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Physical distancing implementation, ambient temperature and Covid-19 containment: An observational study in the United States

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HIGHLIGHTS

• This is an observational study on physical distancing implementation and meteorological factors on COVID-19 in the US.
• Ambient temperature significantly interacts with physical distancing implementation on the transmission of COVID-19.
• The containing effects of high temperature were attenuated by 5.1% when physical distancing was implemented.
• Our study does not recommend relaxing the intervention of physical distancing in warm seasons/areas.

ABSTRACT

Governments may relax physical distancing interventions for coronavirus disease 2019 (Covid-19) containment in warm seasons/areas to prevent economic contractions. However, it is not clear whether higher temperature may offset the transmission risk posed by this relaxation. This study aims to investigate the associations of the effective reproductive number (Rt) of Covid-19 with ambient temperature and the implementation of physical distancing interventions in the United States (US). This study included 50 states and one territory of the US with 4,532,650 confirmed cases between 29 January and 31 July 2020. We used an interrupted time-series model with a state-level random intercept for data analysis. An interaction term of physical distancing×temperature was included to examine their interactions. Stratified analyses by temperature and physical distancing implementation were also performed to analyse the modifying effects. The overall median (interquartile range) Rt was 1.2 (1.0–2.3). The implementation of physical distancing was associated with a 12% decrease in the risk of Rt (relative risk [RR]: 0.88, 95% confident interval [CI]: 0.86–0.89), and each 5 °C increase in temperature was associated with a 2% decrease (RR: 0.98, 95%CI: 0.97–0.98). We observed a statistically significant interaction between temperature and physical distancing implementation, but all the RRs were small (close to one). The containing effects of high temperature were attenuated by 5.1% when physical distancing was implemented. The association of COVID-19 Rt with physical distancing implementation was more stable (0.88 vs. 0.86).
1. Introduction

Coronavirus disease 2019 (Covid-19) caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) was declared as a pandemic disease by the World Health Organization (WHO) on 12 March 2020. As of 5 May 2021, approximately 154 million cases and 3.2 million deaths due to Covid-19 had been reported worldwide, and the number of newly confirmed cases was increasing continuously (World Health Organization, 2021). This unprecedented pandemic imposed severe global health and economic impacts. Covid-19 transmission is further complicated by multidimensional factors, including but not limited to medical treatments, non-pharmaceutical interventions (NPIs), meteorological factors, and the natural development of the virus (Wiersinga et al., 2020; Shakil et al., 2020; Flaxman et al., 2020).

The transmissibility of Covid-19 was reported to be associated with various meteorological factors (Van Doremalen et al., 2013; Casanova et al., 2020), among which, ambient temperature may take the lead. Recent studies have shown that higher ambient temperature was associated with a slower transmission of Covid-19 during the early stage of this pandemic (Guo et al., 2020a; Baker et al., 2020; Pan et al., 2020a; Sajadi et al., 2020; Runkle et al., 2020; Lin et al., 2020a). Previous studies found that the associations of Covid-19 with temperature were relatively stronger as compared to the associations with relative humidity and wind speed (Guo et al., 2020a; Ma et al., 2020; Yuan et al., 2021), although it might be inappropriate to compare the associations directly. Previous studies also found that increasing temperature due to seasonality was associated with the decline in the infection of severe acute respiratory syndrome which emerged in 2003 (Bi et al., 2007; Chan et al., 2011; Tan et al., 2005), and influenza transmission is generally enhanced in cold weather (Xu et al., 2013). In addition, temperature can alter human behaviors, through which the effectiveness of physical distancing implementation might be affected. Accordingly, it is proposed that governments may relax various NPIs, especially physical distancing interventions in warm seasons/areas to prevent sharp contractions in the global economy.

Nevertheless, the potential interrelationship between ambient temperature and NPIs on the control of Covid-19 transmission remained unclear. Currently, NPIs are still the most important approaches to containing this global outbreak, given that most of the world’s population have not been vaccinated and medical treatments cannot interrupt the transmission. Among the various NPIs, physical distancing might be the most effective way to control the transmission of Covid-19 (Tanne, 2020). Thus, it is crucial to understand the role of ambient temperature in Covid-19 transmission and whether the benefits of increasing ambient temperature may offset the increased risk of Covid-19 transmission due to the relaxation of NPIs. Several studies investigated the main effects of physical distancing and temperature simultaneously (Rubin et al., 2020; Lin et al., 2020b; Juni et al., 2020), but only one examined the interaction by simulating a humidity-driven pandemic of SARS-CoV-2 using different basic reproduction numbers (Baker et al., 2020).

Another study performed subgroup analyses on the meteorology-Covid-19 associations stratified by the stringency index of NPIs (Choma et al., 2020). Further studies based on real-world data are necessary to enhance our understanding of the interactions between ambient temperature and physical distancing implementation on the transmission of Covid-19.

This study therefore aimed to investigate the modifying effects of ambient temperature on the associations between the implementation of physical distancing interventions and Covid-19 transmission in the 51 states/territories of the United States (US) between 29 January and 31 July 2020.

2. Materials and methods

2.1. Study population and design

This was an observational time-series study. Information on the number of daily confirmed Covid-19 cases was obtained from the data repository developed by Johns Hopkins University Centre for Systems Science and Engineering, which acquired real-time daily data from the Centres for Disease Control and Prevention of the US (Dong et al., 2020). Data from 50 states and one territory (Virgin Islands) of the US during the period of 29 January to 31 July 2020 were included in this study.

2.2. Meteorological factors

We collected hourly meteorological data, including mean temperature, relative humidity, and wind speed from the ground-based monitoring network of the World Meteorological Organization Global Telecommunications System. The daily average meteorological data were then calculated by aggregating the hourly data. If a study site had more than one monitoring stations, we calculated the population density-weighted averages of the meteorological factors using the following formula:

$$\text{Population weighted average} = \frac{T_1 \times W_1 + T_2 \times W_2 + \ldots + T_N \times W_N}{W_1 + W_2 + \ldots + W_N}$$

where, $T_i$ is the meteorological factor at the $i$th monitoring station within a state/territory and $W_i$ is the corresponding weight, i.e., the population density of the same state/territory. $W_i = 1, 2, 3, 4,$ and 5 represent the population densities of $<10$, $\geq 10$ to $<100$, $\geq 100$ to $<1000$, $\geq 1000$ to $<10,000$, and $\geq 10,000$ persons/km$^2$, respectively. A 14-day moving average of the meteorological factors was used to account for their delayed effects (Guo et al., 2020a). The relative risk (RR) of COVID-19 transmission was estimated for each 5°C increase in the mean temperature.

2.3. The implementation of physical distancing interventions

Information on the implementation of physical distancing interventions was obtained from the Oxford Covid-19 Government Response Tracker (OxCGRRT), which was developed and is regularly updated by the University of Oxford (Thomas et al., 2020). The data have been described in detail in a working paper series (Hale et al., 2020). Briefly, the Oxford team records the political interventions including physical distancing, economic reliefs and other healthcare related interventions from over 180 countries worldwide. In this study, we focused on the implementation of physical distancing intervention, which refers to the implementation of one or more of the following five components: school closing, workplace closing, mass gatherings restriction (a combination of public events cancellations and gathering restrictions), lockdown (a combination of stay at home requirements and internal movement restrictions) and public transport closing (Islam et al., 2020). We considered a 7-day lag effect of physical distancing in this study. That is, the period before the implementation of the interventions and the first 7 days of the implementation was treated as the pre-
intervention period (Islam et al., 2020). Physical distancing was therefore treated as a dummy variable, with 1 indicating the implementation in the post-intervention period and 0 indicating the non-implementation in the pre-intervention period.

2.4. Covariates

Information on demographics (including population, population density [persons per square kilometre], and median age [years]) and gross domestic product (GDP) per capita (dollars/year) was obtained from the United Nations, Department of Economic and Social Affairs, Population Division (Elaboration of Data by United Nations DoEaSA, Population Division, 2019). We also collected the daily test positivity rate of Covid-19, which refers to the number of persons who were tested positive for each 100,000 persons who had tests. The test positivity rate was from the COVID Tracking Project, a volunteer organisation launched by The Atlantic in the US (Atlantic et al., 2020). Geographic locations (latitude and longitude) were obtained from Google Maps. Public holidays, days of week and the time index were also included.

2.5. Daily effective reproduction number

We assessed Covid-19 transmission over time by using the daily effective reproduction number ($R_t$). $R_t$ refers to the mean number of secondary infections caused by a primary infected person at time t. $R_t > 1$ indicates that an epidemic may continue to expand, while $R_t < 1$ indicates that an epidemic is under control. The daily $R_t$ and its 95% confidence interval (CI) were calculated based on the method developed by Cori et al. (Cori et al., 2013). To make the estimates stable, a 7-day moving average of $R_t$ was used. The serial interval was assumed to follow a gamma distribution with a mean of 3.96 and standard deviation of 4.75 (Du et al., 2020).

2.6. Statistical analysis

An interrupted time-series analysis was used to investigate the associations of Covid-19 transmission with ambient temperature and the implementation of physical distancing interventions. We hypothesised that the $R_t$ of Covid-19 follows a logarithmic normal distribution (Li et al., 2021). A state-level random intercept was included to account for clustering effects within the same state. The following factors were included in the model as covariates: latitude, longitude, positive rate, median age, GDP per capita, the logarithm of population, day of week, holidays, 14-day average of relative humidity and wind speed, a natural cubic spline function of the time index (to control for the seasonality (Liu et al., 2019)), and the $R_t$ of Covid-19 in the previous day (to account for the temporal autocorrelation). The statistical model was specified as follows:

$$
\log (E(R_{t,0-6})) = \alpha + \beta_1 \text{temp}_{t,0-13} + \beta_2 \text{humi}_{t,0-13} + \beta_3 \text{wind}_{t,0-13} + \beta_4 \text{PD}_{t,7} + \log \left( R_{t-1,0-6} \right) + \text{offset} \left( \log \left( \text{Pop}_t \right) \right) + I(DOW_t) + I(Holiday_t) + ns(time, 4) + Cov_t + \beta_5 \text{temp}_{t,0-13} \times PD_{t,7}
$$

In which, $R_{t,0-6}$ is the 7-day moving average of the $R_t$ of Covid-19 in the $t^{th}$ state/territory ($i = 1, 2, 3, \ldots, 51$) on the $t^{th}$ day (from 29 Jan to 31 Jul 2020). $\alpha$ is the state-level random intercept. $\text{temp}_{t,0-13}$, $\text{humi}_{t,0-13}$ and $\text{wind}_{t,0-13}$ is the 14-day average moving average of temperature, relative humidity and wind speed, respectively. $\beta_1$, $\beta_2$, and $\beta_3$ is the corresponding coefficient of the meteorological factors. $PD_{t,7}$ is the implementation of physical distancing interventions at a lag of 7 days and $\beta_4$ is the corresponding coefficient. $R_{t-1,0-6}$ is the 7-day moving average $R_t$ on the (t-1)" day, $\log \left( R_{t-1,0-6} \right)$ is the log of $R_t$ on the (t-1)" day, $Pop_t$, $DOW_t$, $Holiday_t$, and $Cov_t$ is the population, day of the week, holiday indicator, and other covariates (including latitude, longitude, positive rate, median age, GDP per capita) in the $t^{th}$ state. $ns(time,4)$ is the natural cubic spline function of time with 4 degrees of freedom. $\text{temp}_{t,0-13} \times PD_{t,7}$ refers to the interaction effect between ambient temperature and physical distancing implementation, and $\beta_5$ is the corresponding coefficient. The relative risk (RR) of Covid-19 transmission was estimated by calculating the exponential transformation of the corresponding coefficients. We first assessed the main associations of the $R_t$ of Covid-19 with ambient temperature and physical distancing implementation separately; in other words, ambient temperature and physical distancing implementation were included in the model as independent variables. We then mutually adjusted for temperature and physical distancing implementation for comparison; that is, we further adjusted for temperature to investigate the association between the $R_t$ of Covid-19 and physical distancing implementation, or further adjusted for physical distancing to investigate the association between the $R_t$ of Covid-19 and temperature. To explore the interaction effect of temperature and physical distancing implementation, an additional test for interaction was performed by including an interaction term of ‘temperature $\times$ physical distancing’ in the model. RRs with a 95% confidence interval (CI) were used to present the strengths of the associations of Covid-19 $R_t$ with temperature and physical distancing implementation.

Stratified analyses were performed to examine the modifying effects of ambient temperature on the associations between physical distancing implementation and Covid-19 transmission. The modifying effects of ambient temperature on the five specific components of physical distancing implementation were also examined. We also compared the temperature $− R_t$ associations stratified by the implementation and non-implementation of physical distancing interventions. We further plotted the concentration − response curves between temperature and $R_t$ stratified by the implementation of physical distancing interventions.

We performed a series of sensitivity analyses to examine the stability of the estimated associations by 1) using temperature quartiles (i.e., stratified the observations equally divided into four groups based on quartiles) to examine whether the interactions between the implementation of physical intervention interventions and temperature quartiles were different; 2) using the 7-day or 10-day moving average of mean temperature instead of the 14-day moving average; 3) examining the 5-day or 10-day delayed effects of physical distancing implementation; 4) excluding the territory, Virgin Islands from the main analysis; 5) examining the physical distancing implementation that were implemented consistently in each whole state (i.e., both the non-implementation period and the period when only a few counties/cities implemented the interventions were treated as the pre-intervention period); 6) including the intensity of the interventions: school closing (0 = no measures, 1 = recommend/require closing at some levels, and 2 = require closing at all levels), workplace closing (0 = no measures, 1 = recommend/require closing at some levels, and 2 = require closing at all levels), gatherings restriction (0 = no measures, 1 = recommend cancelling public events or restrict gatherings between 100 and 1000 people, and 2 = require cancelling public events or restrict gathering of 100 people or less), lock down (0 = no measures, 1 = recommend not leaving home or not traveling between regions/cities, and 2 = require not leaving home or traveling in place), public transport closing (0 = no measures, 1 = recommend closing, and 2 = require closing), and overall physical distancing (0 = no measures, 1 = recommends cancelling public events or restrict gatherings at all levels, and 2 = requires), for days when different interventions were implemented with different intensities, the highest intensity was used; and 7) including an interaction term between physical distancing implementation and time to examine whether the effects of physical distancing implementation may decrease overtime.

R version 4.0.2 (R Core Team, Vienna, Austria) was used to perform all data analyses. The estimated associations were treated as statistically significant if a two-tailed $P$ value $<0.05$.

3. Results

In this study, a total of 50 states and one territory of the US, which reported 4,532,650 confirmed cases of Covid-19 between 29 January
and 31 July 2020 were included. The number of sample size was 9435. As of 31 July 2020, the top five states with the largest number of confirmed cases were California, Florida, Texas, New York, and Georgia (Table S1 in Appendix A). The overall median Rt value was 1.2, with an interquartile range (IQR) of 1.0–2.3 over the study period (Table S1 in Appendix A). As the same date, only 19 (37.3%) states had a median Rt of <1. The overall median temperature over the study period was 15 °C, with an IQR of 7 °C–23 °C. The median (IQR) relative humidity and wind speed were 68% (57%–77%) and 3 m/s (2 m/s–4 m/s), respectively (Table S1 in Appendix A). Washington was the first state in the US to implement physical distancing for Covid-19 control on 4 March 2020, while most other states implemented physical distancing approximately one week later (Table S2 in Appendix A). Fig. 1 shows the temporal distributions of Covid-19 cases, the overall Rt, and the mean temperature. The median Rt generally decreased during the study period and reached 1.034 (IQR: 0.998–1.069) on 31 July 2020.

Table 1 shows the associations of the Rt of Covid-19 with daily mean temperature and the implementation of physical distancing interventions. Both higher temperature and implementation of physical distancing interventions were associated with a lower Rt of Covid-19. The Rt of Covid-19 decreased 2% for each 5 °C increase in mean temperature and the corresponding RR was 0.98 (95% CI: 0.97–0.98). The implementation of physical distancing was associated with a 12% decrease in the Rt (RR [95%CI]: 0.88 [0.86–0.89]). Regarding the five specific components of physical distancing, we observed that Rt decreased 13% (RR [95%CI]: 0.87 [0.86–0.89]) for school closing, 12% (0.88 [0.86–0.89]) for workplace closing, 12% (0.89 [0.87–0.91]) for gatherings restriction, 11% (0.89 [0.87–0.91]) for lockdown, and 2% (0.98 [0.97–0.99]) for public transport. The effects of mean temperature and the implementation of physical distancing interventions on the Rt of Covid-19 were generally comparable after mutual adjustment (Table 1). Significant interactions between mean temperature and the implementation of physical distancing interventions on the Rt were observed, with P values ranging from 0.001 to 0.012. However, all RRs for the interaction terms were minor (RR [95%CI]: 1.01 [1.00–1.01]) (Table 1).

Table 2 shows the associations between Covid-19 Rt and the implementation physical distancing inventions and its components stratified by ambient temperature with the median value (13 °C) as the cut-off point. The Rt of Covid-19 showed significant associations with the implementation of all physical distancing components in both low- and high-temperature groups except for the public transport closing component in the low-temperature group. The RRs of Covid-19 Rt for the implementation of physical distancing interventions and its components were generally comparable between the low- and high-temperature groups (the differences in corresponding RRs ranged from −1.1% to 3.3%).

The associations between Covid-19 Rt and daily mean temperature stratified by the implementation and non-implementation of physical distancing interventions are shown in Table 3. As compared to the RtRs when physical distancing was implemented, the RR decreased 5.1% when physical distancing was not implemented (0.94 vs. 0.99). No significant associations between temperature and Covid-19 Rt were observed when school and workplace closing, gatherings restriction and lockdown was not implemented. However, significant associations were observed when physical distancing interventions was implemented, although these yielded relatively small RRs (each 5 °C increase in temperature was associated with a 1%–2% lower RR of Covid-19 Rt). Fig. 2 presents the concentration–response curves between temperature and Covid-19 Rt stratified by the implementation of physical distancing interventions.
Associations between the effective reproduction number of Covid-19 and ambient temperature or physical distancing interventions in the United States.

| Interventions | Temperature (°C) | Physical distancing | School closing | Workplace closing | Gatherings restriction | Lock down | Public transport closing | Intervention (yes vs. no) | Temperature (5 °C) | Intervention (yes vs. no) | Public transport closing |
|---------------|-----------------|---------------------|---------------|------------------|-----------------------|----------|-------------------------|-------------------------|-------------------|------------------------|------------------------|
| No mutual adjustment | RR (95%CI) | P value | RR (95%CI) | P value | RR (95%CI) | P value | RR (95%CI) | P value | RR (95%CI) | P value | RR (95%CI) | P value |
| Physical distancing | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 |
| School closing | 0.88 (0.86, 0.89) | <0.001 | 0.88 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 |
| Workplace closing | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 |
| Gatherings restriction | 0.88 (0.86, 0.89) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 |
| Lock down | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 | 0.98 (0.97, 0.98) | <0.001 |
| Public transport closing | 0.88 (0.86, 0.89) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 | 0.87 (0.85, 0.88) | <0.001 |

Abbreviations: Covid-19, coronavirus disease 2019; RR, relative risk; CI, confidence interval.

Sensitivity analyses generally yielded similar results when we used the 7-day or 10-day moving average of temperature (Tables S4 and S5 in Appendix A), when we used the 5-day or 10-day lag of physical distancing implementation (Tables S6 and S7), or when we excluded the territory-Virgin Islands (Table S8), when we used different pre-intervention period (Table S9) and including the intensity of the interventions (Table S10). The interactions between physical distancing implementation and temperature were statistically significant for all temperature quartiles except the 4th quartile (Table S3). The effects of physical distancing implementation were generally stable over the intervention period (RRs ranged from 1.00 to 1.01), the interactions were statistically significant (Table S11).

4. Discussion

This time-series study investigated the associations between ambient temperature, physical distancing implementation, and Covid-19 transmission based on the real-world observational data. Both higher temperature and the implementation of physical distancing interventions were associated with a lower Rt of Covid-19. However, the associations of Covid-19 transmission with the implementation of physical distancing interventions (implemented vs not implemented) were much stronger than those with temperature (every 5 °C), indicating the importance of physical distancing interventions in Covid-19 containment. We observed statistically significant interactions of ambient temperature and physical distancing implementation on Covid-19 transmission, but the modifying effects of temperature on the associations between physical distancing implementation and Covid-19 transmission were small. This suggests that higher temperature did not offset the containing effects of physical distancing implementation on Covid-19 transmission. Our results suggest that physical distancing interventions should be continued in warm seasons/areas to effectively contain the transmission of Covid-19.

4.1. Comparison with previous studies

We observed that the implementation of physical distancing interventions were negatively and consistently associated with Covid-19 transmission, which is in line with previous studies that focused on
the Covid-19 incidence (Islam et al., 2020; Pan et al., 2020b) or Rt (Koo et al., 2020; Bo et al., 2020). All the five specific components of physical distancing were associated with a lower $R_t$, and closing school and workplace seemed to be the most effective measurements in the US (Table 1). Overall, our study found that the implementation of physical distancing and its five components could reduce the risk of Covid-19 Rt by 4%–13%. Islam et al. (Islam et al., 2020) also observed that the implementation of physical distancing decreased the Covid-19 incidence by 13% in 149 countries worldwide. Similar effects of implementing gatherings restriction were observed in the US as compared to the effect in the world (12% vs. 10.6%) (Bo et al., 2020). In contrast, the effects of implementing the intervention of closing public transport were relatively weaker in the US than those in other countries in the World (4% vs. 9.6%) (Bo et al., 2020). This is possibly because only one state implemented this intervention consistently in each county of the state in the US. Stronger associations between other NPIs and the Covid-19 transmission were observed in our previous study (Guo et al., 2020a; Bo et al., 2020) of examining the interaction effects between ambient temperature and the implementation of physical distancing interventions on the transmission of Covid-19. We observed a statistically significant interaction between ambient temperature and physical distancing implementation on Covid-19 transmission. However, the modifying effects of ambient temperature on the associations between physical distancing implementation and Covid-19 transmission were small (e.g., the containing effects of physical distancing implementation were enhanced by $-0.9%$–$3.3%$ in areas with a median temperature of $\geq 13^\circ$C (Table 2). Baker et al (Baker et al., 2020) performed a modelling study and observed that NPIs may moderate the associations between the peak incidence size and climate (i.e. season and humidity). This interaction might be explained by the fact that physical distancing can

We also observed significant associations between Covid-19 transmission and ambient temperature with relatively weak $R_R$, which were supported by recent publications (Rubin et al., 2020; Jia et al., 2020; Guo et al., 2020b; Wang et al., 2020; Yu, 2020). Our previous study also reported similar findings on the associations between ambient temperature and the Covid-19 incidence (Guo et al., 2020a). Although it is inappropriate to directly compare the estimated associations because different outcomes were used, we found that ambient temperature may have a higher effect on the incidence than on the $R_t$ of Covid-19 ($0.75$ vs. $0.96$ for each $11 ^\circ$C increase in ambient temperature). This suggests that ambient temperature may have a weaker effect on the transmissibility of Covid-19 among general population. In contrast, three studies in China (Poirier et al., 2020; Jamil et al., 2020) and other countries (Pan et al., 2020a) that used the $R_t/R_{proxy}$ as an indicator of transmission did not find significant associations.

In this study, we extended our previous two studies (Guo et al., 2020a; Bo et al., 2020) of examining the interaction effects between ambient temperature and the implementation of physical distancing interventions on the transmission of Covid-19. We observed a statistically significant interaction between ambient temperature and physical distancing implementation on Covid-19 transmission. However, the modifying effects of ambient temperature on the associations between physical distancing implementation and Covid-19 transmission were small (e.g., the containing effects of physical distancing implementation were enhanced by $-0.9%$–$3.3%$ in areas with a median temperature of $\geq 13^\circ$C (Table 2). Baker et al (Baker et al., 2020) performed a modelling study and observed that NPIs may moderate the associations between the peak incidence size and climate (i.e. season and humidity). This interaction might be explained by the fact that physical distancing can

![Fig. 2. Concentration–response curves between ambient temperature and the effective reproduction number of Covid-19 and their associations stratified by physical distancing implementation.](image-url)
restrict people’s activities and thus reduce exposure to deteriorative weather and deplete the susceptibility to SARS-CoV-2. Notably, we observed that the containing effects of physical distancing implementation were also slightly enhanced in warm weather/areas, possibly through reductions in the activity and viability of the virus. In contrast, our study was different from the study conducted by Choma et al. (Choma et al., 2020) that found no associations between ambient temperature and Covid-19 incidence after stratifying by the stringency index of NPIs. Other studies mainly investigated the main effects of ambient temperature or NPIs on Covid-19 transmission or incidence after adjusting for each other rather than examining the interaction effects (Rubin et al., 2020; Lin et al., 2020b; Juni et al., 2020; Jia et al., 2020; Yu, 2020; Shen et al., 2020). Further studies are warranted to confirm the potential interaction effects between physical distancing and meteorological factors on Covid-19 transmission.

4.2. Strengths and limitations

This study investigated the interaction effects between ambient temperature and the implementation of physical distancing interventions on the Rt of Covid-19 based on real-world time-series data and the findings are novel. The relatively large sample size enabled us to obtain more stable results. In addition, we adjusted for a series of important confounders, such as the test positivity rate, which was ignored in some previous studies. The test positivity rate, along with the number of confirmed cases is crucial to the provision of reliable evidence on the transmission and infection of Covid-19.

A few limitations should be acknowledged. First, we conducted this study in the US. Thus, we should be cautious when generalising the findings to other countries. Further research is warranted to examine whether the interactions remain consistent in other countries or at a global scale. Second, a few potential confounders, such as air pollutants and personal hygiene were not included in this study. Third, the state-level data, including the implementation of physical distancing interventions, meteorological factors and Covid-19 Rt, were used in this study. These state-level data were relatively crude and cannot capture the within-state variations. However, the differences in the physical distancing implementations by state and local governments only affect 16% population (Gupta et al., 2020; Yehya et al., 2020). Studies with a higher spatial resolution should be conducted to examine the associations between physical distancing implementation, temperature and Covid-19 transmission in near future. Finally, the implementation of physical distancing interventions was included as a single binary indicator in the main analysis. The type and intensity of physical distancing interventions may vary over time and other NPIs were not included in this study. However, the sensitivity analysis by including the intensity of physical distancing interventions shows that this may not significantly bias our main findings (Table S10).

5. Conclusions

In summary, we found that both higher ambient temperature and the implementation of physical distancing interventions were associated with a lower risk of Covid-19 transmission. Covid-19 transmission was much more strongly associated with physical distancing implementation than with ambient temperature. Thus, physical distancing implementation may play a more important role in the containment of Covid-19, at least in the early stage of the pandemic. We also observed a significant interaction between ambient temperature and physical distancing implementation. However, the increased temperature in warm seasons/areas cannot offset the containing effects of physical distancing implementation on Covid-19 transmission. Our study suggests that a reliance solely on increased temperature to contain Covid-19 transmission is not sufficient. Physical distancing interventions should be implemented continuously in warm seasons/areas to achieve effective Covid-19 containment.

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CRediT authorship contribution statement

XQL, CG, and AKHL conceptualized and designed the study. AKHL, CG, CL, JWMC, and DWY acquired the data. CG, SHTC, YZ, and YB searched literature. CG analyzed data. CG, XQL, and AKHL interpreted the data. CG, SHTC, and XQL drafted the manuscript and produced the figures. All authors critically revised the manuscript. XQL and AKHL obtained the funding and supervised this study.

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Declaration of competing interest

The authors declared that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147876.

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