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Effectiveness of public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality: systematic review and meta-analysis

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ABSTRACT OBJECTIVE

To review the evidence on the effectiveness of public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality.

DESIGN

Systematic review and meta-analysis.

DATA SOURCES

Medline, Embase, CINAHL, Biosis, Joanna Briggs, Global Health, and World Health Organization COVID-19 database (preprints).

ELIGIBILITY CRITERIA FOR STUDY SELECTION

Observational and interventional studies that assessed the effectiveness of public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality.

MAIN OUTCOME MEASURES

The main outcome measure was incidence of covid-19. Secondary outcomes included SARS-CoV-2 transmission and covid-19 mortality.

DATA SYNTHESIS

DerSimonian Laird random effects meta-analysis was performed to investigate the effect of mask wearing, handwashing, and physical distancing measures on incidence of covid-19. Pooled effect estimates with corresponding 95% confidence intervals were computed, and heterogeneity among studies was assessed using Cochran's Q test and the I² metrics, with two tailed P values.

RESULTS

72 studies met the inclusion criteria, of which 35 evaluated individual public health measures and

37 assessed multiple public health measures as a "package of interventions." Eight of 35 studies were included in the meta-analysis, which indicated a reduction in incidence of covid-19 associated with handwashing (relative risk 0.47, 95% confidence interval 0.19 to 1.12, I²=12%), mask wearing (0.47, 0.29 to 0.75, I²=84%), and physical distancing (0.75, 0.59 to 0.95, I²=87%). Owing to heterogeneity of the studies, meta-analysis was not possible for the outcomes of quarantine and isolation, universal lockdowns, and closures of borders, schools, and workplaces. The effects of these interventions were synthesised descriptively.

CONCLUSIONS

This systematic review and meta-analysis suggests that several personal protective and social measures, including handwashing, mask wearing, and physical distancing are associated with reductions in the incidence covid-19. Public health efforts to implement public health measures should consider community health and sociocultural needs, and future research is needed to better understand the effectiveness of public health measures in the context of covid-19 vaccination.

SYSTEMATIC REVIEW REGISTRATION

PROSPERO CRD42020178692.

Introduction

The impact of SARS-CoV-2 on global public health and economies has been profound.¹ As of 14 October 2021, there were 239 007 759 million cases of confirmed covid-19 and 4 871 841 million deaths with covid-19 worldwide.²

A variety of containment and mitigation strategies have been adopted to adequately respond to covid-19, with the intention of deferring major surges of patients in hospitals and protecting the most vulnerable people from infection, including elderly people and those with comorbidities.³ Strategies to achieve these goals are diverse, commonly based on national risk assessments that include estimation of numbers of patients requiring hospital admission and availability of hospital beds and ventilation support.

Globally, vaccination programmes have proved to be safe and effective and save lives.⁴⁻⁵ Yet most vaccines do not confer 100% protection, and it is not known how vaccines will prevent future transmission of SARS-CoV-2,⁶ given emerging variants.⁷⁻⁹ The proportion of the population that must be vaccinated against covid-19 to reach herd immunity depends

WHAT IS ALREADY KNOWN ON THIS TOPIC

Public health measures have been identified as a preventive strategy for influenza pandemics

The effectiveness of such interventions in reducing the transmission of SARS-CoV-2 is unknown

WHAT THIS STUDY ADDS

The findings of this review suggest that personal and social measures, including handwashing, mask wearing, and physical distancing are effective at reducing the incidence of covid-19

More stringent measures, such as lockdowns and closures of borders, schools, and workplaces need to be carefully assessed by weighing the potential negative effects of these measures on general populations

Further research is needed to assess the effectiveness of public health measures after adequate vaccination coverage

greatly on current and future variants.¹⁰ This vaccination threshold varies according to the country and population's response, types of vaccines, groups prioritised for vaccination, and viral mutations, among other factors.⁶ Until herd immunity to covid-19 is reached, regardless of the already proven high vaccination rates,¹¹ public health preventive strategies are likely to remain as first choice measures in disease prevention,¹² particularly in places with a low uptake of covid-19 vaccination. Measures such as lockdown (local and national variant), physical distancing, mandatory use of face masks, and hand hygiene have been implemented as primary preventive strategies to curb the covid-19 pandemic.¹³

Public health (or non-pharmaceutical) interventions have been shown to be beneficial in fighting respiratory infections transmitted through contact, droplets, and aerosols.^{14 15} Given that SARS-CoV-2 is highly transmissible, it is a challenge to determine which measures might be more effective and sustainable for further prevention.

Substantial benefits in reducing mortality were observed in countries with universal lockdowns in place, such as Australia, New Zealand, Singapore, and China. Universal lockdowns are not, however, sustainable, and more tailored interventions need to be considered; the ones that maintain social lives and keep economies functional while protecting high risk individuals.^{16 17} Substantial variation exists in how different countries and governments have applied public health measures,¹⁸ and it has proved a challenge for assessing the effectiveness of individual

public health measures, particularly in policy decision making.¹⁹

Previous systematic reviews on the effectiveness of public health measures to treat covid-19 lacked the inclusion of analytical studies,²⁰ a comprehensive approach to data synthesis (focusing only on one measure),²¹ a rigorous assessment of effectiveness of public health measures,²² an assessment of the certainty of the evidence,²³ and robust methods for comparative analysis.²⁴ To tackle these gaps, we performed a systematic review of the evidence on the effectiveness of both individual and multiple public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality. When feasible we also did a critical appraisal of the evidence and meta-analysis.

Methods

This systematic review and meta-analysis were conducted in accordance with PRISMA²⁵ (supplementary material 1, table 1) and with PROSPERO (supplementary material 1, table 2).

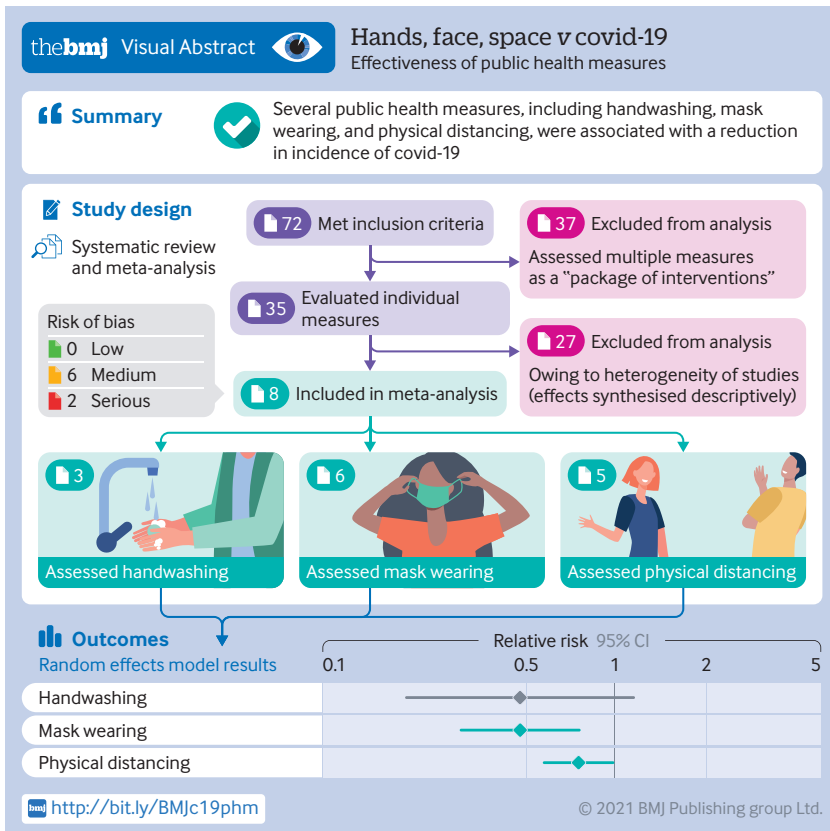
Eligibility criteria

Articles that met the population, intervention, comparison, outcome, and study design criteria were eligible for inclusion in this systematic review (supplementary material 1, table 3). Specifically, preventive public health measures that were tested independently were included in the main analysis. Multiple measures, which generally contain a “package of interventions”, were included as supplementary material owing to the inability to report on the individual effectiveness of measures and comparisons on which package led to enhanced outcomes. The public health measures were identified from published World Health Organization sources that reported on the effectiveness of such measures on a range of communicable diseases, mostly respiratory infections, such as influenza.

Given that the scientific community is concerned about the ability of the numerous mathematical models, which are based on assumptions, to predict the course of virus transmission or effectiveness of interventions,²⁶ this review focused only on empirical studies. We excluded case reports and case studies, modelling and simulation studies, studies that provided a graphical summary of measures without clear statistical assessments or outputs, ecological studies that provided a descriptive summary of the measures without assessing linearity or having comparators, non-empirical studies (eg, commentaries, editorials, government reports), other reviews, articles involving only individuals exposed to other pathogens that can cause respiratory infections, such as severe acute respiratory syndrome or Middle East respiratory syndrome, and articles in a language other than English.

Information sources

We carried out electronic searches of Medline, Embase, CINAHL (Cumulative Index to Nursing and



Allied Health Literature, Ebsco), Global Health, Biosis, Joanna Briggs, and the WHO COVID-19 database (for preprints). A clinical epidemiologist (ST) developed the initial search strategy, which was validated by two senior medical librarians (LR and MD) (supplementary material 1, table 4). The updated search strategy was last performed on 7 June 2021. All citations identified from the database searches were uploaded to Covidence, an online software designed for managing systematic reviews,²⁷ for study selection.

Study selection

Authors ST, DG, SS, AM, ET, JR, XL, WX, IME, and XZ independently screened the titles and abstracts and excluded studies that did not match the inclusion criteria. Discrepancies were resolved in discussion with the main author (ST). The same authors retrieved full text articles and determined whether to include or exclude studies on the basis of predetermined selection criteria. Using a pilot tested data extraction form, authors ST, SS, AM, JR, XL, WX, AM, IME, and XZ independently extracted data on study design, intervention, effect measures, outcomes, results, and limitations. ST, SS, AM, and HW verified the extracted data. Table 5 in supplementary material 1 provides the specific criteria used to assess study designs. Given the heterogeneity and diversity in how studies defined public health measures, we took a common approach to summarise evidence of these interventions (supplementary material 1, table 6).

Risk of bias within individual studies

SS, JR, XL, WX, IME, and XZ independently assessed risk of bias for each study, which was cross checked by ST and HW. For non-interventional observational studies, a ROBINS-I (risk of bias in non-randomised studies of interventions) risk of bias tool was used.²⁸ For interventional studies, a revised tool for assessing risk of bias in randomised trials (RoB 2) tool was used.²⁹ Reviewers rated each domain for overall risk of bias as low, moderate, high, or serious/critical.

Data synthesis

The DerSimonian and Laird method was used for random effects meta-analysis, in which the standard error of the study specific estimates was adjusted to incorporate a measure of the extent of variation, or heterogeneity, among the effects observed for public health measures across different studies. It was assumed that the differences between studies are a result of different, yet related, intervention effects being estimated. If fewer than five studies were included in meta-analysis, we applied a recommended modified Hartung-Knapp-Sidik-Jonkman method.³⁰

Statistical analysis

Because of the differences in the effect metrics reported by the included studies, we could only perform quantitative data synthesis for three interventions: handwashing, face mask wearing, and physical distancing. Odds ratios or relative risks

with corresponding 95% confidence intervals were reported for the associations between the public health measures and incidence of covid-19. When necessary, we transformed effect metrics derived from different studies to allow pooled analysis. We used the Dersimonian Laird random effects model to estimate pooled effect estimates along with corresponding 95% confidence intervals for each measure. Heterogeneity among individual studies was assessed using the Cochran Q test and the I² test.³¹ All statistical analyses were conducted in R (version 4.0.3) and all P values were two tailed, with P=0.05 considered to be significant. For the remaining studies, when meta-analysis was not feasible, we reported the results in a narrative synthesis.

Public and patient involvement

No patients or members of the public were directly involved in this study as no primary data were collected. A member of the public was, however, asked to read the manuscript after submission.

Results

A total of 36 729 studies were initially screened, of which 36 079 were considered irrelevant. After exclusions, 650 studies were eligible for full text review and 72 met the inclusion criteria. Of these studies, 35 assessed individual interventions and were included in the final synthesis of results (fig 1) and 37 assessed multiple interventions as a package and are included in supplementary material 3, tables 2 and 3. The included studies comprised 34 observational studies and one interventional study, eight of which were included in the meta-analysis.

Risk of bias

According to the ROBINS-I tool,²⁸ the risk of bias was rated as low in three studies,³²⁻³⁴ moderate in 24 studies,³⁵⁻⁵⁸ and high to serious in seven studies.⁵⁹⁻⁶⁵ One important source of serious or critical risk of bias in most of the included studies was major confounding, which was difficult to control for because of the novel nature of the pandemic (ie, natural settings in which multiple interventions might have been enforced at once, different levels of enforcement across regions, and uncaptured individual level interventions such as increased personal hygiene). Variations in testing capacity and coverage, changes to diagnostic criteria, and access to accurate and reliable outcome data on covid-19 incidence and covid-19 mortality, was a source of measurement bias for numerous studies (fig 2). These limitations were particularly prominent early in the pandemic, and in low income environments.^{47 52 62 63 65} The randomised controlled trial⁶⁶ was rated as moderate risk of bias according to the ROB-2 tool. Missing data, losses to follow-up, lack of blinding, and low adherence to intervention all contributed to the reported moderate risk. Tables 1 and 2 in supplementary material 2 summarise the risk of bias assessment for each study assessing individual measures.

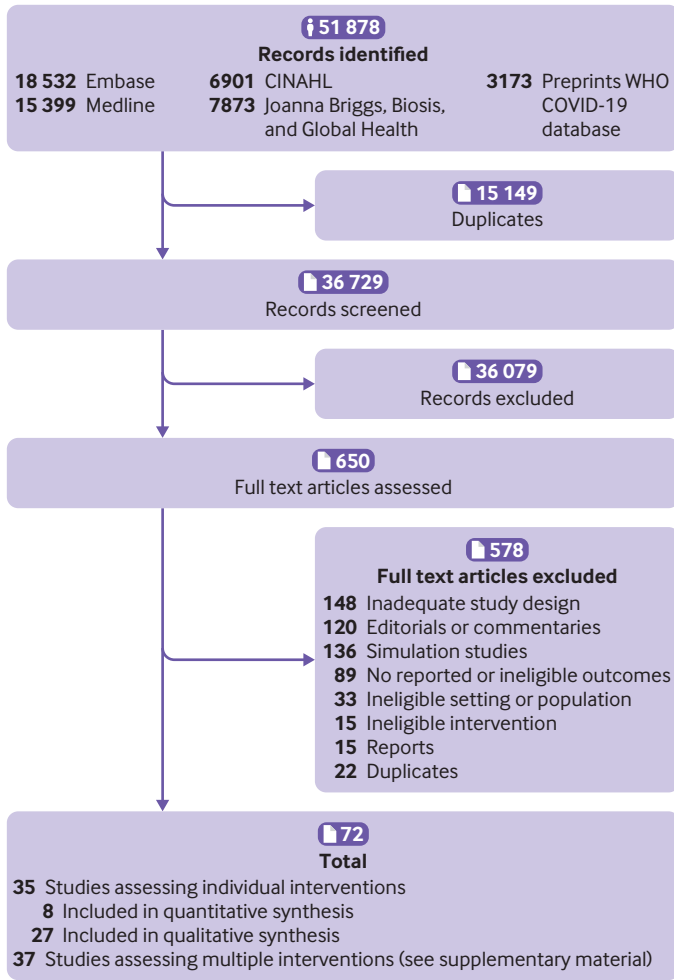


Fig 1 | Flow of articles through the review. WHO=World Health Organization

Study characteristics

Studies assessing individual measures

Thirty five studies provided estimates on the effectiveness of an individual public health measures. The studies were conducted in Asia (n=11), the United

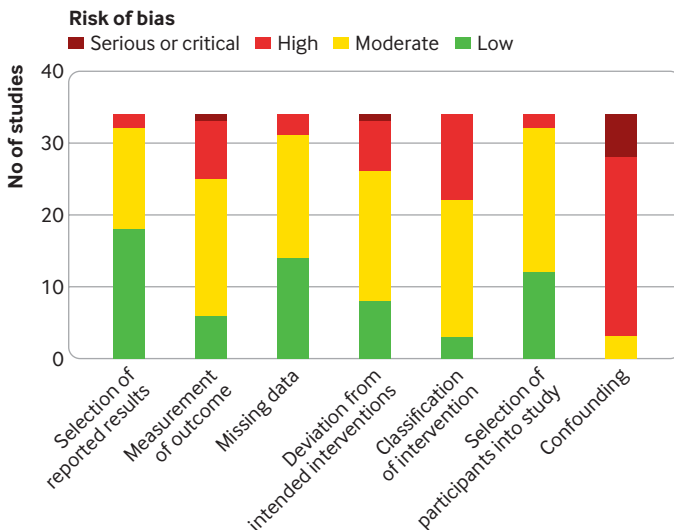


Fig 2 | Summary of risk of bias across studies assessing individual measures using risk of bias in non-randomised studies of interventions (ROBINS-I) tool

States (n=9), Europe (n=7), the Middle East (n=3), Africa (n=3), South America (n=1), and Australia (n=1). Thirty four of the studies were observational and one was a randomised controlled trial. The study designs of the observational studies comprised natural experiments (n=11), quasi-experiments (n=3), a prospective cohort (n=1), retrospective cohorts (n=8), case-control (n=2), and cross sectional (n=9). Twenty six studies assessed social measures,^{32 34 35 37-42 44 46-48 52 53 55-61 63-65 67}

12 studies assessed personal protective measures,^{36 43 45 49 50 57 58 60 63 66 68} three studies assessed travel related measures,^{54 58 62} and one study assessed environmental measures⁵⁷ (some interventions overlapped across studies). The most commonly measured outcome was incidence of covid-19 (n=18), followed by SARS-CoV-2 transmission, measured as reproductive number, growth number, or epidemic doubling time (n=13), and covid-19 mortality (n=8). Table 1 in supplementary material 3 provides detailed information on each study.

Effects of interventions

Personal protective measures

Handwashing and covid-19 incidence—Three studies with a total of 292 people infected with SARS-CoV-2 and 10 345 participants were included in the analysis of the effect of handwashing on incidence of covid-19.^{36 60 63} Overall pooled analysis suggested an estimated 53% non-statistically significant reduction in covid-19 incidence (relative risk 0.47, 95% confidence interval 0.19 to 1.12, I²=12%) (fig 3). A sensitivity analysis without adjustment showed a significant reduction in covid-19 incidence (0.49, 0.33 to 0.72, I²=12%) (fig 4). Risk of bias across the three studies ranged from moderate^{36 60} to serious or critical⁶³ (fig 2).

Mask wearing and covid-19 incidence—Six studies with a total of 2627 people with covid-19 and 389 228 participants were included in the analysis examining the effect of mask wearing on incidence of covid-19 (table 1).^{36 43 57 60 63 66} Overall pooled analysis showed a 53% reduction in covid-19 incidence (0.47, 0.29 to 0.75), although heterogeneity between studies was substantial (I²=84%) (fig 5). Risk of bias across the six studies ranged from moderate^{36 57 60 66} to serious or critical^{43 63} (fig 2).

Mask wearing and transmission of SARS-CoV-2, covid-19 incidence, and covid-19 mortality—The results of additional studies that assessed mask wearing (not included in the meta-analysis because of substantial differences in the assessed outcomes) indicate a reduction in covid-19 incidence, SARS-CoV-2 transmission, and covid-19 mortality. Specifically, a natural experiment across 200 countries showed 45.7% fewer covid-19 related mortality in countries where mask wearing was mandatory (table 1).⁴⁹ Another natural experiment study in the US reported a 29% reduction in SARS-CoV-2 transmission (measured as the time varying reproductive number Rt) (risk ratio 0.71, 95% confidence interval 0.58 to 0.75) in states where mask wearing was mandatory.⁵⁸

A comparative study in the Hong Kong Special Administrative Region reported a statistically

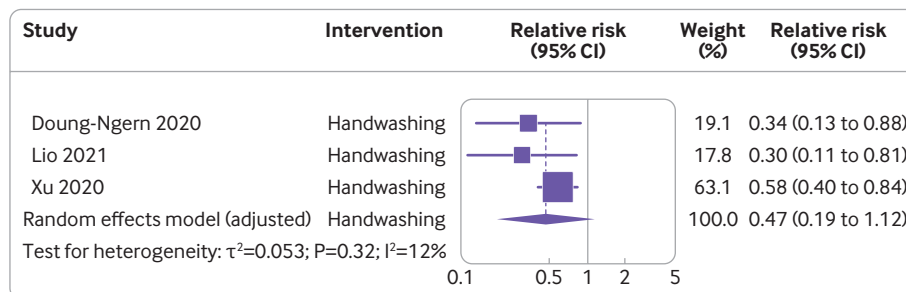


Fig 3 | Meta-analysis of evidence on association between handwashing and incidence of covid-19 using modified Hartung-Knapp-Sidik-Jonkman adjusted random effect model

significant lower cumulative incidence of covid-19 associated with mask wearing than in selected countries where mask wearing was not mandatory (table 1).⁶⁸ Similarly, another natural experiment involving 15 US states reported a 2% statistically significant daily decrease in covid-19 transmission (measured as case growth rate) at ≥ 21 days after mask wearing became mandatory,⁵⁰ whereas a cross sectional study reported that a 10% increase in self-reported mask wearing was associated with greater odds for control of SARS-CoV-2 transmission (adjusted odds ratio 3.53, 95% confidence interval 2.03 to 6.43).⁴⁵ The five studies were rated at moderate risk of bias (fig 2).

Environmental measures

Disinfection in household and covid-19 incidence

Only one study, from China, reported the association between disinfection of surfaces and risk of secondary transmission of SARS-CoV-2 within households (table 1).⁵⁷ The study assessed disinfection retrospectively by asking participants about their “daily use of chlorine or ethanol-based disinfectant in households,” and observed that use of disinfectant was 77% effective at reducing SARS-CoV-2 transmission (odds ratio 0.23, 95% confidence interval 0.07 to 0.84). The study did not collect data on the concentration of the disinfectant used by participants and was rated at moderate risk of bias (fig 2).

Social measures

Physical distancing and covid-19 incidence

Five studies with a total of 2727 people with SARS-CoV-2 and 108 933 participants were included in the analysis that examined the effect of physical distancing

on the incidence of covid-19.^{37 53 57 60 63} Overall pooled analysis indicated a 25% reduction in incidence of covid-19 (relative risk 0.75, 95% confidence interval 0.59 to 0.95, $I^2=87\%$) (fig 6). Heterogeneity among studies was substantial, and risk of bias ranged from moderate^{37 53 57 60} to serious or critical⁶³ (fig 2).

Physical distancing and transmission of SARS-CoV-2 and covid-19 mortality

Studies that assessed physical distancing but were not included in the meta-analysis because of substantial differences in outcomes assessed, generally reported a positive effect of physical distancing (table 2). A natural experiment from the US reported a 12% decrease in SARS-CoV-2 transmission (relative risk 0.88, 95% confidence interval 0.86 to 0.89),⁴⁰ and a quasi-experimental study from Iran reported a reduction in covid-19 related mortality ($\beta -0.07$, 95% confidence interval -0.05 to -0.10 ; $P<0.001$).⁴⁷ Another comparative study in Kenya also reported a reduction in transmission of SARS-CoV-2 after physical distancing was implemented, reporting 62% reduction in overall physical contacts (reproductive number pre-intervention was 2.64 and post-intervention was 0.60 (interquartile range 0.50 to 0.68)).⁶¹ These three studies were rated at moderate risk of bias^{40 61} to serious or critical risk of bias⁴⁷ (fig 2).

Stay at home or isolation and transmission of SARS-CoV-2

All the studies that assessed stay at home or isolation measures reported reductions in transmission of SARS-CoV-2 (table 2). A retrospective cohort study from the US reported a significant reduction in the odds of having

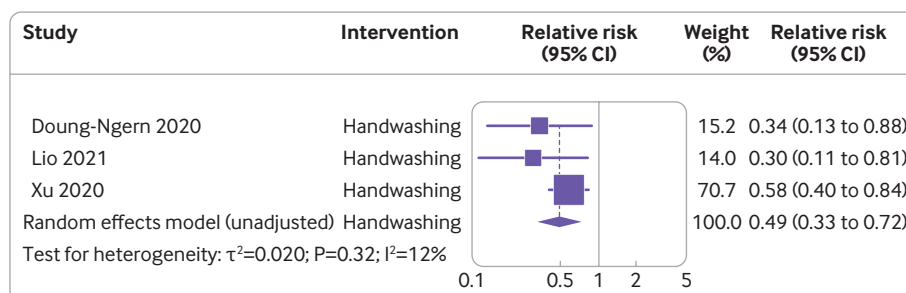


Fig 4 | Meta-analysis of evidence on association between handwashing and incidence of covid-19 using unadjusted random effect model

Table 1 | Study characteristics and main results from studies that assessed individual personal protective and environmental measures

Reference, country	Study design	Public health measure	Sample size	Outcome measure	Study duration	Effect estimates: conclusions	Risk of bias
Doung-Ngern et al, ⁶³ Thailand	Case-control	Handwashing	211 cases, 839 controls	Incidence	1-31 Mar 2020	Regular handwashing: adjusted odds ratio 0.34 (95% confidence interval 0.13 to 0.87): associated with lower risk of SARS-CoV-2*	Serious or critical
Lio et al, ³⁶ China	Case-control	Handwashing	24 cases, 1113 controls	Incidence	17 Mar-15 Apr 2020	Adjusted odds ratio 0.30 (95% confidence interval 0.11 to 0.80): reduction in odds of becoming infectious*	Moderate
Xu et al, ⁶⁰ China	Cross sectional comparative	Handwashing	n=8158	Incidence	22 Feb-5 Mar 2020	Relative risk 3.53 (95% confidence interval 1.53 to 8.15): significantly increased risk of infection with no handwashing*	Moderate
Bundgaard et al, ⁶⁶ Denmark	Randomised controlled	Mask wearing	2392 cases, 2470 controls	Incidence	Apr and May 2020	Odds ratio 0.82 (95% confidence interval 0.54 to 1.23): 46% reduction to 23% increase in infection*	Moderate
Doung-Ngern et al, ⁶³ Thailand	Case-control	Mask wearing	211 cases, 839 controls	Incidence	1-31 Mar 2020	Adjusted odds ratio 0.23 (95% confidence interval 0.09 to 1.60): associated with lower risk of SARS-CoV-2 infection*	Serious or critical
Lio et al, ³⁶ China	Case-control	Mask wearing	24 cases, 1113 controls	Incidence	17 Mar-15 Apr 2020	Odds ratio 0.30 (95% confidence interval 0.10 to 0.86): 70% risk reduction*	Moderate
Xu et al, ⁶⁰ China	Cross sectional comparative	Mask wearing	8158 people	Incidence	22 Feb-5 Mar 2020	Relative risk 12.38 (95% confidence interval 5.81 to 26.36): significantly increased risk of infection*	Moderate
Krishnamachari et al, ⁴³ US	Natural experiment	Mask wearing	50 states	Incidence (cumulative rate)	Apr 2020	3-6 months, adjusted odds ratio 1.61 (95% confidence interval 1.23 to 2.10): >6 months, 2.16 (1.64 to 2.88): higher incidence rate with later mask mandate than with mask mandate in first month*	Serious or critical
Wang et al, ⁵⁷ China	Retrospective cohort	Mask wearing	335 people	Incidence (assessed as attack rate†)	28 Feb-27 Mar 2020	Odds ratio 0.21 (95% confidence interval 0.06 to 0.79): 79% reduction in transmission of SARS-CoV-2*	Moderate
Cheng et al, ⁶⁸ China	Longitudinal comparative	Mask wearing (South Korea v HKSAR)	961 cases (HKSAR), average control not available	Incidence	31 Dec 2019-8 Apr 2020	Incidence rate 49.6% (South Korea) v 11.8% (HKSAR) P<0.001: 37.8% less SARS-CoV-2 cases*	Moderate
Leffler et al, ⁴⁹ US	Natural experiment	Mask wearing	200 countries	Mortality (per capita)	Jan-9 May 2020	No masks: mortality rate 61.9% (95% confidence interval 37.0% to 91.0%); masks: 16.2% (-14.4% to 57.4%): 45.7% fewer mortality*	Moderate
Lyu et al, ⁵⁰ US	Natural experiment	Mask wearing	15 states	Case growth rate	31 Mar-22 May 2020	Mandatory mask wearing: case growth rate 2%: 2% decrease in daily covid-19 growth rate at ≥21 days (P<0.05)*	Moderate
Rader et al, ⁴⁵ US	Cross sectional	Mask wearing	378 207 people	R0	3 Jun-27 Jul	Adjusted odds ratio 3.53 (95% confidence interval 2.03 to 6.43): 10% increase in self-reported mask wearing was associated with an increased odds of transmission control*	Moderate
Liu et al, ⁵⁸ US	Natural experiment	Mask wearing	50 states	Rt	21 Jan-31 May 2020	Risk ratio 0.71 (95% confidence interval 0.58 to 0.75): 29% reduction in Rt*	Moderate
Wang et al, ⁵⁷ China	Retrospective cohort	Chlorine or ethanol based disinfectant	335 people	Incidence (attack rate†)	28 Feb-27 Mar 2020	Odds ratio 0.23 (95% confidence interval 0.07 to 0.84): 77% reduction in transmission of SARS-CoV-2*	Moderate

HKSAR=Hong Kong Special Administrative Region of China; R0=reproductive number; Rt=time varying reproductive number.

*Interpretation of findings as reported in the original manuscript.

†Percentage of individuals who tested positive over a specified period.

a positive reproductive number (R0) result (odds ratio 0.07, 95% confidence interval 0.01 to 0.37),⁴¹ and a natural experiment reported a 51% reduction in time varying reproductive number (Rt) (risk ratio 0.49, 95% confidence interval 0.43 to 0.54).⁵⁸

A study from the UK reported a 74% reduction in the average daily number of contacts observed for each participant and estimated a decrease in reproductive number: the reproductive number pre-intervention was 3.6 and post-intervention was 0.60 (95% confidence interval 0.37 to 0.89).⁶⁵ Similarly, an Iranian study projected the reproductive number using serial interval

distribution and the number of incidence cases and found a significant decrease: the reproductive number pre-intervention was 2.70 and post-intervention was 1.13 (95% confidence interval 1.03 to 1.25).⁵⁵ Three of the studies were rated at moderate to serious or critical risk of bias,^{55 58 65} and one study was rated at low risk of bias⁴¹ (fig 2).

Quarantine and incidence and transmission of SARS-CoV-2

Quarantine was assessed in two studies (table 2).^{34 59} A prospective cohort study from Saudi Arabia reported

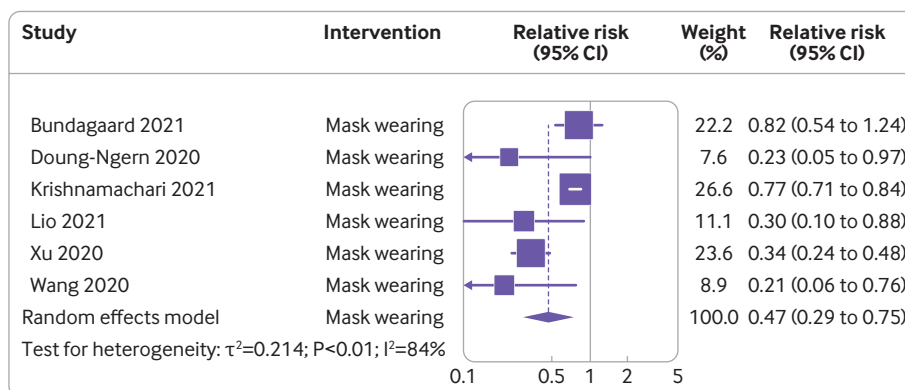


Fig 5 | Meta-analysis of evidence on association between mask wearing and incidence of covid-19 using unadjusted random effect model

a 4.9% decrease in the incidence of covid-19 at eight weeks after the implementation of quarantine.³⁴ This study was rated at low risk of bias (fig 2). A retrospective cohort study from India reported a 14 times higher risk of SARS-CoV-2 transmission associated with no quarantine compared with strict quarantine (odds ratio 14.44, 95% confidence interval 2.42 to 86.17).⁵⁹ This study was rated at moderate risk of bias (fig 2).

School closures and covid-19 incidence and covid-19 mortality

Two studies assessed the effectiveness of school closures on transmission of SARS-CoV-2, incidence of covid-19, or covid-19 mortality (table 2).^{44 48} A US population based longitudinal study reported on the effectiveness of state-wide closure of primary and secondary schools and observed a 62% decrease (95% confidence interval -49% to -71%) in incidence of covid-19 and a 58% decrease (-46% to -68%) in covid-19 mortality.⁴⁸ Conversely, a natural experiment from Japan reported no effect of school closures on incidence of covid-19 (α coefficient 0.08, 95% confidence interval -0.36 to 0.65).⁴⁴ Both studies were rated at moderate risk of bias (fig 2).

School closures and transmission of SARS-CoV-2

Two natural experiments from the US reported a reduction in transmission (ie, reproductive number); with one study reporting a reduction of 13% (relative

risk 0.87, 95% confidence interval 0.86 to 0.89)⁴⁰ and another reporting a 10% (0.90, 0.86 to 0.93) reduction (table 2).⁵⁸ A Swedish study reported an association between school closures and a small increase in confirmed SARS-CoV-2 infections in parents (odds ratio 1.17, 95% confidence interval 1.03 to 1.32), but observed that teachers in lower secondary schools were twice as likely to become infected than teachers in upper secondary schools (2.01, 1.52 to 2.67).³² All three studies were rated at moderate risk of bias (fig 2).

Business closures and transmission of SARS-CoV-2

Two natural experiment studies assessed business closures across 50 US states and reported reductions in transmission of SARS-CoV-2 (table 2).^{40 58} One of the studies observed a significant reduction in transmission of 12% (relative risk 0.88, 95% confidence interval 0.86 to 0.89)⁴⁰ and the other reported a significant 16% (risk ratio 0.84, 0.79 to 0.90) reduction.⁵⁸ Both studies were rated at moderate risk of bias (fig 2).

Lockdown and incidence of covid-19

A natural experiment involving 202 countries suggested that countries that implemented universal lockdown had fewer new cases of covid-19 than countries that did not (β coefficient -235.8 (standard error -11.04), $P<0.01$) (table 2).⁵² An Indian quasi-experimental study reported a 10.8% reduction in incidence of covid-19 post-lockdown,⁵⁶ whereas a South African

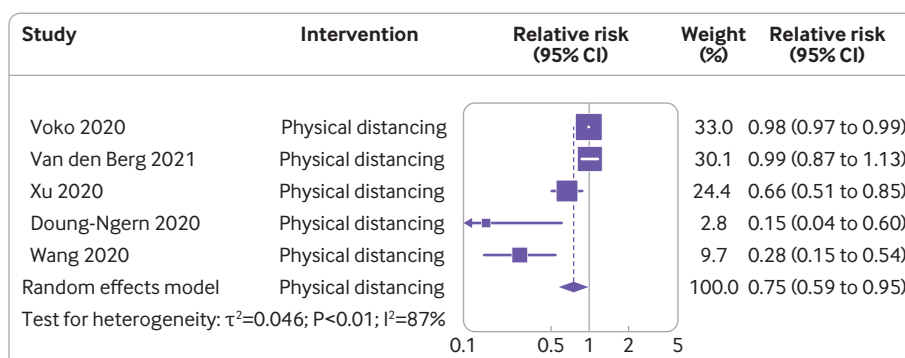


Fig 6 | Meta-analysis of evidence on association between physical distancing and incidence of covid-19 using unadjusted random effect model

Table 2 | Study characteristics and main results from studies assessing individual social measures

Reference, country	Study design	Public health measure	Sample size	Outcome	Study duration	Effect estimates: conclusions	Risk of bias
Jarvis et al, ⁶⁵ UK	Cross sectional	Stay at home or isolation	1356 cases	RO	Feb-24 Mar 2020	RO: pre-intervention 3.6, post-intervention 0.60 (95% confidence interval 0.37 to 0.89): 3.0 RO decrease	Serious or critical
Khosravi et al, ⁵⁵ Iran	Cross sectional	Stay at home or isolation	993 cases	RO	20 Feb-01 Apr 2020	RO: pre-intervention 2.70 (95% confidence interval 2.10 to 3.40), post-intervention 1.13 (1.03 to 1.25): 1.5 RO decrease	Moderate
Dreher et al, ⁴¹ US	Retrospective cohort	Stay at home or isolation	49 states and territories	RO	NS	Odds ratio 0.07 (95% confidence interval 0.01 to 0.37): decrease in odds of having a positive RO result*	Low
Liu et al, ⁵⁸ US	Natural experiment	Stay at home or isolation	50 states	Rt	21 Jan-31 May 2020	Risk ratio 0.49 (95% confidence interval 0.43 to 0.54): contributed about 51% to reduction in Rt*	Moderate
Alfano et al, ⁵² Italy	Natural experiment	Lockdown	202 countries, 22 018 people	Incidence	22 Jan-10 May 2020	β coefficient -235.8 (standard error -11.04), P<0.01	Serious or critical
Thayer et al, ⁵⁶ India	Quasi-experimental	Lockdown	NS	Incidence (% median)	2 Mar-1 Sept 2020	Incidence rate: pre-lockdown 15.8% (95% confidence interval 7.0% to 20.2%), post-lockdown 5.0% (4.7% to 5.4%): 10.8% reduction in average incidence rate*	Moderate
Pillai et al, ⁴⁶ South Africa	Retrospective cohort	Lockdown	162 528	Attack rate†	5 Mar-30 June 2020	Attack rate: pre-lockdown 18.5%, full lockdown 4.1%: 14.1% reduction in risk*	Moderate
Siedner et al, ³⁵ US	Natural experiment	Lockdown	45 states	Case growth rate, mortality growth rate	10-25 Mar 2020	Case growth rate 0.9% decrease (95% confidence interval 1.40% to 0.4%)/day (after 4 days)*; mortality growth rate 2.0% mortality decrease (-3.0% to 0.9%)/day*	Moderate
Silva et al, ⁴² Brazil	Quasi-experimental	Lockdown	Nationwide	Mortality	5-30 Mar 2020	Post-intervention changes in mortality, São Luís (β coefficient -0.13, P<0.001), Recife (β coefficient -0.06, P<0.001), Belém (β coefficient -0.10, P<0.001), Fortaleza (β coefficient -0.09, P<0.001): 27.4% average difference in mortality	Moderate
Tobias et al, ³⁸ Spain	Natural experiment	Lockdown	Spain and Italy	Mortality	24 Feb-5 Apr 2020	Mortality rates: Italy pre-intervention -32.8 (95% confidence interval 21.0 to 44.6), Italy post-intervention -0.2 (-1.5 to 1.0), Spain pre-intervention 59.3 (23.0 to 95.2), Spain post-intervention -1.8 (-5.0 to 3.1): beneficial effect in both countries*	Moderate
Wang et al, ⁶⁹ China	Retrospective cohort	Lockdown	Nationwide	RO	10 Jan-16 Feb 2020	RO: pre-intervention 4.95 (95% confidence interval 4.26 to 5.67), post-intervention 0.98 (0.96 to 1.03): 3.97 decrease	Low
Guzzetta et al, ³⁹ Italy	Longitudinal comparative	Lockdown	Nationwide	RO	10-25 Mar 2020	RO: pre-intervention 2.03, 3 weeks 0.76 (95% confidence interval 0.67 to 0.85): 1.27 decrease	Low
Basu et al, ⁶⁴ India	Retrospective cohort	Lockdown	Nationwide	RO	24 Mar-31 May 2020	RO: pre-intervention 3.36 (95% confidence interval 3.03 to 3.71), post-intervention 1.27 (1.26 to 1.28): 2.09 decrease	Moderate
Guo et al, ⁴⁰ US	Natural experiment	Lockdown	50 states and one territory (Virgin Islands)	Rt	29 Jan-31 Jul 2020	Relative risk 0.89 (95% confidence interval 0.88 to 0.91): associated with a 11% decrease in risk of Rt*	Moderate
Al-Tawfiq et al, ³⁴ Saudi Arabia	Prospective cohort	Quarantine	1928 cases	Incidence	14 Mar-6 Jun 2020	Incidence rate: 4 weeks 5.9%, 8 weeks 1.0%, 13 weeks 0%: 4.9% decrease at 8 weeks	Low
Vaman et al, ⁵⁹ India	Retrospective cohort	Quarantine	179 cases	Risk of transmission	24 Mar-30 Apr 2020	Odds ratio 14.44 (95% confidence interval 2.42 to 86.17), relative risk 11.85 (95% confidence interval 2.91 to 48.23): >14 times higher risk without quarantine compared with strict quarantine.* Significant risk of transmission*	Moderate
Auger et al, ⁴⁸ US	Longitudinal comparative	School closure	Nationwide	Incidence, mortality (adjusted relative change)	9 Mar-7 May 2020	Incidence -62% (95% confidence interval -49% to -71%), mortality rate -58% (95% confidence interval -46% to -68%): decreased covid-19 incidence and mortality*	Moderate
Vlachos et al, ³² Sweden	Cross sectional comparative	School closure	Teachers and parents, number not specified	Incidence	25 Mar-1 Apr 2020	Odds ratio 2.01 (95% confidence interval 1.52 to 2.67): teachers in lower secondary schools twice as likely to become infected with SARS-CoV-2 than teachers in upper secondary school*	Moderate
Iwata et al, ⁴⁴ Japan	Natural experiment	School closure	Not specified	Incidence	27-Feb 31 Mar 2020	α coefficient 0.08 (95% confidence interval -0.36 to 0.65): no decrease in incidence of SARS-CoV-2†	Moderate
Liu et al, ⁵⁸ US	Natural experiment	School closure	50 states	Rt	21 Jan-31 May 2020	Risk ratio 0.90 (95% confidence interval 0.86 to 0.93): contributed about 10% to reduction in Rt*	Moderate
Guo et al, ⁴⁰ US	Natural experiment	School closure	50 states and one territory (Virgin Islands)	Rt	29 Jan-31 July 2020	Relative risk 0.87 (95% confidence interval 0.86 to 0.89): associated with 13% decrease in risk of Rt*	Moderate
Liu et al, ⁵⁸ US	Natural experiment	Business closure	50 states	Rt	21 Jan-31 May 2020	Risk ratio 0.84 (95% confidence interval 0.79 to 0.90): contributed about 26% reduction in Rt*	Moderate

(Continued)

Table 2 | Continued

Reference, country	Study design	Public health measure	Sample size	Outcome	Study duration	Effect estimates: conclusions	Risk of bias
Guo et al, ⁴⁰ US	Natural experiment	Business closure	50 states and one territory (Virgin Islands)	Rt	29 Jan-31 July 2020	Relative risk 0.88 (95% confidence interval 0.86 to 0.89): associated with 12% decrease in risk of Rt*	Moderate
Voko et al, ⁵³ Europe	Natural experiment	Physical distancing	28 countries	Incidence	1 Feb-18 Apr 2020	Incidence rate ratio 1.23 (95% confidence interval 1.19 to 1.28), 0.98 (0.97 to 0.99): 26% decrease in incidence*	Moderate
Van den Berg et al, ³⁷ US	Retrospective cohort	Physical distancing	99 390 staff	Incidence (adjusted)	24 Sep 2020-27 Jan 2021	≥3 v ≥6 feet adjusted incidence rate ratio 1.01 (95% confidence interval 0.75 to 1.36), larger physical distancing not associated with lower rates of SARS-CoV-2*†	Moderate
Xu et al, ⁶⁰ China	Cross sectional comparative	Physical distancing	8158 people	Incidence	22 Feb-5 Mar 2020	Relative risk 2.63 (95% confidence interval 1.48 to 4.67): significantly increased risk of infection*	Moderate
Doung-Ngern et al, ⁶³ Thailand	Case-control	Physical distancing	211 cases, 839 controls	Incidence	1-31 Mar 2020	>1m physical distance adjusted odds ratio 0.15; 95% confidence interval 0.04 to 0.63): associated with lower risk of SARS-CoV-2 infection*	Serious or critical
Wang et al, ⁵⁷ China	Retrospective cohort	Physical distancing	335 people	Incidence (proportions assessed as attack rate†)	28 Feb-27 Mar 2020	Odds ratio 18.26 (95% confidence interval 3.93 to 84.79): risk of household transmission was 18 times higher with frequent daily close contact with the primary case*	Moderate
Alimohamadi et al, ⁴⁷ Iran	Quasi-experimental	Physical distancing	NS	Incidence, mortality	20 Feb-13 May 2020	Incidence β coefficient -1.70 (95% confidence interval -2.3 to 1.1), mortality β coefficient -0.07 (-0.05 to -0.10): reduced incidence and mortality*	Serious or critical
Quaife et al, ⁶¹ Africa	Cross-sectional comparative	Physical distancing	237 cases	RO	1 -31 May 2020	RO: pre-intervention 2.64, post-intervention 0.60 (interquartile range 0.50-0.68): 2.04 decrease in RO	Moderate
Guo et al, ⁴⁰ US	Natural experiment	Physical distancing	50 states and one territory (Virgin Islands)	Rt	29 Jan-31 Jul 2020	Relative risk 0.88 (95% confidence interval 0.86 to 0.89): associated with a 12% decrease in risk of Rt*	Moderate

RO=reproductive number; Rt=time varying reproductive number.

*Interpretation of findings as reported in the original manuscript.

†Percentage of individuals who tested positive over a specified period.

‡Not an effective intervention.

retrospective cohort study observed a 14.1% reduction in risk after implementation of universal lockdown (table 2).⁴⁶ These studies were rated at high risk of bias⁵² and moderate risk of bias^{46 56} (fig 2).

Lockdown and covid-19 mortality

The three studies that assessed universal lockdown and covid-19 mortality generally reported a decrease in mortality (table 2).^{35 38 42} A natural experiment study involving 45 US states reported a decrease in covid-19 related mortality of 2.0% (95% confidence interval -3.0% to 0.9%) daily after lockdown had been made mandatory.³⁵ A Brazilian quasi-experimental study reported a 27.4% average difference in covid-19 related mortality rates in the first 25 days of lockdown.⁴² In addition, a natural experiment study reported about 30% and 60% reductions in covid-19 related mortality post-lockdown in Italy and Spain over four weeks post-intervention, respectively.³⁸ All three studies were rated at moderate risk of bias (fig 2).

Lockdown and transmission of SARS-CoV-2

Four studies assessed universal lockdown and transmission of SARS-CoV-2 during the first few months of the pandemic (table 2). The decrease in reproductive number (RO) ranged from 1.27 in Italy (pre-intervention 2.03, post-intervention 0.76)³⁹ to 2.09 in India (pre-intervention 3.36, post-intervention 1.27),⁶⁴ and 3.97 in China (pre-intervention 4.95, post-intervention 0.98).³³ A natural experiment from the US

reported that lockdown was associated with an 11% reduction in transmission of SARS-CoV-2 (relative risk 0.89, 95% confidence interval 0.88 to 0.91).⁴⁰ All the studies were rated at low risk of bias^{33 39} to moderate risk^{40 64} (fig 2).

Travel related measures

Restricted travel and border closures

Border closure was assessed in one natural experiment study involving nine African countries (table 3).⁶² Overall, the countries recorded an increase in the incidence of covid-19 after border closure. These studies concluded that the implementation of border closures within African countries had minimal effect on the incidence of covid-19. The study had important limitations and was rated at serious or critical risk of bias. In the US, a natural experiment study reported that restrictions on travel between states contributed about 11% to a reduction in SARS-CoV-2 transmission (table 3).³⁶ The study was rated at moderate risk of bias (fig 2).

Entry and exit screening (virus or symptom screening)

One retrospective cohort study assessed screening of symptoms, which involved testing 65 000 people for fever (table 3).⁵⁴ The study found that screening for fever lacked sensitivity (ranging from 18% to 24%) in detecting people with SARS-CoV-2 infection. This translated to 86% of the population with SARS-CoV-2 remaining undetected when screening for fever. The study was rated at moderate risk of bias (fig 2).

Table 3 | Study characteristics and main results from studies that assessed individual travel measures

Reference, country	Study design	Public health measure	Sample size	Outcome measure	Study duration	Effect estimates: conclusions	Risk of bias
Emeto et al, ⁶² Africa	Natural experiment	Border closure	9 countries	Rt	14 Feb-19 Jul 2020	See supplementary table for data on all countries: minimal effect on reducing transmission (Rt)*†	Serious or critical
Liu et al, ⁵⁸ USA	Natural experiment	Interstate travel restrictions	50 states	Rt	21 Jan-31 May 2020	Risk ratio 0.89 (95% confidence interval 0.84 to 0.95): contributed about 11% to reduction in Rt*	Moderate
Mitra et al, ⁵⁴ Australia	Retrospective cohort	Screening for fever	65 000 people	Daily growth rate	9 Mar-13 May 2020	Sensitivity 24%: 86% of cases not detected—poor sensitivity of identifying people with SARS-CoV-2*	Moderate

RO=reproductive number; Rt=time varying reproductive number.
 *Interpretation of findings as reported in the original manuscript.
 †Not an effective intervention

Multiple public health measures

Study characteristics

Overall, 37 studies provided estimates on the effectiveness of multiple public health measures, assessed as a collective group. Studies were mostly conducted in Asia (n=15), the US (n=11), Europe (n=6), Africa (n=4), and South America (n=1). All the studies were observational. The most commonly measured outcome was transmission of disease (ie, measured as reproductive number, growth number, or epidemic doubling time) (n=23), followed by covid-19 incidence (n=19) and covid-19 mortality (n=8). This review attempted to assess the overall effectiveness of the public health intervention packages by reporting the percentage difference in outcome before and after implementation of measures or between regions or countries studied. Eleven of the 37 included studies noted a difference of between 26% and 50% in transmission of SARS-CoV-2 and incidence of covid-19,⁷⁰⁻⁸⁰ nine noted a difference of between 51% and 75% in SARS-CoV-2 transmission, covid-19 incidence, and covid-19 mortality,⁸¹⁻⁸⁹ and 14 noted a difference of more than 75% in transmission of SARS-CoV-2, covid-19 incidence and covid-19 mortality.^{79 80 89-100} For the remaining studies, the overall effectiveness was not assessed owing to a lack of comparators (see supplementary material 3, table 3). Two studies that assessed universal lockdown and physical distancing reported a decrease of between 0% and 25% in SARS-CoV-2 transmission and covid-19 incidence.^{79 101} Studies that included school and workplace closures,^{91 95 96} isolation or stay at home measures,^{80 94} or a combination of both^{79 89 93 97-99} reported decreases of more than 75% in SARS-CoV-2 transmission. Supplementary material 3, table 2 provides detailed information on each study.

Discussion

Worldwide, government and public health organisations are mitigating the spread of SARS-CoV-2 by implementing various public health measures. This systematic review identified a statistically significant reduction in the incidence of covid-19 through the implementation of mask wearing and physical distancing. Handwashing interventions also indicated a substantial reduction in covid-19 incidence, albeit not statistically significant in the adjusted model. As the random effects model tends to underestimate confidence intervals when a meta-analysis includes a

small number of individual studies (<5), the adjusted model for handwashing showed a statistically non-significant association in reducing the incidence of covid-19 compared with the unadjusted model.

Overall effectiveness of these interventions was affected by clinical heterogeneity and methodological limitations, such as confounding and measurement bias. It was not possible to evaluate the impact of type of face masks (eg, surgical, fabric, N95 respirators) and compliance and frequency of wearing masks owing to a lack of data. Similarly, it was not feasible to assess the differences in effect that different recommendations for physical distancing (ie, 1.5 m, 2m, or 3 m) have as preventive strategies.

The effectiveness of measures such as universal lockdowns and closures of businesses and schools for the containment of covid-19 have largely been effective, but depended on early implementation when incidence rates of covid-19 were still low.^{42 52 58} Only Japan reported no decrease in covid-19 incidence after school closures,⁴⁴ and other studies found that different public health measures were sometimes implemented simultaneously or soon after one another, thus the results should be interpreted with caution.^{32 46 56}

Isolation or stay at home was an effective measure in reducing the transmission of SARS-CoV-2, but the included studies used results for mobility to assess stay at home or isolation and therefore could have been limited by potential flaws in publicly available phone data,^{41 58 102} and variations in the enforcement of public health measures in different states or regions were not assessed.^{55 58 102} Quarantine was found to be as effective in reducing the incidence of covid-19 and transmission of SARS-CoV-2, yet variation in testing and case detection in low income environments was substantial.^{59 96 98} Another study reported that quarantine was effective in reducing the transmission of SARS-CoV-2 in a cohort with a low prevalence of the virus, yet it is unknown if the same effect would be observed with higher prevalence.³⁴

It was not possible to draw conclusions about the effectiveness of restricted travel and full border closures because the number of empirical studies was insufficient. Single studies identified that border closure in Africa had a minimal effect in reducing SARS-CoV-2 transmission, but the study was assessed as being at high risk of bias.⁶² Screening for fever was also identified to be ineffective, with only 24% of positive cases being captured by screening.⁵⁴

Comparison with other studies

Previous literature reviews have identified mask wearing as an effective measure for the containment of SARS-CoV-2¹⁰³; the caveat being that more high level evidence is required to provide unequivocal support for the effectiveness of the universal use of face masks.^{104 105} Additional empirical evidence from a recent randomised controlled trial (originally published as a preprint) indicates that mask wearing achieved a 9.3% reduction in seroprevalence of symptomatic SARS-CoV-2 infection and an 11.9% reduction in the prevalence of covid-19-like symptoms.¹⁰⁶ Another systematic review showed stronger effectiveness with the use of N95, or similar, respirators than disposable surgical masks,¹⁰⁷ and a study evaluating the protection offered by 18 different types of fabric masks found substantial heterogeneity in protection, with the most effective mask being multilayered and tight fitting.¹⁰⁸ However, transmission of SARS-CoV-2 largely arises in hospital settings in which full personal protective measures are in place, which suggests that when viral load is at its highest, even the best performing face masks might not provide adequate protection.⁵¹ Additionally, most studies that assessed mask wearing were prone to important confounding bias, which might have altered the conclusions drawn from this review (ie, effect estimates might have been underestimated or overestimated or can be related to other measures that were in place at the time the studies were conducted). Thus, the extent of such limitations on the conclusions drawn remain unknown.

A 2020 rapid review concluded that quarantine is largely effective in reducing the incidence of covid-19 and covid-19 mortality. However, uncertainty over the magnitude of such an effect still remains,¹⁰⁹ with enhanced management of quality quarantine facilities for improved effective control of the epidemics urgently needed.¹¹⁰ In addition, findings on the application of school and workplace closures are still inconclusive. Policy makers should be aware of the ambiguous evidence when considering school closures, as other potentially less disruptive physical distancing interventions might be more appropriate.²¹ Numerous findings from studies on the efficacy of school closures showed that the risk of transmission within the educational environment often strongly depends on the incidence of covid-19 in the community, and that school closures are most successfully associated with control of SARS-CoV-2 transmission when other mitigation strategies are in place in the community.¹¹¹⁻¹¹⁷ School closures have been reported to be disruptive to students globally and are likely to impair children's social, psychological, and educational development^{118 119} and to result in loss of income and productivity in adults who cannot work because of childcare responsibilities.¹²⁰

Speculation remains as how best to implement physical distancing measures.¹²¹ Studies that assess physical distancing measures might interchangeably study physical distancing with lockdown^{35 52 56 64} and other measures and thus direct associations are difficult to assess.

Empirical evidence from restricted travel and full border closures is also limited, as it is almost impossible to study these strategies as single measures. Current evidence from a recent narrative literature review suggested that control of movement, along with mandated quarantine, travel restrictions, and restricting nationals from entering areas of high infection, are effective measures, but only with good compliance.¹²² A narrative literature review of travel bans, partial lockdowns, and quarantine also suggested effectiveness of these measures,¹²³ and another rapid review further supported travel restrictions and cross border restrictions to stop the spread of SARS-CoV-2.¹²⁴ It was impossible to make such observations in the current review because of limited evidence. A German review, however, suggested that entry, exit, and symptom screening measures to prevent transmission of SARS-CoV-2 are not effective at detecting a meaningful proportion of cases,¹²⁵ and another review using real world data from multiple countries found that border closures had minimal impact on the control of covid-19.¹²⁶

Although universal lockdowns have shown a protective effect in lowering the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality, these measures are also disruptive to the psychosocial and mental health of children and adolescents,¹²⁷ global economies,¹²⁸ and societies.¹²⁹ Partial lockdowns could be an alternative, as the associated effectiveness can be high,¹²⁵ especially when implemented early in an outbreak,⁸⁵ and such measures would be less disruptive to the general population.

It is important to also consider numerous sociopolitical and socioeconomic factors that have been shown to increase SARS-CoV-2 infection^{130 131} and covid-19 mortality.¹³² Immigration status,⁸² economic status,^{81 101} and poverty and rurality⁹⁸ can influence individual and community compliance with public health measures. Poverty can impact the ability of communities to physically distance,¹³³ especially in crowded living environments,^{134 135} as well as reduce access to personal protective measures.^{134 135} A recent study highlights that "a one size fits all" approach to public health measures might not be effective at reducing the spread of SARS-CoV-2 in vulnerable communities¹³⁶ and could exacerbate social and economic inequalities.^{135 137} As such, a more nuanced and community specific approach might be required. Even though screening is highly recommended by WHO¹³⁸ because a proportion of patients with covid-19 can be asymptomatic,¹³⁸ screening for symptoms might miss a larger proportion of the population with covid-19. Hence, temperature screening technologies might need to be reconsidered and evaluated for cost effectiveness, given such measures are largely depended on symptomatic fever cases.

Strengths and limitations of this review

The main strength of this systematic review was the use of a comprehensive search strategy to identify and select studies for review and thereby minimise selection bias. A clinical epidemiologist developed the search

strategy, which was validated by two senior medical librarians. This review followed a comprehensive appraisal process that is recommended by the Cochrane Collaboration³¹ to assess the effectiveness of public health measures, with specifically validated tools used to independently and individually assess the risk of bias in each study by study design.

This review has some limitations. Firstly, high quality evidence on SARS CoV-2 and the effectiveness of public health measures is still limited, with most studies having different underlying target variables. Secondly, information provided in this review is based on current evidence, so will be modified as additional data become available, especially from more prospective and randomised studies. Also, we excluded studies that did not provide certainty over the effect measure, which might have introduced selection bias and limited the interpretation of effectiveness. Thirdly, numerous studies measured interventions only once and others multiple times over short time frames (days v month, or no timeframe). Additionally, the meta-analytical portion of this study was limited by significant heterogeneity observed across studies, which could neither be explored nor explained by subgroup analyses or meta-regression. Finally, we quantitatively assessed only publications that reported individual measures; studies that assessed multiple measures simultaneously were narratively analysed with a broader level of effectiveness (see supplementary material 3, table 3). Also, we excluded studies in languages other than English.

Methodological limitations of studies included in the review

Several studies failed to define and assess for potential confounders, which made it difficult for our review to draw a one directional or causal conclusion. This problem was mainly because we were unable to study only one intervention, given that many countries implemented several public health measures simultaneously; thus it is a challenge to disentangle the impact of individual interventions (ie, physical distancing when other interventions could be contributing to the effect). Additionally, studies measured different primary outcomes and in varied ways, which limited the ability to statistically analyse other measures and compare effectiveness.

Further pragmatic randomised controlled trials and natural experiment studies are needed to better inform the evidence and guide the future implementation of public health measures. Given that most measures depend on a population's adherence and compliance, it is important to understand and consider how these might be affected by factors. A lack of data in the assessed studies meant it was not possible to understand or determine the level of compliance and adherence to any of the measures.

Conclusions and policy implications

Current evidence from quantitative analyses indicates a benefit associated with handwashing, mask wearing, and physical distancing in reducing the incidence of

covid-19. The narrative results of this review indicate an effectiveness of both individual or packages of public health measures on the transmission of SARS-CoV-2 and incidence of covid-19. Some of the public health measures seem to be more stringent than others and have a greater impact on economies and the health of populations. When implementing public health measures, it is important to consider specific health and sociocultural needs of the communities and to weigh the potential negative effects of the public health measures against the positive effects for general populations. Further research is needed to assess the effectiveness of public health measures after adequate vaccination coverage has been achieved. It is likely that further control of the covid-19 pandemic depends not only on high vaccination coverage and its effectiveness but also on ongoing adherence to effective and sustainable public health measures.

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Contributors: ST, DG, DI, DL, and ZA conceived and designed the study. ST, DG, SS, AM, HW, WX, JR, ET, AM, XL, XZ, and IME collected and screened the data. ST, DG, and DI acquired, analysed, or interpreted the data. ST, HW, and SS drafted the manuscript. All authors critically revised the manuscript for important intellectual content. XL and ST did the statistical analysis. NA obtained funding. LR and MD provided administrative, technical, or material support. ST and DI supervised the study. ST and DI had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. ST is the guarantor. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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The lead author (ST) affirms that the manuscript is an honest, accurate, and transparent account of the study reported; no important aspects of the study have been omitted. Dissemination to participants and related patient and public communities: It is anticipated to disseminate the results of this research to wider community via press release and social media platforms.

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Supplementary information: additional material