterogeneity across countries was low (I^2=19%).

Meta-regression did not identify any effects on the IRR of days since the first reported case of covid-19 until the first implementation of physical distancing policies (P=0.57) and covid-19 testing rate (P=0.71; n=112). However, a higher GDP per capita (P=0.09), higher percentage of population aged 65 years or older (P<0.001), and higher country health security index (P=0.008) were associated with a greater reduction in the pooled IRR (see appendix, p268).

Comparative effectiveness of physical distancing interventions

Number of interventions

Compared with the pre-intervention period, the rate of reduction in incidence of covid-19 was similar with the five physical distancing measures implemented together (pooled IRR 0.87, 0.85 to 0.90; n=118 countries) compared with changes in incidence in countries with four measures implemented (pooled IRR 0.85, 0.82 to 0.89; n=25 countries) (fig 2). A smaller change in incidence of covid-19 was associated with a three intervention combination (pooled IRR 0.88, 0.77 to 1.00) even though this applied to only four countries.

Combination of interventions

Figure 3 details the association between incidence of covid-19 and combinations of physical distancing interventions, implemented together within a seven day time frame (see appendix pp10-15 for detailed results of the meta-analysis). The decrease in incidence of covid-19 associated with a combination of school closures, workplace closures, restrictions on mass gatherings, and lockdowns (pooled IRR 0.87, 0.84 to 0.91; n=32 countries) was similar when closure of public transport was additionally implemented—that is, all five measures were in place (pooled IRR 0.85, 0.82 to 0.88; n=72 countries). A combination of school closures, workplace closures, and restrictions on mass gatherings with or without closure of public transport was consistently associated with a beneficial effect of a decrease in incidence of covid-19. Evidence was insufficient to determine the association between covid-19 incidence and other combinations of interventions without restrictions on mass gathering (fig 3).

Sequence of interventions

Figure 4 shows the association between the sequence of interventions and the change in the incidence of covid-19 (also see appendix, pp16-25). No consistent pattern of association was found for any specific sequence of interventions. When the effect estimates from all the countries were pooled together, however, a greater reduction in incidence of covid-19 was associated with earlier implementation of lockdown (pooled IRR 0.86, 0.84 to 0.89; n=105 countries) as opposed to later implementation (pooled IRR 0.90, 0.87 to 0.94; n=41 countries) (see appendix, pp26-27).

Sensitivity analysis

When the seven physical distancing policies were considered separately (ie, without merging the two

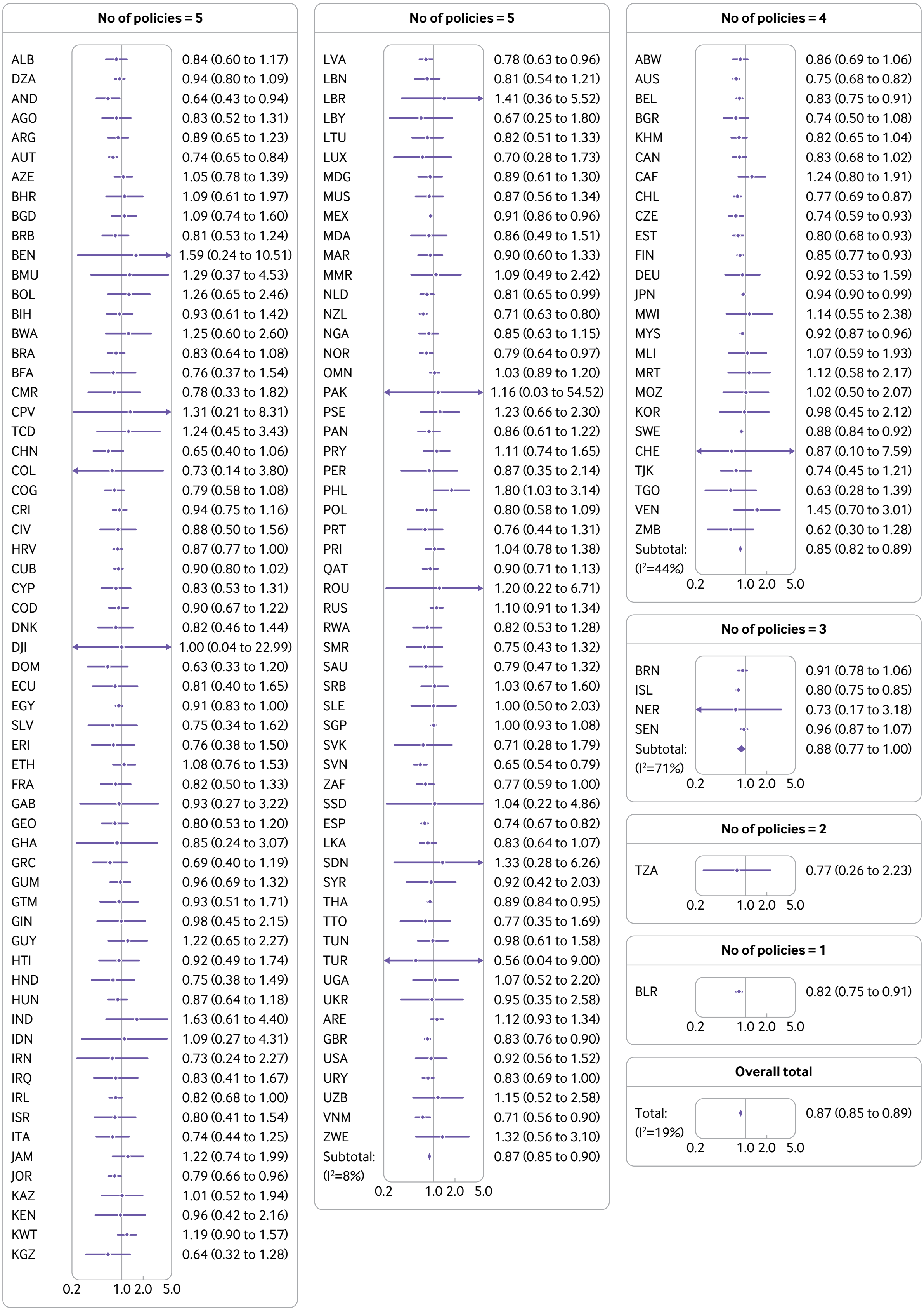

Fig 2 | Pairwise meta-analysis on the association between physical distancing interventions and change in incidence of coronavirus disease 2019. Effects are reported as incidence rate ratios (95% confidence intervals). I^2=an estimate of the percentage of total variation across the countries that is due to heterogeneity rather than chance.[26] Country codes used are based on the Alpha-3 codes by International Organization for Standardization (see appendix, pp4-5)[25]

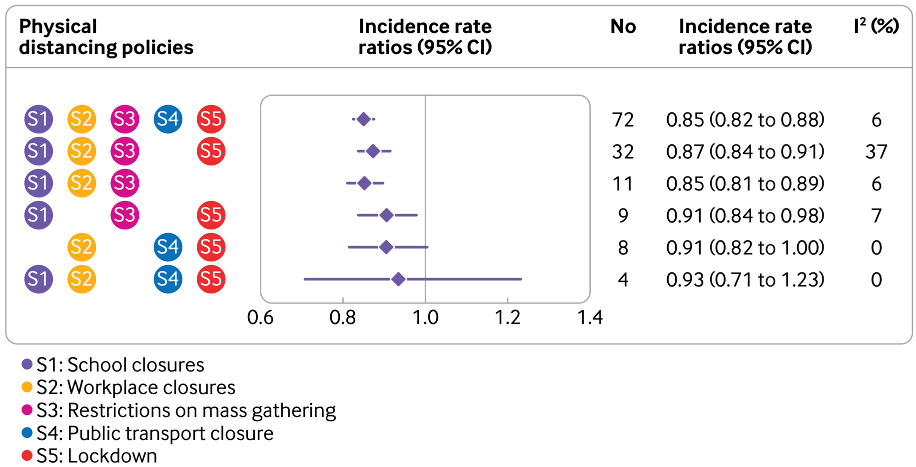

Fig 3 | Association between the combinations of physical distancing interventions and change in incidence of coronavirus disease 2019. I^2=an estimate of the percentage of total variation across the countries that is due to heterogeneity rather than chance[26]

mass gathering interventions or the two lockdown measures), the estimated effects of any physical distancing intervention were similar to those of the primary analysis (IRR 0.86, 0.85 to 0.88) (see appendix, p28). Results from the analysis excluding the seven largest countries were virtually identical to those of the primary analysis (IRR 0.87, 0.85 to 0.89) (see appendix, p29). When a five day lagged time frame was used in the sensitivity analysis, the model did not converge for seven countries (Gabon, Djibouti, India, Indonesia, Libya, Sudan, and Togo) owing to either a shorter pre-intervention follow-up time or fewer cases in the pre-intervention period. Results for the remaining 142 countries were, however, similar to those of the primary analysis (IRR 0.88, 0.87 to 0.90), as were those from the analysis using a 10 day lagged time frame for all 149 countries (IRR 0.86, 0.84 to 0.88) (see appendix, pp30-31).

Discussion

In this study, five commonly introduced physical distancing interventions in 149 countries were associated with on average a 13% reduction in the incidence of covid-19. No additional benefit was found associated with closures of public transport when a combination of school closures, workplace closures, restrictions on mass gatherings, and restrictions of population movement (ie, lockdown) was in place. A greater reduction in incidence was observed when restriction on mass gatherings was included in the intervention combination, and when lockdown was implemented earlier along with school and workplace closures. The reduction in incidence of covid-19 associated with physical distancing interventions was greater in high income countries (higher GDP per capita), those with an older population (higher proportion of population aged ≥65 years), and those with stronger preparedness for the pandemic (country health security index).

Comparison with previous research

Our finding of a beneficial effect associated with physical distancing interventions aligns with the findings from a recent epidemiological study, which reported data on the covid-19 epidemic in Wuhan, China.[8] This study found that a reduction in incidence of covid-19 was associated with a series of non-drug interventions (eg, "cordons sanitaire" or restrictions on movement, traffic restrictions, social distancing, home quarantine, centralised quarantine, and universal symptom survey). A similar study from Hubei and Guangdong in China also reported a reduction in incidence of covid-19.[17] A study from Hong Kong also reported a decrease in the transmission of SARS-CoV-2 associated with physical distancing interventions.[9] A recent study compared the incidence of covid-19 between Spain and Italy and reported a reduction in incidence of covid-19.[26] Previous studies that examined historical data on the physical distancing interventions during the 1918-19 influenza pandemic in the US reported "strong" beneficial effects from school closures, bans on public gatherings, and isolation and quarantine.[27] A more recent study on the economic consequences of the 1918-19 influenza pandemic concluded that physical distancing interventions were associated with a lower mortality.[28] This study also reported that despite adverse effects on the economy from the global pandemic, regions that took earlier and aggressive physical distancing measures grew faster economically in the post-pandemic period.[28] Other modelling studies on covid-19 also predicted a reduction in incidence of the disease associated with physical distancing interventions.[2-4] As outlined in the UK Department of Health's scientific summary on the effectiveness of policy interventions, it is difficult to compare study results because of heterogeneity in methods and approaches.[7] This report highlighted the conflicting findings on, for example, school closures and mass gatherings. Previous studies and reviews

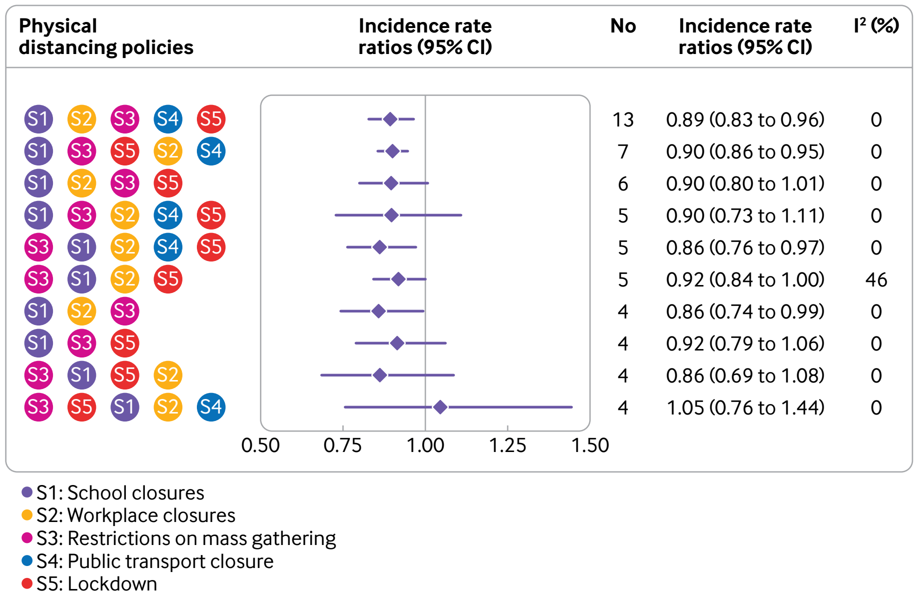

Fig 4 | Association between the sequence of physical distancing interventions and change in incidence of coronavirus disease 2019. I^2=an estimate of the percentage of total variation across the countries that is due to heterogeneity rather than chance[26]

on severe acute respiratory syndrome and Middle East respiratory syndrome also highlighted the lack of robust data on effectiveness.[6 7 29] Our findings add to this evidence base and should help to inform governmental policies on the implementation of combinations and sequences of physical distancing interventions in the future.

Strengths and limitations of this study

In this large empirical study reporting on the potential effectiveness of physical distancing policies on the incidence of covid-19, we pooled data from 149 countries, which varied in terms of economic development and political and health systems. We employed a rapid, comprehensive, and robust methodological and analytical approach to evaluate emerging data on the covid-19 pandemic, and we estimated the relative effectiveness of different policy interventions within each country. Our study answers key questions about the combination and sequence of physical distancing interventions. Closure of public transport can be problematic, especially for those working in vital services, including health, care giving, and emergency response roles. Our study suggests that, in the presence of other physical distancing measures, closure of public transport might not substantially enhance disease control. Closure of schools and workplaces and restrictions on mass gatherings leave fewer people to use public transport, and this might help to make it easier to maintain physical distancing among people working in the key service sectors. We found that intervention combinations that included restrictions on mass gatherings were consistently associated with a greater reduction in incidence of covid-19. We also found that earlier implementation of restrictions on the movement of populations (lockdown) was associated with a greater reduction in incidence of covid-19, as previously suggested by modelling studies.[2 3]

Our study does, however, have limitations. Firstly, we relied solely on the Oxford covid-19 Government Response Tracker, which tracks the measures taken by governments around the world to tackle the covid-19 pandemic.[10] The curators of this database emphasised that they took care to ensure the validity of the collected data. In all practicality, however, it is challenging to collect information on the exact date, nature, and extent of the policies by the different governments. Although our study design enabled us to conduct a comparative effectiveness analysis, it is difficult to know exact combinations and sequences of the interventions, especially when implemented within a short period. This high level dataset might obscure qualitative differences in each of the five physical distancing measures across countries. Moreover, many local and cultural factors can affect the implementation of interventions—that is, what is acceptable in one national context might not be so in another, and compliance might therefore vary widely; we did not assess compliance in this dataset. This variation might be compounded by wide differences in the ability of countries to provide additional monetary and other resources to support the implementation of interventions, although controlling for GDP in this study might have allowed for this to an extent. In many settings, a government declaration does not equate to a mandatory implementation. For example, under Japanese constitutional law, Japan's government does not have the legal authority to compel the closure of workplaces. This might also be the case in other jurisdictions.

A key limitation is that our study design did not allow us to assess the optimum time for implementation of these physical distancing interventions; nor were we able to define the optimum time for lifting of these restrictions. Even though our data were suggestive of a greater benefit if the cancellation of public events and lockdowns are implemented earlier, along with closures of schools and workplaces, many of these estimates came from only a few countries. Our findings therefore should be interpreted with caution. In our meta-regression analysis, we found that the time between the first reported case of covid-19 and implementation of physical distancing policies was not significantly associated with the incidence of covid-19. This is contrary to anecdotal data from some countries that implemented these policies earlier (eg, South Korea) and reported success in slowing down the rate of transmission of SARS-CoV-2. Nevertheless, collated evidence from around the world (see appendix, p32) is far from confirmatory. Many countries implemented physical distancing policies earlier than others but failed to slow down the transmission of SARS-CoV-2. Overall, however, we found that earlier implementation of lockdown together with other physical distancing policies was associated with a larger reduction in the incidence of covid-19.

We did not include restrictions on international travel as this measure, although an important element of a viral containment strategy, is not strictly a physical distancing measure. Moreover, international travel restrictions of one country often affect other countries, regardless of whether those affected countries have implemented the same restrictions; this could violate the assumption of independence across the countries in the meta-analysis.

A further limitation is that, in addition to physical distancing measures, countries have implemented a wide range of other interventions that might be equally or more effective, including deployment of healthcare staff,[30] healthcare financing,[31] increased numbers of hospital beds[30] or ventilators,[32] increased and effective supply of personal protective equipment,[32] use of face coverings (including face masks) by the general population,[33-35] and mobile phone apps for contact tracing and isolation.[36 37] This is not an exhaustive list of potential ways to reduce the transmission of SARS-CoV-2.[38] We were unable to examine the deployment of such measures in this study owing to lack of valid and robust data in most of the countries. Future research will be able to examine these effects with better data availability.

We attempted to collect data on covid-19 testing rates by country, but we could only identify data for 112 countries from a variety of sources, and the validity of these data might be questionable. The outcome metric in our study was incidence, which could be influenced by testing rates. However, testing rates were potentially stable during our study period, as we restricted the analysis up to 30 days post-intervention implementation; covid-19 testing rate was not found to be a significant factor in our meta-regression analysis. Nevertheless, valid longitudinal data on covid-19 testing are yet to become available. Therefore, examining the longitudinal effect of covid-19 testing on the results reported will only be possible when robust data are available.

Ideally, we would also have examined death rates, but at this stage of the pandemic, the numbers of deaths in countries are lower, especially for those only recently experiencing the epidemic and for those that have successfully minimised the numbers of deaths. Covid-19 related deaths are also likely to be under-reported.[30 39] Future research with more complete data on incidence and mortality will help to validate these results, as well as estimate the long term effects more precisely.

Another potential limitation was our inability to examine within country heterogeneity in the implementation of these policy interventions, which is particularly relevant for large countries such as Brazil, Russia, and the US. Although not a perfect solution, we conducted a sensitivity analysis excluding the seven largest countries in our dataset, and the results of our primary analysis remained unchanged. As more data become available at smaller geographical levels, future studies should examine within country heterogeneity.

Lastly, the incidence of covid-19 is still increasing in most countries. We only assessed the short term effectiveness of physical distancing interventions.[8] Further analyses over time will be needed to influence policy decisions.[40]

Interpretation and implications for policy and practice

Despite a range of limitations in our study, the findings suggest beneficial effects of physical distancing interventions in combination, especially restrictions on mass gatherings along with school and workplace closures, allowing the maintenance of active public transport for people working in the key service sectors. Our finding of no additional benefit associated with public transport closure when other interventions are in place is likely a result of fewer people using public transport, making it more convenient to maintain physical distancing during essential travel. The sequence and timing of interventions might also be important, with earlier implementation of restrictions on mass gatherings and restrictions on movement (lockdown) showing promise. The results from this study should help inform public health policy on the effect of implementation of interventions on the incidence of covid-19. However, more empirical data will be required to help decide which interventions to lift first as the epidemic curve starts to flatten, or which interventions to implement should further waves of the covid-19 pandemic occur, as has been suggested.[41 42] As found in our analysis, a combination of interventions without restrictions on public gathering might not play a substantial role in flattening the epidemic curve.

While some forms and combinations of physical distancing policies will likely remain in place until a successful treatment or vaccine for covid-19 becomes available, the psychosocial effects of prolonged restrictions need to be properly assessed.[43 44]

Communicating these psychosocial issues with the public and patients remains a challenging task for public health, primary care, and mental healthcare providers.[43-45] Although some guidelines exist, these are not comprehensive,[45] and further research should explore the most effective ways to communicate risk and risk reduction in trusted and non-judgemental ways.

Unanswered questions and further research

Further research is needed to provide more definitive answers to remaining questions about the extent, intensity, combinations, and sequence of physical distancing interventions, as well as the need for additional interventions, in the short, medium, and long term. Further work that distinguishes physical distancing interventions better in terms of their capability to reduce transmission will help to determine their potential for risk reduction. Urgent work is needed to ensure the validity and reliability of data on covid-19 testing, incidence, mortality, and implementation and compliance with interventions. In our study we have only been able to provide a rapid and relatively crude assessment of physical distancing at a relatively early stage of the covid-19 pandemic. As the pandemic continues to evolve, it will be crucial to repeat and extend this analysis to assess the impacts of interventions in the longer term, as well as to study combinations and sequence of the lifting of physical distancing restrictions.

AUTHOR AFFILIATIONS

[1]Clinical Trial Service Unit and Epidemiological Studies Unit (CTSU), Nuffield Department of Population Health, Big Data Institute, University of Oxford, Oxford OX3 7LF, UK

[2]MRC Epidemiology Unit, University of Cambridge, Cambridge, UK

[3]Department of Population Health Sciences, School of Public Health, Georgia State University, Atlanta, GA, USA

[4]Department of Mechanical Engineering, The Pennsylvania State University, University Park, PA, USA

[5]Harvard TH Chan School of Public Health, Harvard University, Boston, MA, USA

[6]Department of Biostatistics, Boston University School of Public Health, Boston, MA, USA

[7]Department of Mathematics and Statistics, Boston University, Boston, MA, USA

We thank the Oxford covid-19 Government Policy Tracker team, especially Thomas Hale, Anna Patherick, and Toby Phillips for their time in reviewing the conceptual framework of the study, and an earlier version of the manuscript.

Contributors: NI and MW conceptualised the study with input from the co-authors. NI, SJS, and SS did the statistical analysis, with mathematical and statistical inputs and oversight from MW, JMM, and RBD. All authors are guarantors for the study. All authors revised the manuscript, provided critical scholarly feedback, and approved the final version of the manuscript. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Funding: NI receives salary support from the Nuffield Department of Population Health, University of Oxford. Employers/sponsors had no role in the design, analysis, or dissemination of the study. The views expressed in this article are those of the authors and not necessarily those of the entities the authors are affiliated with or supported by, or both.

Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf and declare: NI receives salary support from the Nuffield Department of Population Health, University of Oxford; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: Not required as data are anonymised, aggregated without any personal information, and publicly available.

Data sharing: All the data used in this study are publicly available and properly cited. However, all the data used in this study will be made publicly available on the GitHub repository (https://github.com/shabnam-shbd/COVID-19_Physical_Distancing_Policy) upon publication of the study.

The lead author affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: We will widely disseminate the main findings to members of the public through official (press release, institutional websites, and repositories), personal, and social media.

1 Mossong J, Hens N, Jit M, et al. Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Med* 2008;5:e74. doi:10.1371/journal.pmed.0050074
2 Ferguson NM, Laydon D, Nedjati-Gilani G, et al. *Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand.* Imperial College London, 2020.
3 Koo JR, Cook AR, Park M, et al. Interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. *Lancet Infect Dis* 2020;20:678-88. doi:10.1016/S1473-3099(20)30162-6
4 Prem K, Liu Y, Russell TW, et al, Centre for the Mathematical Modelling of Infectious Diseases COVID-19 Working Group. The effect of control strategies to reduce social mixing on outcomes of the COVID-19 epidemic in Wuhan, China: a modelling study. *Lancet Public Health* 2020;5:e261-70. doi:10.1016/S2468-2667(20)30073-6.
5 Lewnard JA, Lo NC. Scientific and ethical basis for social-distancing interventions against COVID-19. *Lancet Infect Dis* 2020;20:631-3. doi:10.1016/S1473-3099(20)30190-0
6 Nussbaumer-Streit B, Mayr V, Dobrescu AI, et al. Quarantine alone or in combination with other public health measures to control COVID-19: a rapid review. *Cochrane Database Syst Rev* 2020;4:CD013574. doi:10.1002/14651858.CD013574
7 Pandemic Influenza Preparedness Team. *Scientific summary of pandemic influenza & its mitigation: scientific evidence base review.* Department of Health, 2011.
8 Pan A, Liu L, Wang C, et al. Association of public health interventions with the epidemiology of the covid-19 outbreak in Wuhan, China. *JAMA* 2020;10. doi:10.1001/jama.2020.6130
9 Cowling BJ, Ali ST, Ng TWY, et al. Impact assessment of non-pharmaceutical interventions against coronavirus disease 2019 and influenza in Hong Kong: an observational study. *Lancet Public Health* 2020;5:e279-88. doi:10.1016/S2468-2667(20)30090-6
10 Hale T, Petherick A, Phillips T, et al. *Variation in government responses to COVID-19.* Blavatnik School of Government, 2020.
11 European Centre for Disease Prevention and Control. Geographic distribution of COVID-19 cases worldwide. 2020.
12 World Bank. World population prospects: 2019 revision. 2020.
13 International Monetary Fund. IMF data mapper. 2020.
14 Johns Hopkins Center for Health Security, The Economist Intelligence Unit. Global Health Security Index. 2019.
15 Bernal JL, Cummins S, Gasparrini A. Interrupted time series regression for the evaluation of public health interventions: a tutorial. *Int J Epidemiol* 2017;46:348-55. doi:10.1093/ije/dyw098
16 Lauer SA, Grantz KH, Bi Q, et al. The incubation period of coronavirus disease 2019 (covid-19) from publicly reported confirmed cases: estimation and application. *Ann Intern Med* 2020;172:577-82. doi:10.7326/M20-0504
17 de Figueiredo AM, Codina AD, Figueiredo D, et al. Impact of lockdown on COVID-19 incidence and mortality in China: an interrupted time series study. *Bull World Health Organ* 2020. doi:10.2471/BLT.20.256701
18 Rabe-Hesketh S, Everitt B. *A handbook of statistical analyses using Stata.* 4th ed. Chapman & Hall/CRC, 2007.
19 McCullagh P, Nelder JA. *Generalized linear models.* 2nd ed. Chapman & Hall/CRC, 1998.

20 DerSimonian R, Laird N. Meta-analysis in clinical trials. *Control Clin Trials* 1986;7:177-88. doi:10.1016/0197-2456(86)90046-2
21 Platt L, Ross W. *Are some ethnic groups more vulnerable to COVID-19 than others?* Institute for Fiscal Studies, 2020.
22 Garg S, Kim L, Whitaker M, et al. Hospitalization rates and characteristics of patients hospitalized with laboratory-confirmed coronavirus disease 2019 — covid-NET, 14 states, March 1-30, 2020. *MMWR Morb Mortal Wkly Rep* 2020;69:458-64. doi:10.15585/mmwr.mm6915e3
23 Docherty AB, Harrison EM, Green CA, et al. Features of 20 133 UK patients in hospital with covid-19 using the ISARIC WHO Clinical Characterisation Protocol: prospective observational cohort study. *BMJ* 2020;369:m1985. doi:10.1136/bmj.m1985
24 StataCorp. Stata statistical software: release 14. 2015.
25 Python Software Foundation. Python Language Reference, version 2.7. Available at http://www.python.org
26 Tobías A. Evaluation of the lockdowns for the SARS-CoV-2 epidemic in Italy and Spain after one month follow up. *Sci Total Environ* 2020;725:138539. doi:10.1016/j.scitotenv.2020.138539
27 Markel H, Lipman HB, Navarro JA, et al. Nonpharmaceutical interventions implemented by US cities during the 1918-1919 influenza pandemic. *JAMA* 2007;298:644-54. doi:10.1001/jama.298.6.644
28 Correia S, Luck S, Verner E. Pandemics depress the economy, public health interventions do not: evidence from the 1918 flu. Social Science Research Network, 2020, doi:10.2139/ssrn.3561560
29 Viner RM, Russell SJ, Croker H, et al. School closure and management practices during coronavirus outbreaks including COVID-19: a rapid systematic review. *Lancet Child Adolesc Health* 2020;4:397-404. doi:10.1016/S2352-4642(20)30095-X
30 Remuzzi A, Remuzzi G. COVID-19 and Italy: what next?*Lancet* 2020;395:1225-8. doi:10.1016/S0140-6736(20)30627-9
31 Legido-Quigley H, Asgari N, Teo YY, et al. Are high-performing health systems resilient against the COVID-19 epidemic?*Lancet* 2020;395:848-50. doi:10.1016/S0140-6736(20)30551-1
32 Ranney ML, Griffeth V, Jha AK. Critical supply shortages — the need for ventilators and personal protective equipment during the covid-19 pandemic. *N Engl J Med* 2020;382:e41. doi:10.1056/NEJMp2006141
33 Leung NHL, Chu DKW, Shiu EYC, et al. Respiratory virus shedding in exhaled breath and efficacy of face masks [correction in: *Nat Med* 2020;26:981]. *Nat Med* 2020;26:676-80. doi:10.1038/s41591-020-0843-2
34 Leung CC, Lam TH, Cheng KK. Mass masking in the COVID-19 epidemic: people need guidance. *Lancet* 2020;395:945. doi:10.1016/S0140-6736(20)30520-1
35 Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schünemann HJ, COVID-19 Systematic Urgent Review Group Effort (SURGE) study authors. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet* 2020;395:1973-87. doi:10.1016/S0140-6736(20)31142-9
36 Tian H, Liu Y, Li Y, et al. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science* 2020;368:638-42. doi:10.1126/science.abb6105
37 Buckee CO, Balsari S, Chan J, et al. Aggregated mobility data could help fight COVID-19. *Science* 2020;368:145-6. doi:10.1126/science.abb8021
38 BioRISC. Informing management of lockdowns and a phased return to normality: a Solution Scan of non-pharmaceutical options to reduce SARS-CoV-2 transmission. 2020.
39 Ing E, Xu AQ, Salimi A. Physician deaths from corona virus disease (covid-19). Social Science Research Network, 2020. doi:10.2139/ssrn.3566141
40 Kupferschmidt K. Ending coronavirus lockdowns will be a dangerous process of trial and error. *Science* 2020;14. doi:10.1126/science.abc2507
41 Leung K, Wu JT, Liu D, Leung GM. First-wave COVID-19 transmissibility and severity in China outside Hubei after control measures, and second-wave scenario planning: a modelling impact assessment. *Lancet* 2020;395:1382-93. doi:10.1016/S0140-6736(20)30746-7
42 Xu S, Li Y. Beware of the second wave of COVID-19. *Lancet* 2020;395:1321-2. doi:10.1016/S0140-6736(20)30845-X
43 Razai MS, Oakeshott P, Kankam H, Galea S, Stokes-Lampard H. Mitigating the psychological effects of social isolation during the covid-19 pandemic. *BMJ* 2020;369:m1904. doi:10.1136/bmj.m1904
44 Venkatesh A, Edirappuli S. Social distancing in covid-19: what are the mental health implications?*BMJ* 2020;369:m1379. doi:10.1136/bmj.m1379
45 Gray NA, Back AL. Covid-19 communication aids. *BMJ* 2020;369:m2255. doi:10.1136/bmj.m2255

Web appendix: Supplementary appendix