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Effectiveness of non-pharmaceutical interventions on COVID-19 transmission in 190 countries from 23 January to 13 April 2020

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ABSTRACT

Background: To evaluate and compare the effectiveness of four types of non-pharmaceutical interventions (NPIs) to contain the time-varying effective reproduction number (Rt) of coronavirus disease-2019 (COVID-19).

Methods: This study included 1,908,197 confirmed COVID-19 cases from 190 countries between 23 January and 13 April 2020. The implemented NPIs were categorised into four types: mandatory face mask in public, isolation or quarantine, social distancing and traffic restriction (referred to as mandatory mask, quarantine, distancing and traffic hereafter, respectively).

Results: The implementations of mandatory mask, quarantine, distancing and traffic were associated with changes (95% confidence interval, CI) of −15.14% (from −21.79% to −7.93%), −11.40% (from −13.66% to −9.07%), −42.94% (from −44.24% to −41.60%) and −9.26% (from −11.46% to −7.01%) in the Rt of COVID-19 when compared with those without the implementation of the corresponding measures. Distancing and the simultaneous implementation of two or more types of NPIs seemed to be associated with a greater decrease in the Rt of COVID-19.

Conclusion: Our study indicates that NPIs can significantly contain the COVID-19 pandemic. Distancing and the simultaneous implementation of two or more NPIs should be the strategic priorities for containing COVID-19.

Introduction

The coronavirus disease-2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was first reported in Wuhan, China, in December 2019. The World Health Organization (WHO) declared it as a pandemic on 12 March 2020. As of 28 May 2020, there are more than 5.5 million confirmed cases of COVID-19 and 353,373 related deaths worldwide (World Health Organization, 2020). Many countries have implemented a series of non-pharmaceutical interventions (NPIs), such as traffic restriction and social distancing, to contain the outbreak of this disease (Jon Cohen, 2020; Lewnard and Lo, 2020).

Owing to the rapid transmission of COVID-19 worldwide and the lack of an efficient vaccine or treatment for this novel infectious disease, NPIs are among the few approaches to cope with the resulting pandemic. There is an urgent need to understand whether these NPIs are effective and which of these NPIs are more efficient. However, the information on this topic is limited.

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Most previous studies have focused on evaluating a single NPI within a single city or country using a modelling method, and the results of these studies are inconsistent. Few studies have investigated the simultaneous implementation of multiple NPIs and compared the effectiveness of different NPIs (Lai et al., 2020; Min et al., 2020). To the best of our knowledge, no study has examined the association between various NPIs and the time-varying effective reproduction number (Rt) of COVID-19 on the global scale. Therefore, we investigated and compared the effectiveness of four types of NPIs, namely mandatory face mask in public, isolation or quarantine, social distancing and traffic restriction, on the transmission of COVID-19 in 190 countries between 23 January and 13 April 2020.

Method

Study design and setting

This ecological study included a total of 415 sites (comprising 235 cities from 10 countries and 180 countries) between 23 January and 13 April 2020. Information on the daily number of confirmed COVID-19 cases was extracted from a data repository sourced from Johns Hopkins University Center for Systems Science and Engineering and the Wind Financial database, which archive data from the official websites of health ministries worldwide (Dong et al., 2020; Wind, 2020).

Data pertaining to the implementation of NPIs during the study period were obtained from official webpages of high-circulation newspapers published in the 415 cities/countries. In brief, we first recorded any legal NPIs announced by the government of each site and its implementation date [i.e., start date and end date (if applicable before the study end date)]. Then, we categorised the NPIs into the following four types: 'mandatory face mask in public' (referred to as mandatory mask hereinafter), 'isolation or quarantine' (referred to as quarantine hereinafter), 'social distancing' (referred to as distancing hereinafter) and 'traffic restriction' (referred to as traffic hereinafter). Details pertaining to the process of categorising the NPIs are summarised in Table S1. If any NPI of a type was deemed officially announced as being in force at a site on any day of the study period, then that NPI type was treated as 'on' for that site on that day in our data analysis. In contrast, if no NPI of a type was found to be effective at a site on any day of the study period, the NPI type was treated as 'off' in our data analysis.

Moreover, we collected demographic and socioeconomic status data for each site. Data on population size (number of persons), population density (persons per square km) and median age (years) were obtained from United Nations, Department of Economic and Social Affairs, Population Division (Elaboration of data by United Nations, 2019) and/or statistics bureau of the countries studied. Data on the percentage of populations aged 65 years or older were obtained from the World Bank data portal (2019 revision). Information about the Global Health Security Index (GHSI) was collected from the GHSI report (Johns Hopkins, 2019). Because only country-level GHSI data were available, we applied them to all cities within a given country.

Calculation of time-varying effective reproduction number (Rt)

We used Rt, which represents the average number of secondary infected cases generated by a primary infected individual at time t, to estimate the changes in COVID-19 transmissibility. Rt >1 indicates an expansionary trend of the epidemic, whereas Rt <1 indicates a contractionary trend of the epidemic. We calculated the Rt and its 95% credible interval for each day by applying the method developed by Cori et al. (2013) through a 7-day moving average. We assumed that the serial interval distribution of COVID-19 followed a gamma distribution with a mean of 3.96 days and a standard deviation (SD) of 4.75 days (Du et al., 2020).

Data analysis

First, we used the generalised linear mixed model (GLMM) to assess the effectiveness of the four types of NPIs on the transmission of COVID-19 separately. The implementation status (on/off) of each type of NPI (i.e., mandatory mask, quarantine, distancing and traffic) at each site on each day was included in the model as an independent variable. The dependent variable was Rt, which was log-transformed to normalise before data analysis and then retransformed to the original scale for presentation. Effect estimations were reported as percentage differences in the Rt between sites with a given type of NPI and sites without the corresponding type of NPI as the reference. A city/country-level random intercept was included in the model to control for clustering effects within the same city/country. Two models were developed. Model 1 included the following covariates: calendar time to control seasonal and long-term trends over the study period; Rt of the previous day to account for temporal autocorrelation; public health response time, which was defined as the number of days between the date of activation of the first NPI and the date on which the first case was reported; an indicator for the day of the week and public holidays to account for weekly or periodic variations in the number of people who underwent the SARS-CoV-2 test; duration for which a type of NPI was implemented to control for the potential effects of implementation duration; population density to account for a higher transmission rate in regions with high population density; median age to account for higher incidence rates among the elderly; and GHSI to account for countries' capacity to prevent and mitigate epidemics and pandemics. Model 2 was further mutually adjusted for the other three types of NPIs, for example, adjusted for quarantine, distancing and traffic to determine the association between the 'mandatory mask' type of NPI and Rt.

Second, we compared the effectiveness of the different types of NPIs implemented. We classified the 415 sites into the following 16 mutually exclusive groups: no implementation of NPIs; implementation of any one type of NPIs, namely mandatory mask only, quarantine only, distancing only or traffic only; implementation of any two types of NPIs, namely 'distancing + mandatory mask', 'distancing + quarantine', 'traffic + mandatory mask', 'traffic + quarantine', 'traffic + distancing' or 'quarantine + mandatory mask'; implementation of any three types of NPIs, namely 'distancing + quarantine + mandatory mask', 'traffic + quarantine + mandatory mask', 'traffic + distancing + mandatory mask' or 'traffic + distancing + quarantine'; and implementation of all four types of NPIs, that is, 'traffic + distancing + quarantine + mandatory mask'. We applied the GLMM mentioned above with the same covariates as those used in Model 1. The reference group was 'no implementation of NPIs'.

Third, stratified analyses were performed to investigate whether these associations were modified by WHO regions, population density and GHSI.

Finally, we performed three sensitivity analyses to examine the robustness of the estimated associations and the lag effects: (1) We used the Rt on the third day (Lag 3), the seventh day (Lag 7) and the 14th day (Lag 14) as the dependent variable to examine the lag effect; (2) we investigated the associations by excluding Hubei province in China, which was a significant outlier in the model; and (3) we investigated the associations by adjusting for percentages of populations aged 65 years or older instead of median age to consider the effects of age structure.

All data analyses were performed using R 3.6.1 (R Core Team, Vienna, Austria). A two-tailed *P* value of <0.05 was considered statistically significant.

Result

A total of 415 sites (i.e., 235 cities from 10 countries and 180 countries) were included in this study. Table S2 summarises the relevant information on COVID-19 and the NPIs implemented in the 190 countries during the study period. As of 13 April 2020, 1,908,197 cases of COVID-19 infection were reported. The highest number of cases was reported in the United States of America [577,165 (30.25% of the total number of cases reported worldwide)], followed by Spain, Italy, France, Germany, the United Kingdom, China, Iran, Turkey and Belgium.

Table 1 shows the data pertaining to the implementation of NPIs at the study sites over the study period. No official NPIs were ever implemented in 382 sites. In many sites, two or more types of NPIs were implemented simultaneously during the study period. The common types of NPIs or combinations of NPI types that were implemented across the sites were 'traffic only' (138 sites), 'traffic + quarantine' (130 sites), 'traffic + distancing' (177 sites) and 'traffic + distancing + quarantine' (218 sites). The implementation durations of each type of NPI or each combination of NPI types ranged from 4 to 38 days. Relatively long median durations of implementation were observed for 'traffic only' (12.5 days), 'distancing + mandatory mask' (16 days), 'traffic + quarantine' (33 days), 'traffic + distancing' (19 days), 'traffic + quarantine + mandatory mask' (38 days), 'traffic + distancing + quarantine' (24 days) and 'traffic + distancing + quarantine + mandatory mask' (37 days).

Table 2 presents the associations between each type of NPI and the Rt of COVID-19. The implementations of any type of NPI were significantly associated with a decrease in the Rt of COVID-19. Mutual adjustments substantially diluted these associations. The implementations of mandatory mask, quarantine, distancing and traffic were associated with changes of −15.14% (from −21.79% to −7.93%), −11.40% (from −13.66% to −9.07%), −42.94% (from −44.24% to −41.60%) and −9.26% (from −11.46% to −7.01%) in the Rt of COVID-19, respectively, when compared with the Rt in the sites without the implementation of the corresponding measures.

Table 3 shows the comparisons of the effectiveness of different NPIs on the Rt of COVID-19. 'Distancing only' led to a greater decrease in the Rt of COVID-19 than 'traffic only' and 'quarantine only'. The combinations of other types of NPIs with distancing were generally associated with a greater decrease in the Rt when compared with the combinations without distancing. The combinations with more types of NPIs were generally associated with a greater decrease in the Rt. No significant associations were observed for 'mandatory mask only', 'distancing + mandatory mask', 'traffic + mandatory mask' and 'traffic + distancing + mandatory mask'.

As shown in Table 4, subgroup data analysis generally yielded similar results. The association strengths differed slightly for some subgroups, that is, greater decreases in the Rt were observed for the subgroups of 'higher population density' and 'lower GHSI'. No significant associations were observed for some subgroups.

Tables S3-S5 summarise the results of our sensitivity analyses. The decreased magnitudes in the Rts were generally smaller on days Lag 3, Lag 7 and Lag 14 when compared with those on the current day (Table S3). Similar results were obtained by excluding the outlier province (Hubei, China) (Table S4) and by adjusting for percentages of subjects aged ≥65 years instead of median age (Table S5).

Discussion

This comprehensive ecological study covering 190 countries indicated that the implementation of any type of NPI, namely traffic, distancing, mandatory mask or quarantine was significantly associated with a decrease in the Rt of COVID-19. All NPI implementations involving distancing were associated with a greater decrease in the Rt of COVID-19 than those not involving distancing. Accordingly, combinations with more types of NPIs seemed to be associated with a greater decrease in the Rt of COVID-19.

Most previous studies have investigated the effectiveness of a single NPI rather than a group of NPIs despite the fact that two or more NPIs are commonly implemented simultaneously (Auger et al., 2020; Chinazzi et al., 2020; Hernandez et al., 2020; Milne and Xie, 2020). The results of our study were consistent with those of the studies, which concluded that the implementation of NPIs was

Table 1
Non-pharmaceutical interventions implemented in the 190 countries between 23 January 2020 and 13 April 2020 (N = 415).

Type of NPIs	No. of sites that implemented the NPIs (%)	Median duration (range) of NPI implementation (days)
0 NPIs	382 (92.05%)	N/A
Any one type of NPI		
Mandatory mask only	1 (0.24%)	4 (N/A)
Quarantine only	48 (11.57%)	7 (1–53)
Distancing only	40 (9.64%)	4 (1–31)
Traffic only	138 (33.25%)	12.5 (1–75)
Any two types of NPIs		
Distancing + mandatory mask	1 (0.24%)	16 (N/A)
Distancing + quarantine	21 (5.06%)	6 (1–35)
Traffic + mandatory mask	1 (0.24%)	4 (N/A)
Traffic + quarantine	130 (31.33%)	33 (1–72)
Traffic + distancing	177 (42.65%)	19 (1–38)
Quarantine + mandatory mask	0 (0.00%)	N/A
Any three types of NPIs		
Distancing + quarantine + mandatory mask	2 (0.48%)	8.5 (1–16)
Traffic + quarantine + mandatory mask	36 (8.67%)	38 (2–42)
Traffic + distancing + mandatory mask	1 (0.24%)	7 (N/A)
Traffic + distancing + quarantine	218 (52.53%)	24 (2–49)
All four types of NPIs		
Traffic + distancing + quarantine + mandatory mask	60 (14.46%)	37 (1–75)

NPIs: Non-pharmaceutical interventions.
%: Percentage of sites implementing corresponding types of NPI among the 415 included sites.
N/A: not applicable.

Table 2
Associations of individual type of non-pharmaceutical intervention with the Rt of COVID-19.

Type of NPI	Model 1		Model 2	
	Difference (95% CI)	*P*	Difference (95% CI)	*P*
Mandatory mask (Yes vs. No)	−33.35% (-39.07 to -27.09)	<0.001	−15.14% (-21.79 to -7.93)	<0.001
Quarantine (Yes vs. No)	−32.98% (-34.59 to -31.33)	<0.001	−11.40% (-13.66 to -9.07)	<0.001
Distancing (Yes vs. No)	−46.46% (-47.63 to -45.27)	<0.001	−42.94% (-44.24 to -41.60)	<0.001
Traffic (Yes vs. No)	−29.09% (-30.73 to -27.42)	<0.001	−9.26% (-11.46 to -7.01)	<0.001

NPIs: Non-pharmaceutical interventions.
Sites without the corresponding type of NPI as the reference.
Results are presented as percentage differences in the Rt with [95% Confidence Interval (CI)].
Model 1: Adjusted for the calendar time, Rt on the previous day, public health response time defined as the time in days between the activation of the first NPI and the date of reporting of the first case, an indicator of the day of the week and public holidays, implementation duration of NPIs, population density, median age and GHSI.
Model 2: Further mutually adjusted for the other three types of NPIs, for example, adjusted for quarantine, distancing and traffic in the model for the association between 'mandatory mask' type of NPI and Rt.

Table 3
Comparison of effectiveness of different NPI types or combinations on the Rt of COVID-19.

Type of NPIs	Difference (95% CI)	*P*
Any one type of NPIs		
Mandatory mask only	−34.06% (-60.78 to 10.87)	0.116
Quarantine only	−10.6% (-15.31 to -5.64)	<0.001
Distancing only	−23.03% (-28.43 to -17.22)	<0.001
Traffic only	−9.64% (-12.21 to -7.00)	<0.001
Any two types of NPIs		
Distancing + mandatory mask	53.30% (-2.50–141.03)	0.064
Distancing + quarantine	−38.58% (-44.23 to -32.37)	<0.001
Traffic + mandatory mask	−66.58% (-92.67 to 52.41)	0.157
Traffic + quarantine	−17.83% (-20.07 to -15.53)	<0.001
Traffic + distancing	−44.11% (-46.37 to -41.76)	<0.001
Any three types of NPIs		
Distancing + quarantine + mandatory mask	−69.73% (-82.48 to -47.69)	<0.001
Traffic + quarantine + mandatory mask	−17.06% (-24.99 to -8.29)	<0.001
Traffic + distancing + mandatory mask	−54.32% (-79.59 to 2.24)	0.057
Traffic + distancing + quarantine	−54.12% (-55.63 to -52.56)	<0.001
All four types of NPIs		
Traffic + distancing + quarantine + mandatory mask	−62.81% (-66.27 to -58.98)	<0.001

NPIs: Non-pharmaceutical interventions.
Sites with No NPI implementation are the reference.
Results are presented as percentage differences in the Rt with [95% Confidence Interval (CI)].
Adjusted for calendar time, Rt on the previous day, public health response time defined as the number of days between the date of activation of the first NPI and the date of reporting of the first case, an indicator of the day of the week and public holidays, implementation duration of a type of NPI, population density, median age and GHSI.

associated with a decrease in transmissibility, such as the studies in mainland China showing that travel restrictions might delay the progression of the COVID-19 epidemic by 3–5 days (Chinazzi et al., 2020; Tian et al., 2020), and the study in New York showing that wearing a mask could reduce daily deaths by 17%–45% over 2 months (Eikenberry et al., 2020). Moreover, two studies reported social distancing to be an effective NPI (Hernandez et al., 2020; Zhang et al., 2020). A study conducted in China showed that social distancing and epicentre lockdown might reduce the number of new infection cases by up to 98.9% (Zhang et al., 2020), while another study indicated that social distancing reduced the growth rate of confirmed cases in five countries (Austria, Belgium, Italy, Malaysia and South Korea) by 52.37% on average (SD 13.37%) (Hernandez et al., 2020). A few studies investigated the effectiveness of multiple NPIs in China (Cowling et al., 2020; Lai et al., 2020; Milne and Xie, 2020; Pan et al., 2020), European countries (Flaxman et al., 2020), the United Kingdom (Davies et al., 2020) and Singapore (Koo et al., 2020). Their results showed that the implementation of multiple NPIs was associated with a reduction in the transmission of COVID-19. In contrast, a study conducted in 20 European countries revealed that stay-at-home orders, closure of all non-essential businesses and wearing of face masks in public were not significantly associated with the incidence rate of confirmed cases (Hunter et al., 2020). It is difficult to directly compare the results of our study with those of previous studies owing to multiple reasons, such as differences in study design and period, targeted populations and transmissibility parameters. Moreover, most previous studies used modelling methods to simulate the epidemic with the implementation of NPIs. In contrast, we used the data published on the official webpages of the governments of 190 countries to provide direct evidence about the effectiveness of NPI implementation on COVID-19 transmission. Nevertheless, our study and most previous studies support the implementation of NPIs as a measure for containing the global pandemic of COVID-19.

Few studies have compared the effectiveness of different NPIs and their combinations for containing COVID-19. Our results showed that the NPI of distancing and its combinations with other NPI types are associated with a greater decrease in the Rt of COVID-19, suggesting that distancing should be adopted as a priority NPI for COVID-19 containment. This is in line with a modelling study in China, which also suggested that social distancing seemed to have a greater impact on the containment of COVID-19 outbreak than travel restrictions (Lai et al., 2020). Moreover, our study indicated

Table 4
Subgroup analysis of association between non-pharmaceutical interventions and the Rt of COVID-19 transmission.

Types of NPIs	Subgroup analysis			
	Stratified by continents			
	European	American	Asia	African
Comparison of individual types of NPIs[a]				
Mandatory mask (Yes vs. No)	−1.33% (-13.02–11.94)	−23.68% (-41.5 to -0.45)	−0.26% (-6.15 to 6.01)	−28.56% (-48.8 to -0.31)
Quarantine (Yes vs. No)	−18.27% (-22.14 to -14.21)	−4.23% (-10.07 to 1.99)	−4.55% (-8.47 to -0.46)	−10.72% (-16.04 to -5.07)
Distancing (Yes vs. No)	−39.4% (-42.07 to -36.59)	−42.87% (-45.37 to -40.27)	−17.76% (-20.56 to -14.85)	−16.05% (-21.33 to -10.41)
Traffic (Yes vs. No)	−11.26% (-15.18 to -7.17)	−8.34% (-13.75 to -2.58)	−8.62% (-11.95 to -5.17)	−30.86% (-34.83 to -26.66)
Comparison of combinations of NPI types[b]				
Any one type of NPI				
Mandatory mask only	−41.49% (-65.82 to 0.16)	N/A	N/A	N/A
Quarantine only	−20.21% (-27.00 to -12.79)	0.84 % (-10.00–12.98)	−11.62% (-18.83 to -3.76)	−4.01% (-15.45 to 8.97)
Distancing only	−38.35% (-45.64 to -30.09)	−33.33% (-42.93 to -22.12)	−18.8% (-30.30 to -5.41)	11.55 % (-3.32 to 28.71)
Traffic only	−9.21% (-13.65 to -4.54)	−15.12% (-22.68 to -6.81)	−12.58% (-16.2 to -8.81)	−24.60% (-30.13 to -18.62)
Any two types of NPIs				
Distancing + mandatory mask	N/A	N/A	7.27 % (-26.61 to 56.77)	N/A
Distancing + quarantine	−48.75% (-56.37 to -39.80)	−50.46% (-63.40 to -32.95)	−20.51% (-34.83 to -3.06)	−15.48% (-26.91 to -2.27)
Traffic + mandatory mask	N/A	N/A	N/A	−74.36% (-96.01–64.91)
Traffic + quarantine	−42.60% (-48.81 to -35.65)	−11.70% (-15.46 to -7.78)	−9.24% (-13.91 to -4.31)	−34.84% (-40.35 to -28.83)
Traffic + distancing	−49.10% (-52.82 to -45.08)	−38.73% (-44.72 to -32.1)	−17.13% (-22.00 to -11.96)	−41.59% (-46.93 to -35.71)
Any three types of NPIs				
Distancing + quarantine + mandatory mask	14.41 % (-34.75–100.60)	N/A	−41.40% (-66.30 to1.90)	N/A
Traffic + quarantine + mandatory mask	−35.98% (-56.39 to -6.02)	−31.04% (-74.06–83.34)	−5.07% (-11.73 to 2.09)	N/A
Traffic + distancing + mandatory mask	N/A	N/A	−28.19% (-64.91 to 46.93)	N/A
Traffic + distancing + quarantine	−55.24% (-58.04 to -52.26)	−50.94% (-53.41 to -48.34)	−26.66% (-31.42 to -21.55)	−48.26% (-53.16 to -42.85)
All four types of NPIs				
Traffic + distancing + quarantine + mandatory mask	−54.03% (-60.16 to -46.94)	−62.40% (-71.60 to -50.24)	−30.90% (-35.65 to -25.79)	−57.91% (-69.86 to -41.21)
	Stratified by population density		Stratified by GHSI	
	≤ 110.5 pears/km^2	> 110.5 pears/km^2	≤ 58.5	>58.5
Comparison of individual types of NPIs[a]				
Mandatory mask (Yes vs. No)	0.33 % (-8.71 -10.26)	−24.22% (-33.10 to -14.16)	−24.64% (-30.01 to -18.86)	−17.85% (-41.76 to 15.88)
Quarantine (Yes vs. No)	−8.09% (-11.03 to -5.06)	−20.38% (-23.80 to -16.80)	−22.16% (-24.61 to -19.63)	21.06 % (14.22–28.31)
Distancing (Yes vs. No)	−42.58% (-44.30 to -40.80)	−43.00% (-45.01 to -40.91)	−41.40% (-43.1 to -39.64)	−39.37% (-41.82 to -36.82)
Traffic (Yes vs. No)	−11.46% (-14.05 to -8.79)	−3.93% (-8.04 to 0.36)	−13.32% (-15.8 to -10.77)	−27.64% (-32.22 to -22.75)
Comparison of combinations of NPI[b]				
Any one type of NPI				
Mandatory mask only	−32.62% (-60.74 to 15.66)	N/A	−40.27% (-64.91 to 1.68)	N/A
Quarantine only	2.11 % (-4.02–8.64)	−35.8% (-41.93 to -29.01)	−27.97% (-32.60 to -23.02)	30.17 % (20.21–40.96)
Distancing only	−17.39% (-26.00 to -7.77)	−30.13% (-36.64 to -22.96)	−32.09% (-37.69 to -25.99)	−8.65% (-21.22 to 5.93)
Traffic only	−11.61% (-14.64 to -8.49)	−5.10% (-10.11 to 0.18)	−12.86% (-15.64 to -10.00)	−26.96% (-33.39 to -19.91)
Any two types of NPIs				
Distancing + mandatory mask	N/A	40.99 % (-10.17–121.29)	21.86 % (-21.3–88.7)	N/A
Distancing + quarantine	−34.91% (-44.27 to -23.98)	−41.29% (-48.06 to -33.64)	−46.29% (-51.7 to -40.27)	−31.53% (-49.42 to -7.32)
Traffic + mandatory mask	−68.2% (-94.53–84.7)	N/A	−70.57% (-93.53 to 33.82)	N/A
Traffic + quarantine	−18.25% (-20.99 to -15.42)	−21.94% (-25.62 to -18.08)	−30.81% (-33.99 to -27.48)	−10.56% (-14.78 to -6.13)
Traffic + distancing	−40.23% (-43.34 to -36.94)	−47.4% (-50.75 to -43.82)	−48.01% (-50.53 to -45.37)	−44.41% (-49.82 to -38.43)
Any three types of NPIs				
Distancing + quarantine + mandatory mask	37.89 % (-20.47–139.08)	−81.93% (-90.65 to -65.08)	−79.01% (-88.57 to -61.46)	N/A
Traffic + quarantine + mandatory mask	6.79 % (-5.37 to 20.51)	−38.47% (-46.73 to -28.93)	−42.60% (-47.41 to -37.35)	−7.17% (-63.86–138.44)
Traffic + distancing + mandatory mask	−52.9% (-79.49 to 8.13)	N/A	−59.44% (-81.96 to -8.79)	N/A
Traffic + distancing + quarantine	−53.76% (-55.64 to -51.8)	−55.27% (-57.74 to -52.65)	−58.75% (-60.70 to -56.69)	−48.26% (-50.58 to -45.82)
All four types of NPIs				
Traffic + distancing + quarantine + mandatory mask	−54.29% (-59.07 to -48.96)	−71.21% (-75.22 to -66.54)	−72.36% (-74.83 to -69.65)	−56.94% (-70.12 to -37.95)

N/A: not applicable due to no sites implemented the corresponding type of NPIs.
Results are presented as percentage differences in the Rt with [95% Confidence Interval (CI)].
[a] Sites without the corresponding type of NPI as the reference. Adjusted for calendar time, Rt on the previous day, public health response time defined as the number of days between the date of activation of the first NPI and the date of reporting of the first case, an indicator of day of the week and public holidays, implementation duration of a type of NPI, population density, median age and GHSI and mutually adjusted for the other three types of NPIs, for example, adjusted for quarantine, distancing, and traffic in the model for the association between the 'mandatory mask' type of NPI and Rt.
[b] Sites with No NPI implementation are the reference. Adjusted for calendar time, Rt on the previous day, public health response time defined as the number of days between the date of activation of the first NPI and the date of reporting of the first case, an indicator of the day of the week and public holidays, implementation duration of a type of NPI, population density, median age and GHSI

that the simultaneous implementation of two or more NPI types seems to be associated with a greater decrease in the Rt of COVID-19.

In the comparisons of the effectiveness of different NPIs and their combinations, we found non-significant associations for 'mandatory mask only' and the combinations 'distancing + mandatory mask', 'traffic + mandatory mask' and 'traffic + distancing + mandatory mask' (Table 3). Non-significant associations were also found in some subgroup analyses (Table 4), which were inconsistent with previous studies reporting that the face mask was associated with reduced risk of COVID-19 infection (Cheng et al., 2020; Chu et al., 2020; Eikenberry et al., 2020). The lack of statistical significance for these associations in our study may be ascribed to the small number of cities or countries that implemented the above NPI types and combinations.

Our study has several important strengths. First, we captured the available data on confirmed cases of COVID-19 infection and legal NPIs implemented from 190 countries, which suggests that our findings are applicable in most countries worldwide. The large sample size allowed us to obtain more stable estimates and conduct a series of subgroup and sensitivity analyses, which generally yielded similar results, indicating that the associations observed in our study are robust. Second, we adjusted for a series of important confounders in the model, including socio-demographics and health security capacities. Finally, this study is the first to present a comprehensive and quantitative comparison of the effectiveness of various NPIs and their combinations at a global scale, which may provide timely evidence for policymakers to adopt appropriate NPIs in different countries to control the outbreak of COVID-19.

Several limitations should be noted. First, we treated an NPI as 'on' in the data analysis if the NPI was officially announced as being in force by a government. We were unable to account for the intensity of enforcement and people's compliance, which might have varied across countries and cities. Also, contents of each NPI at different sties might be somewhat different. However, we included a city-level random intercept that may control the between-city variations in intensity and compliance. Second, we considered four types of NPIs that were legally and officially announced by the governments of countries and cities considered in this study. A few NPIs, such as knowledge promotion, voluntary isolation and voluntarily wearing a mask were not considered. Moreover, some cultural factors such as personal hygiene, social habits and family size may influence the spread of COVID-19. Further investigations are warranted to assess the effects of these factors. Third, the information of testing capacities in each site was not available. However, we already adjusted for GHSI, which is an important indicator reflecting testing capacity. Fourth, although our results show non-significant associations of Rt with 'mandatory mask only' and the combinations 'distancing + mandatory mask', 'traffic + mandatory mask' and 'traffic + distancing + mandatory mask', we should interpret with caution because these estimates came from only a few sites. Fifth, because all the cities or countries took action to separate infected persons from uninfected persons at the outset, the effects of not separating infected persons remain unknown. Additionally, the effects of different NPIs may be highly correlated because they commonly, synchronously occurred and were jointly implemented, which may contradict the assumption of independent covariates in GLMM model. However, the results could also be affected by other NPIs if only one type of NPIs was considered. Thus, we gradually introduced two models and presented them separately in Table 2. The two models will allow us to compare the potential influences of additional three other NPIs on the effect of an individual NPI. Furthermore, mutually adjusted for the other three types of NPIs did not materially affect the conclusion.

In conclusion, we found that any type of NPI, namely mandatory face mask in public, isolation or quarantine, social distancing and traffic restriction, may reduce the spread of COVID-19. Social distancing seems more effective than the other three types of NPIs. The simultaneous implementation of two or more types of NPIs may be more effective for containing the spread of COVID-19.

Conflict of interests

None declared.

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Ethical approval

No ethical approval was required.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijid.2020.10.066.

References

Auger KA, Shah SS, Richardson T, Hartley D, Hall M, Warniment A, et al. Association between statewide school closure and COVID-19 incidence and mortality in the US. JAMA 2020;324(9):859–70.
Cheng VC, Wong SC, Chuang VW, So SY, Chen JH, Sridhar S, et al. The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. J Infect 2020;81(1):107–14.
Chinazzi M, Davis JT, Ajelli M, Gioannini C, Litvinova M, Merler S, et al. The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. Science (New York, NY) 2020;368(6489):395–400.
Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schünemann HJ. 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 (London, England) 2020;395(10242):1973–87.
Cori A, Ferguson NM, Fraser C, Cauchemez S. A new framework and software to estimate time-varying reproduction numbers during epidemics. Am J Epidemiol 2013;178(9):1505–12.
Cowling BJ, Ali ST, Ng TWY, Tsang TK, Li JCM, Fong MW, et al. Impact assessment of non-pharmaceutical interventions against coronavirus disease 2019 and influenza in Hong Kong: an observational study. Lancet Pub Health 2020;5 (5):e279–88.
Davies NG, Kucharski AJ, Eggo RM, Gimma A, Edmunds WJ. Effects of non-pharmaceutical interventions on COVID-19 cases, deaths, and demand for hospital services in the UK: a modelling study. Lancet Pub Health 2020;5(7): e375–85.
Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. Lancet Infect Dis 2020;20(5):533–4.
Du Z, Xu X, Wu Y, Wang L, Cowling BJ, Meyers LA. Serial interval of COVID-19 among publicly reported confirmed cases. Emerg Infect Dis 2020;26(6):1341–3.
Eikenberry SE, Mancuso M, Iboi E, Phan T, Eikenberry K, Kuang Y, et al. To mask or not to mask: modeling the potential for face mask use by the general public to curtail the COVID-19 pandemic. Infect Dis Model 2020;5:293–308.
Elaboration of data by United Nations DoEaSA. Population Division. World Population Prospects: The 2019 Revision. 2019.
Flaxman S, Mishra S, Gandy A, Unwin H, Coupland H, Mellan T, et al. Report 13: Estimating the Number of Infections and the Impact of Non-Pharmaceutical Interventions on COVID-19 in 11 European Countries. 2020.
Hernandez A, Correa-Agudelo E, Kim H, Branscum AJ, Miller FD, MacKinnon N, et al. On the impact of early non-pharmaceutical interventions as containment strategies against the COVID-19 pandemic. medRxiv 2020;(May):20092304.
Hunter PR, Colon-Gonzalez F, Brainard JS, Rushton S. Impact of non-pharmaceutical interventions against COVID-19 in Europe: a quasi-experimental study. medRxiv 2020;(May):20088260.
Johns Hopkins BsoPH. Global Health Security Index. 2019.

Jon Cohen KK. Mass testing, school closings, lockdowns: countries pick tactics in 'war' against coronavirus. Science (New York, NY) 2020;.
Koo JR, Cook AR, Park M, Sun Y, Sun H, Lim JT, et al. Interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. Lancet Infect Dis 2020;20(6):678–88.
Lai S, Ruktanonchai NW, Zhou L, Prosper O, Luo W, Floyd JR, et al. Effect of non-pharmaceutical interventions to contain COVID-19 in China. Nature 2020;585 (7825):410–3.
Lewnard JA, Lo NC. Scientific and ethical basis for social-distancing interventions against COVID-19. Lancet Infect Dis 2020;20(6):631–3.
Milne GJ, Xie S. The effectiveness of social distancing in mitigating COVID-19 spread: a modelling analysis. medRxiv 2020;(March):20040055.
Min KD, Kang H, Lee JY, Jeon S, Cho SI. Estimating the effectiveness of non-pharmaceutical interventions on COVID-19 control in Korea. J Korean Med Sci 2020;35(35):e321.
Pan A, Liu L, Wang C, Guo H, Hao X, Wang Q, et al. Association of public health interventions with the epidemiology of the COVID-19 outbreak in Wuhan, China. JAMA 2020;323(19):1–9.
Tian H, Liu Y, Li Y, Wu C-H, Chen B, Kraemer MUG, et al. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. Science (New York, NY) 2020; eabb6105.
Wind. Wind Financial Database. 2020.
World Health Organization. Coronavirus Disease (COVID-2019) Situation Reports. 2020.
Zhang Y, Jiang B, Yuan J, Tao Y. The impact of social distancing and epicenter lockdown on the COVID-19 epidemic in mainland China: a data-driven SEIQR model study. medRxiv 2020;(March):20031187.